DIAGNOSIS OF HEADWATER SEDIMENT DYNAMICS IN NEPAL'S MIDDLE MOUNTAINS: IMPLICATIONS FOR LAND MANAGEMENT

by

Martin Carver

B.Sc., University of Manitoba, 1984
M.A.Sc., University of Waterloo, 1988

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

THE FACULTY OF GRADUATE STUDIES

(Interdisciplinary Studies in
Resource Management Science)

We accept this thesis as conforming
to the required standard

The University of British Columbia

June, 1997

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

~~Department~~ Faculty of Graduate Studies - Interdisciplinary Studies.

The University of British Columbia
Vancouver, Canada

Date June 4, 1997

DE-6 (2/88)

DE-6 (2/88)

Diagnosis of Headwater Sediment Dynamics in Nepal's Middle Mountains: Implications for Land Management

Abstract

An evaluation of headwater erosion and sediment dynamics was carried out to assess the health of the Middle Mountain agricultural system in Nepal. Controversial statements predicting this system's imminent demise and identifying Middle Mountain farming practices as major contributors to downstream sedimentation and flooding have long been promoted and have suggested the following research hypothesis: soil and sediment dynamics and the indigenous management techniques within headwater Middle Mountains basins do not indicate a deterioration in the health of the agricultural system. Three questions were addressed in this research. What are the main controls on normal-regime erosion? How effective is the system of indigenous management at modifying sediment dynamics? What do headwater sediment budgets (erosion, storage, and yield) reveal about the health of the agricultural system? Answers to these questions are suggested and development initiatives proposed.

Intensive monitoring was carried out during 1992-1994 within nested basins ranging in size from 72 to 11 141 ha. Variation of storm-period variables in time and space was assessed using five recording rain gauges and a network of up to fifty 24-hour gauges. Surface erosion was measured from five erosion plots on steep *bari* (rainfed cultivated land). Suspended sediment behaviour was examined through event sampling at seven hydrometric stations. Basin sediment yield was determined for three of these nested basins. Sediment storage was assessed using accumulation pins in *khet* fields (irrigated cultivated land), *khet* canals, and *bari* ditches and through erosion and channel surveys.

An annual average of 77 storms were identified over the three-year period with 3.5% of these delivering more than 30 mm total rainfall and a peak 10-minute rainfall intensity of more than 50 mm/h. About 1/3 of all storms regardless of magnitude occurred during the pre-monsoon season. Pre-monsoon and monsoon storms delivered equivalent high-intensity short-term rainfall disputing the hypothesis that it is a higher rainfall intensity in the pre-monsoon season which causes an elevated sediment regime

during that season. Total storm rainfall was significantly higher during the monsoon season whereas the period without rain before a storm begins was longer for pre-monsoon storms.

The source of suspended sediment was found to vary with season and spatial scale. During the pre-monsoon season, surface erosion from *bari* was severe when high-intensity rain fell on bare ground. Indigenous farming practices were found to be effective at limiting surface erosion except during the pre-monsoon season when targeted intervention may be useful. During the pre-monsoon season, nutrient loss from headwater basins due to sediment export was at its highest. Severely degraded land remained bare throughout the rainy season, producing sediment at an elevated rate and in relation to total rainfall.

The onset of the monsoon season reduced this *bari* source markedly due to the complete development of a vegetative cover under conventional management. The pre-monsoon-season surface-erosion mechanism of sediment production was replaced with scale-dependent mechanisms resulting from the higher total rainfall of monsoon-season storms. Within the steep terraced hillslopes, the capacity of runoff ditches was more often exceeded resulting in episodic-regime rilling, gullying, and in some instances, terrace failure. When sufficiently heavy and widespread, monsoon storm rainfall led also to stream discharge high enough to damage riparian areas and the system of irrigation dams.

The farmers alter the sediment regimes profoundly and their management activities reduce soil loss collectively over all spatial scales. Sediment budgets reveal that a significant component of the sediment produced in the study basin (5.3 km^2) was recaptured (35% to 50%) because of these indigenous farming practices. Objective calibration of indigenous knowledge showed it to be well founded but inconsistent. Farmers practise techniques which are well adapted to this environment reflecting their stated receptiveness to innovation and outside support.

The detailed measurements show that the important controls on erosion are variable temporally and spatially over scales too small to be considered by conventional monitoring programs in these environments. Spatial differences in rainfall delivery, hysteresis effects, variability in land-surface response, and management activities conspire to yield sediment dynamics which are difficult or impossible to quantify with typical limited monitoring. Site-specific opportunities for investigation should be exploited and a high degree of uncertainty be anticipated.

Management recommendations focus on two topics. An improved vegetative cover during the pre-monsoon season is required to reduce soil erosion during that period. Greater retention of these nutrient-rich soils would directly benefit the upland farmer. Rehabilitation of degraded lands and the halting or reversing of further degradation would benefit all farmers by providing a greater land base for biomass production especially in light of an increasing population. Both strategies would benefit hydropower developments by limiting reservoir sedimentation. Above all, proposed changes should enhance - not undermine - indigenous management.

Current soil dynamics may be sustainable but it is unlikely that they can remain so in the future under the increased landuse intensification that may be necessary with projected population increases unless support is provided strategically from outside sources. Working with the farmers to develop techniques to improve their ability to recapture previously-eroded soil is a useful area of applied research. The high degree of skill and adaptability of the farmers within this environment suggest that carefully designed intervention which targets vulnerable aspects of the agricultural system while not undermining the present methods have a reasonable likelihood for success.

**Diagnosis of Headwater Sediment Dynamics in
Nepal's Middle Mountains: Implications for Land Management**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

ASCE	American Society of Civil Engineers
DHM	Department of Hydrology and Meteorology
DSCWM	Department of Soil Conservation and Watershed Management
FAO	Food and Agricultural Organisation
HMG	His Majesty's Government
SDR	sediment delivery ratio
USLE	Universal Soil Loss Equation

LIST OF SYMBOLS

λ	ratio of the error variances (E_C^2/E_Q^2)
a	coefficient of the power-law relation $C=aQ^b$
b	exponent of the power-law relation $C=aQ^b$
C	total suspended sediment concentration, g/l (cover factor in USLE)
C_R	event runoff coefficient (erosion plots)
	= the percentage of incoming storm rainfall which runs off the plot
CF	correction factor for calculating stream discharge
CV	coefficient of variation
E	realised measurement error
E_C^2	error variance of C
E_Q^2	error variance of Q
F	falling limb
GH	gauge height (cm)
I_{10}	maximum 10-minute storm rainfall intensity (mm/h)
I_{60}	maximum 60-minute storm rainfall intensity (mm/h)
K	soil erodibility factor (USLE)
L	slope length factor (USLE)
M	monsoon season
n	sample size
N	number of storms
P	pre-monsoon season (management factor in USLE)
Q	stream flow rate (m^3/s)
R	falling limb (rainfall factor in USLE)
R^2	correlation coefficient

R_{MIN} minimum total event rainfall to be considered a storm (mm).

R_T total storm rainfall (mm).

s sample standard error

S time without rain between storms, h (slope steepness factor in USLE)

s_r standard error of the estimate

S_{MIN} minimum time without rain to declare new storm (h)

t student's t-distribution

T transition season

T_{10} timing of I_{10} relative to the storm start (h)

T_{60} timing of I_{60} relative to the storm start (h)

T_{DUR} total storm duration (h).

V flow velocity (m/s)

x sample mean

COMMON SUBSCRIPTS

exp expected value (based on marginal regression)

f result from functional analysis

meas measured value

min minimum

max maximum

r result from marginal regression

surface measured at the surface

T total

ACKNOWLEDGEMENTS

I would like to express my thanks to the International Development Research Centre for its direct support of this research through a Young Canadian Researcher's Award to me and their ongoing support of the Mountain Resources Management Project of which this research has been a part. I would also like to thank the Natural Sciences and Engineering Research Council of Canada for supporting me financially during 1990-1992. In addition, the International Centre for Integrated Mountain Development (ICIMOD, Kathmandu) and the Integrated Survey Section (His Majesty's Government, Kathmandu) both provided invaluable assistance and administrative support during my field seasons in Nepal during 1991-1994.

The dedication of Dr. Hans Schreier, my research supervisor, in collaboration with Mr. Pravakar B. Shah (ICIMOD) made this work possible. Without their tenacity in keeping the larger project alive, this research would not have occurred. I would also like to thank my entire Supervisory Committee - Dr. Hans Schreier, Dr. Mike Church, Dr. Les Lavkulich, Dr. Tim Ballard, and Dr. Hamish Kimmins - for giving direction especially during the earlier years of this work.

An interdisciplinary research project like this is rarely achieved without the support and participation of many people. A dedicated team of individuals in Nepal under the direction of Mr. Pravakar B. Shah assured the completion of this research. The tireless enthusiasm of Mr. Gopal Nakarmi and the calm thoroughness of Mr. Bhuban Shrestha were instrumental in motivating field staff and making the field work successful. My stay in the field was made much easier and more enjoyable by the collaboration of Mr. A. Raj Pathak whose good humour and capacity for field work is well known throughout Nepal.

Many farmers within the study area participated directly in this research through data collection. I am grateful to them and would like to mention in particular Mr. Dipak Bhetwal, Mr. Uddav Pathak, Mr. Hirinath Bhetwal, Mr. Prem Lama, and Mr. Sudarsan Accharya and their families for their partnership and the high quality of their work.

Technical support in both Canada and Nepal has been invaluable. Claire Dat, Kathi Hofmann, and SiPing Tu worked diligently with irreplaceable sediments in the UBC Soil Science and Geography laboratories. Technical support from Sandra Brown, Yao Cui, and Wayne Tamagi in the Geographic Information System Laboratory (UBC) is also gratefully acknowledged. Andrew Faulkner's suggestions on database management improved the efficiencies of the analyses.

I have benefitted greatly from discussions with many other scientists. Mr. Brian Carson kindly shared with me his experience and reflections from his years of work in Nepal. Dr. Johannes Ries and Petra Schweizer provided hospitality and inspiration on the mechanics of carrying out the field work required for this study. Similarly, Ms. Susanne Wymann and Dr. Jemuel Perino shared their experiences of carrying out research in Nepal. Discussions with Dr. Marwan Hassan, Dr. Judy Haschenburger, and Dr. Tony Kozak at UBC were always very helpful. Thanks also to my office friend, Kathy Cook, who shared with me her critical thinking.

A special appreciation is extended to Dr. Mike Church who influenced profoundly the study design and data analysis in this research and whose level of involvement in this work, for me, matched that of a co-supervisor. His ability to marry the highest standard of scientific endeavour with the realities of applied research will have a long-lasting effect on my future research activities and scientific interpretations.

And most of all, thank you to Kathi for accepting these years of research and for being there at their conclusion.

FOREWORD

The findings reported in this document are based on extensive field and laboratory data. The original data are available on diskette by contacting the author through the Institute for Resources and Environment, University of British Columbia, 436E-2206 East Mall, Vancouver, B.C., CANADA V6T 1Z3 (or via email at ire@unixg.ubc.ca).

PART I Biophysical Analyses

1. General Introduction

1.1 Problem Statement

Nepal's dramatic mountainous relief, frequently incompetent bedrock, rapid tectonic uplift, and warm monsoonal climate all indicate that weathering and erosion have long been intense and an important aspect of life in Nepal for a very long time. More recently, with expanding populations both in Nepal and in downstream neighbouring regions, there has been increasing alarm about steepland cultivation and other agricultural landuse practices in the mountainous regions due to the presumed acceleration of erosion. Concern about stream sediment levels and their potential both for endangering the viability of upland farming and for yielding negative consequences downstream have led to many strong statements about sediment dynamics on these southern slopes of the Himalaya (World Bank 1979; Eckholm 1975). Unfortunately, when the bases of these statements are examined, little or no quantitative scientific data are available to substantiate the statements made.

A clearer picture of the fertility and landuse dynamics of these headwater catchments is emerging. Detailed measurements in the Jhikhu River basin show that although there have been significant increases in both forest cover and cultivated land from 1972 to 1990 (Schreier et al. 1994), the fertility of the agricultural land (Wymann 1993) and the quality of the forests (Schmidt 1992) are declining. We do not, however, have equivalent quantitative measurements of erosion and sediment transport even though tolerable rates of surface erosion are an essential underpinning to a sustainable agricultural system. No matter how good the economy might be, and no matter how many inputs can be brought in from the outside, if erosion is excessive, widespread site degradation will put the entire system into decline.

It is clear that rates of erosion in the steepland agricultural areas of Nepal are high. What is far less clear is what these rates are over various spatial and temporal scales, whether these rates are acceptable within the framework of a sustainable agricultural system, and how effective the indigenous population is at controlling erosion. By looking in detail at sediment dynamics in low-order Middle Mountains catchments of varying size, this study tries to answer some of these questions.

This study is also relevant to a debate which has persisted for the past two decades concerning the influence of landuse practices in the uplands on flooding in the distant lowlands. Eckholm (1975), Myers (1986) and others have promoted the notion that deforestation in the upland agricultural areas of Nepal is causing massive stream sedimentation and consequent devastating floods in the lowlands of Bangladesh and that there will be no forests left in Nepal by the turn of the century. These forecasts of Himalayan environmental catastrophe greatly influenced development activity until the mid-1980s. Many other authors and researchers (*e.g.*, Gilmour 1988; Ives and Messerli 1989; Lauterburg 1993) have tried to show that the linkages are mythical and statements of imminent forest and agricultural demise are unfounded.

No one study can answer all of the questions posed and suggested above. In this study, the focus is on headwater catchments. The steep topography and intense rainfall in these areas present a challenging environment for agriculture. These natural factors, combined with the heavily manipulated agricultural lands, render these headwater areas vulnerable to severe erosion. Because of population increase, the headwater areas are under tremendous pressures from landuse intensification. Thus, important baseline information must be established if we hope to improve the diagnosis of this agricultural system to enhance its future viability.

1.2 Research Context

Ives and Messerli (1989) have summarised others' hypotheses of this region's imminent catastrophe calling it the Theory of Himalayan Environmental Degradation. In the theory, it is assumed that population growth is the root cause of all environmental degradation in the Himalayan region. The mountain farmer is seen as an ignorant accomplice in a vicious cycle of resource extraction and environmental demise. The upland degradation is soon followed by widespread flooding and sedimentation causing further disruption and demise for a far greater population. Though based on economic indicators and real data describing landuse change, these statements ignored scientific understanding about highland-lowland linkages.

Until the late 1970s, there was an absence of any quantitative measurements of erosion and sediment transport in the Middle Mountains. From the late 1970s through the late 1980s, a number of independent studies (Kandel 1978; Mulder 1978; Laban 1978; Upadhaya *et al.* 1991; DSCWM 1991; Sherchan *et al.* 1991) attempted to examine erosion quantitatively in the southern Himalaya and in the Middle Mountains. These initial attempts to assess erosion in the Middle Mountains, reviewed later in Chapter 5, emphasise surface-erosion estimates over fixed spatial and temporal scales. Spatial scales varied from an erosion-plot scale (10 to 100 m^2) to specific catchment scales (10 to 1000 km^2) with little or no intermediate resolution. Similarly, the results were generally presented as annual rates with little or no temporal resolution.

There was a growing awareness in the 1980s that the Theory of Himalayan Environmental Degradation should be challenged on the basis of its inadequate data and fundamental misunderstandings about both the behaviour of highland-lowland systems and the role of the people living within the area. This recognition was formalised at the Mohonk Mountain Conference in 1985 which set the stage for integrated studies of landuse, erosion, and management. Thompson and Warburton (1985) put forth the thesis that uncertainty in the Himalaya is so extreme that uncertainty itself contains the problem and therefore standard scientific approaches to understanding and addressing the Theory of Himalayan Environmental Degradation cannot succeed.

In the 1990s, several long-term integrated studies were initiated, incorporating measurements of surface erosion and mass wasting with related precipitation and landuse parameters (Perino 1993; Ries 1994; Overseas Development Agency 1995). These studies are attempting to reach more meaningful conclusions about catchment-scale processes. For instance, Perino (1993) described a paired-catchment study evaluating the consequences of improved farming methods on total basin sediment output. This study integrated agrometeorologic variables with comprehensive sediment and water measurements for basins of about two hectares. Ries (1994) measured rainfall input, surface erosion, and stream suspended-sediment yield in the High Mountains for low, medium, and high landuse intensity. Overseas Development Agency (1995) described results from three years of research looking at the relations amongst soil erosion, water quality, landuse change, management practices, and in-stream fauna. The conclusions of these studies generally point to a strong, indigenous agricultural system helping to sustain - not undermine - food production.

The above comments point out how limited the database is on erosion and sedimentation in Nepal. In comparison, we have a reasonable understanding of many catchment-scale processes within small temperate-region basins. However, the characteristics of these Middle Mountain catchments are quite distinct from their temperate counterparts. In particular, aspects such as the steep topography, heavy precipitation concentrated within a few months, soil types, and high level of human manipulation over every part of the landscape are likely to create very different outcomes than have been observed elsewhere.

This study tries to fill this gap through an intensive monitoring program over a range of spatial scales from the plot scale (0.01 ha) through basin spatial scales of 100 to 500 to 10 000 ha in size and covering temporal scales from a single flood event (over 300 individual floods are examined) to seasonal and annual timescales during a three-year period. A range of related biophysical measurements are made to describe sediment dynamics within these headwater catchments.

The findings of this study are assembled to produce a diagnostic evaluation of the *health* of these headwater agricultural systems with respect to soil erosion. Ehrenfeld (1992) described ecosystem health as a bridging concept:

Health is an idea that transcends scientific definition...it contains values that are not *amenable to scientific methods of exploration... Health is a bridging concept connecting two worlds: it is not operational in science if you try to pin it down, yet it can be helpful in communicating with non-scientists. Equally important, if used with care in ecology, it can enrich scientific thought with the values and judgments that make science a valid human endeavour.* (Ehrenfeld 1992)

The overall diagnosis is non-scientific but draws heavily from the scientific findings. It is put forth because there is an urgent need for a diagnosis. It is this need which was the genetic influence for the research.

1.3 Goals and Objectives

Spatial and temporal scales impose a number of constraints on research of this kind. The Jhikhu River basin has been chosen for a case study because it is typical of the Middle Mountains with respect to climate, physiography, landuse, and soil type and is representative of the level of landuse intensity likely to affect most other basins in the region in the near future. Further, there already exists a large inventory of physiographic data in a GIS for this basin (Shah et al. 1994).

In applying well-established scientific concepts over manageable spatial and temporal scales in low-order basins of the Middle Mountains of Nepal, this thesis sets out to accomplish four central goals, each with specific research objectives:

1) Diagnose causes of sediment dynamics

- Identify the sources of suspended sediment in Middle Mountain streams.
- Evaluate the importance of topography, rainfall, and landuse (and other management practices) in shaping the sediment regime over relevant spatial and temporal scales.

Research questions:

- What are the significant sediment sources?
- Do seasonal changes in rainfall regime (intensity, duration, frequency, spatial variation), surface condition, and management cause important changes in the sediment regime?
- What is the extent of seasonal changes in sediment loss?

2) Assess the efficacy of indigenous management techniques

- Document all important indigenous soil-management approaches related to erosion and sedimentation.

- Evaluate the influence of these techniques on sediment dynamics.

Research questions:

- Are local farmers effective in modifying sediment dynamics? Do their activities reduce or increase basin sediment loss?
- To what extent are the farmers able to favourably influence the erosive fate of their soils? At what point does their management regime become ineffective?

3) Determine sediment and nutrient budgets

- For the three-year period of study, construct sediment budgets over specific spatial (plot, sub-basins, basin) and temporal (event, season, year) scales to determine the relative importance of sediment sources and sediment storage to basin yield.

- Using phosphorus as a representative limiting nutrient, examine its relative redistribution within sub-basins and net loss from sub-basins; identify the landuse(s) which provide the dominant phosphorus contributions to basin phosphorus loss.

Research questions:

- How does the spatial scale of a basin affect its sediment output?
- What proportion of the annual basin sediment loss is accounted for in the biggest floods?
- Can predictive relations be developed for sediment output?
- What is the significance of surface degradation to basin budgets?
- To what extent are nutrients redistributed within (but not "lost from") sub-basins?

4) Prescribe soil/sediment management recommendations

- If appropriate, suggest management recommendations to improve the effectiveness of present farming techniques.

- Provide a statement clarifying the contribution of headwater areas to downstream concentrations of suspended sediment.

- Provide a statement of sustainability regarding the current management regime with respect to erosion.

Research questions:

- To what extent are the soils redistributed rather than lost in this highland-lowland system?
- Are there feasible options available to the farmers to reduce their risk of soil loss?

The completion of these four research objectives will make it possible to assess the following hypothesis: soil and sediment dynamics and the indigenous management techniques within headwater Middle Mountains basins do not themselves indicate a deterioration of the health of the agricultural system.

The thesis comprises two parts - one, Biophysical Analyses and two, Management and Implications. The first part focuses on quantitative field measurements and their detailed analyses. Chapter 2 provides a description of the study area and Chapter 3 gives a summary of methods used in the entire study. Chapters 4 through 6 address specific biophysical concerns associated with the causes of sediment dynamics laid out as the first goal. Specifically, Chapter 4 presents the precipitation regime of the study area, developing appropriate temporal and spatial scales for relating the precipitation regime to the sediment regime. Chapter 5 examines the many interacting factors involved in sediment transport in the study area - for example, rainfall characteristics, surface cover, soil characteristics, management, and topography. Chapter 6 uses sediment properties (particle-size distribution, colour, and phosphorus content) to look at some fundamental dynamics associated with suspended-sediment transport. These insights have implications for the causes of observed sediment regimes presented in Chapter 5.

The second part is concerned with management and the implications of the findings presented in Part 1. Chapter 7 evaluates the effectiveness of indigenous management techniques. Chapter 8 presents sediment budgets based on the relations developed earlier in Chapters 5 and 6. Finally, Chapter 9 addresses integration and overall conclusions and suggests recommendations for management and further research.

2. Study Area

2.1 Jhikhu River basin

2.1.1 Location and physiography

The Jhikhu River basin is located 35 km east of Kathmandu in Nepal's Middle Mountains as shown in Figure 2.1 and illustrated in Appendix A1. It has an area of 111 km^2 and elevations ranging from 800 to 2030 m. The topography within the basin, presented quantitatively in Table 2.1, includes large areas of steep land. Landuse is dominated by subsistence agriculture though, with recent political changes, a market economy is rapidly developing. The population in this basin was 32 956 in 1990, growing at a rate of 2.9% *per annum* (Shrestha and Brown 1995). The Arniko highway, a major east-west corridor in Nepal, passes through the watershed providing good access to Kathmandu and the Tibetan border.

The geology of the Jhikhu River basin consists of sedimentary rocks which have been affected by low- and high-grade metamorphism (Dongol 1991). These metasediments include phyllite, quartzite, schists and mica-schists.

The geomorphological development of this region has been influenced by tectonic uplift leading to over-steepened slopes that are prone to instability (Saijo 1991). The highly dissected landscape contains ridge slopes formed by soil creep and the weathering of bedrock, erosional slopes formed by landslides, and landforms originating from sediment deposition. The ridge slopes remain active and are the most vulnerable to gully and sheet/rill erosion. Large terraces exist above the Jhikhu River valley bottom, created in the Quaternary Period when this drainage was tectonically dammed (Dongol 1991).

Red soils are dominantly Ultisols and some Alfisols whereas the non-red soils are dominantly Entisols and Inceptisols and some Alfisols. The Ultisols are the oldest soils in the study area; they dominate the terraces above the main valley bottom, though they can be found up to elevations as high as 1400 m. These red soils have a generally lower soil fertility than do the non-red soils.

Figure 2.1 Location of the Jhikhu River basin within Nepal

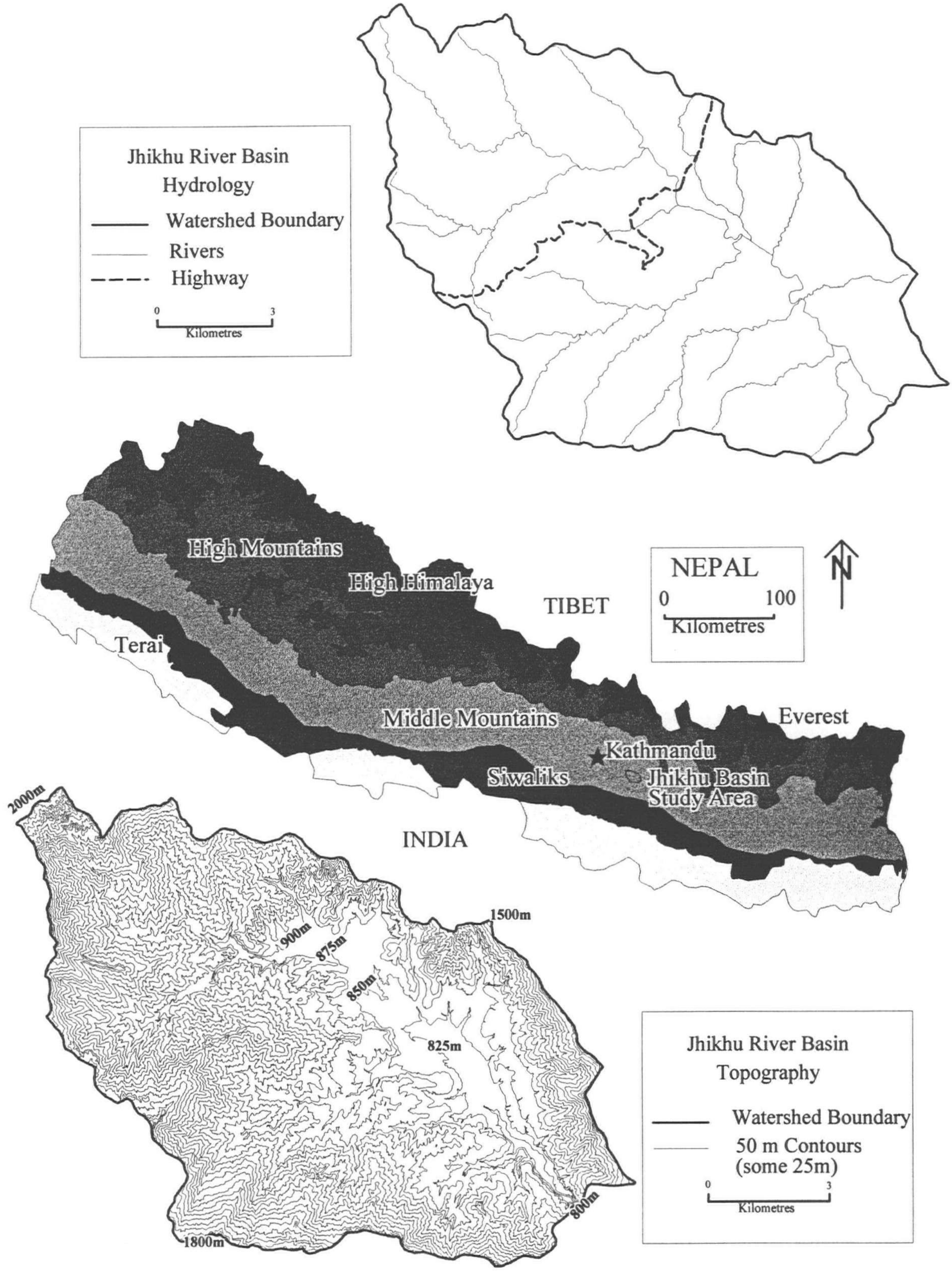


Table 2.1 Slope, aspect, and elevation of the Jhikhu River basin (from 1:20 000 mapping).

	Class	Percentage of Basin Area
Slope (°)	0-10	43.4
	10-20	24.6
	20-30	21.1
	≥30	10.9
Aspect	Flat	16.3
	NE, N, NW	34.0
	E	12.8
	SE, S, SW	29.7
	W	7.2
Elevation (m)	800-999	39.6
	1000-1199	27.7
	>1200	32.7

Note: slope does not consider terracing.

The highly dissected landscape signifies a dense natural drainage network. Tributaries of the Jhikhu River are steep, confined, boulder-bed channels. The Jhikhu River, in contrast, is a meandering sand-bed river in some of its lower reaches with a slope of about 0.1° (0.2 %).

2.1.2 Farming system and landuse

Table 2.2 shows the landuse breakdown in the Jhikhu River basin for 1990. The landscape is dominated by cultivation on slopes of up to 40°. Annually, up to three crops are grown on the irrigated *khet* fields and two crops on the rainfed *bari* land. Rice is the dominant crop on the *khet* land, though recently cash crops such as tomatoes and peppers have risen in importance. Maize continues to dominate on the upland rainfed fields, with millet and wheat grown during the dry season. Legumes are typically intercropped on many fields.

The agricultural system has traditionally relied on the forests for nutrient inputs. Forests provide about 40% of the feed for livestock (Carson 1992) whose dung is incorporated into compost,

Table 2.2 Landuse of the Jhikhu River basin in 1990.

Landuse	Percentage of Basin Area
khet	15.4
bari	39.1
forest	30.2
shrub	8.4
grassland	4.2
other	2.7

becoming the prime source of added nutrients to the cultivated fields. Over the past 20 years, synthetic fertilizers have gained in prominence as landuse pressures have increased (Chitrakar 1990). In the past few years, the cost of these amendments has risen dramatically, placing the cash-poor farmers in a difficult situation. Further, much of the forest land is in a degraded condition with crown cover below 10% and little or no surface cover.

Landuse mapping over the past 50 years shows a steady conversion of land into cultivation (Schmidt 1992). Schreier et al. (1994) showed that between 1947 and 1981, this conversion was at the expense of forest cover. More recent mapping (1972-1990) documents an increase in forest cover and agricultural land at the expense of both shrub land and grassland. Schreier *et al.* (1994) explained that these changes in forest cover reflect widespread deforestation earlier this century followed more recently by both afforestation associated with plantations during the past 15 years and increased tree planting on private land (Gilmour 1991).

2.1.3 Regional climate

The climate of Nepal is strongly influenced by the southwest monsoon across the Indian Subcontinent and by its own abrupt relief. The seasonal reversal of winds associated with the South Asian Monsoon brings warm humid air to much of northern India and southern Nepal during the summer months. Nepal rises from the Indo-Gangetic Plain to the highest mountains on Earth within only 150 km. These two factors combine to yield annual precipitation of over five metres in parts of the country and cold deserts on some leeward mountainsides (Department of Hydrology and Meteorology 1992). Unfortunately, these regional variations are not well described because of the lack of monitoring stations in the country's difficult mountainous regions (Ramanathan 1981).

The Middle Mountains physiographic region (see Figure 2.1) does not experience the extremes of climate found in much of the rest of Nepal. At about 25° north latitude, the climate of this physiographic region varies from warm temperate on high mountain ridges to subtropical in the low valleys. Locally, climatic patterns can vary strongly due to elevation and aspect. Air temperatures span 0°C to 40°C annually (Kenting Earth Sciences Ltd. 1986).

2.1.4 Local climate

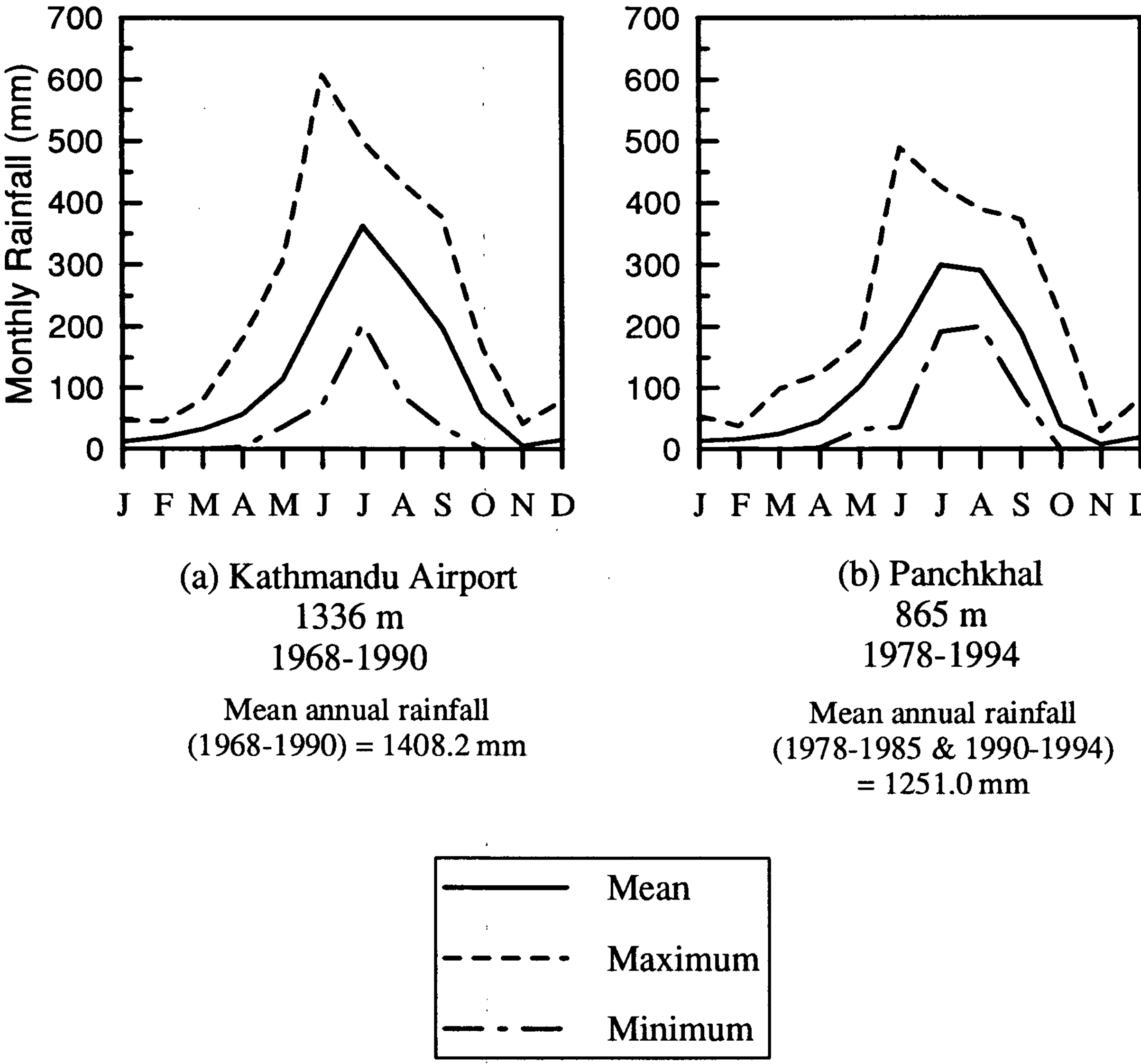
In the Jhikhu River basin, the rainy season starts normally in the beginning of June, ending by the end of September. Precipitation in this basin is in the form of rainfall only and varies typically between 900 and 1600 mm annually. Up to 90% of the annual rainfall falls during the monsoon period with a distinct prolonged period of drought throughout most of the rest of the year.

The local climate of the Jhikhu River basin can be characterised using data from several stations covering a range of elevations. Sources include a long-term monitoring station run by His Majesty's Government (HMG) and found within the valley lowland at 865 m, other long-term HMG climate stations found in the region of the Jhikhu basin, and stations which have been maintained by the present study for three to five years at several points within the study area. The HMG data are used to describe long-term trends in climate in this region. The data from within the Jhikhu basin provide the best picture of the variation in weather occurring within the study site.

Rainfall

One of the longest records of precipitation measurement available near the study basin is that

Figure 2.2 Mean, maximum, and minimum monthly rainfall at (a) Kathmandu airport (HMG Records 1968-1990) and (b) Panchkhal (HMG Records 1978-1994;, means based on 1978-1985 and 1988-1994).



of the Kathmandu airport. At this station, data from 1968 to 1990 are currently available in published government records (Department of Hydrology and Meteorology 1992 etc.). These precipitation measurements are summarised in Figure 2.2a. An HMG climate station at Panchkhal is located within the study area itself with data available from 1978-1994 (Department of Hydrology and Meteorology 1992 etc.). These data are summarised in Figure 2.2b.

Together these data sets provide a long-term indication of averages and extremes expected in the study site. The Panchkhal station is a valley-bottom station indicative of the subtropical lowland areas while the station at the Kathmandu airport is indicative of the more-temperate regions. Both figures show that average monthly precipitation peaks in July at about 300-350 mm per month. Interestingly, the *maximum* monthly precipitation peaks in June at both locations. In each case, this peak is from different events, each of unusual magnitude for the month: in 1971 at the Kathmandu airport and in 1978 in Panchkhal. In fact, while the one station experienced very high rainfall, the other experienced a rainfall of average magnitude yet the two stations are only 30 km apart, within the same Middle Mountain physiographic region.

Figures 2.3 provides summary statistics of precipitation data gathered by the present study at three points within the Jhikhu River basin. The Baluwa station (1992-1994) is within the Andheri River catchment at 900 m, 4 km from the HMG Panchkhal station (also in the valley bottom). The Bela station (1990-1994) is at 1211 m, in the Andheri catchment and also in the upland Kukhuri catchment. The Dhulikhel station (1990-1994) is at 1500 m. The locations of these stations are indicated on Figure 3.1.

As indicated in Figure 2.4a, across these five sites, the average monthly precipitation does not vary greatly. Though the periods of record differ, there appears to be a tendency for the peak monthly rainfall to be higher at the Dhulikhel and Baluwa locations.

Comparing the longer-term records (Figure 2.2) with the records from this study, one can see an obvious difference in the lack of a peak monthly rainfall in June for Baluwa, Bela, and Dhulikhel.

Figure 2.3 Mean, maximum, and minimum monthly rainfall at (a) Baluwa (1992-1994; means based on 1993-1994), (b) Bela (1990-1994), and (c) Dhulikhel (1990-1994).

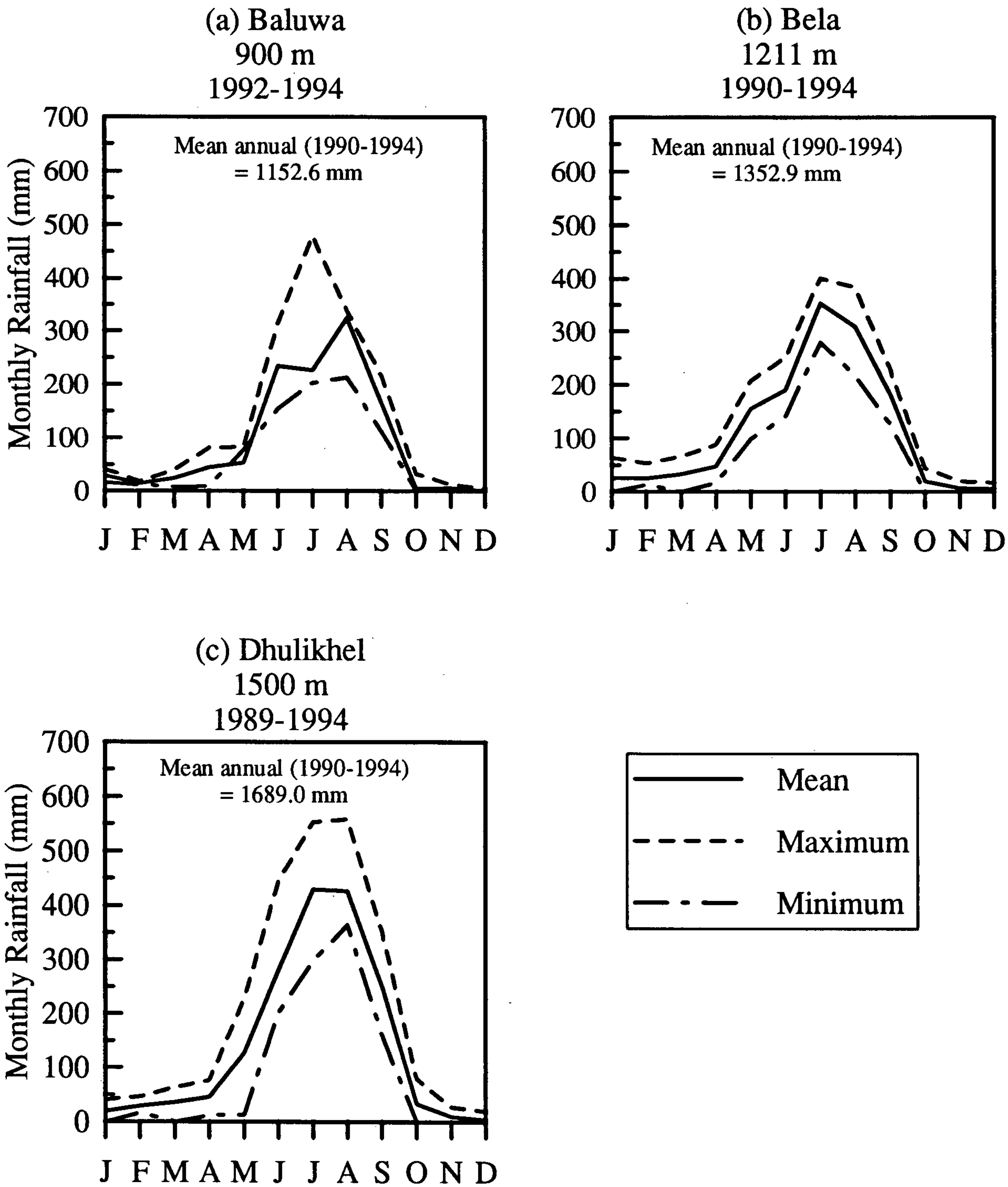
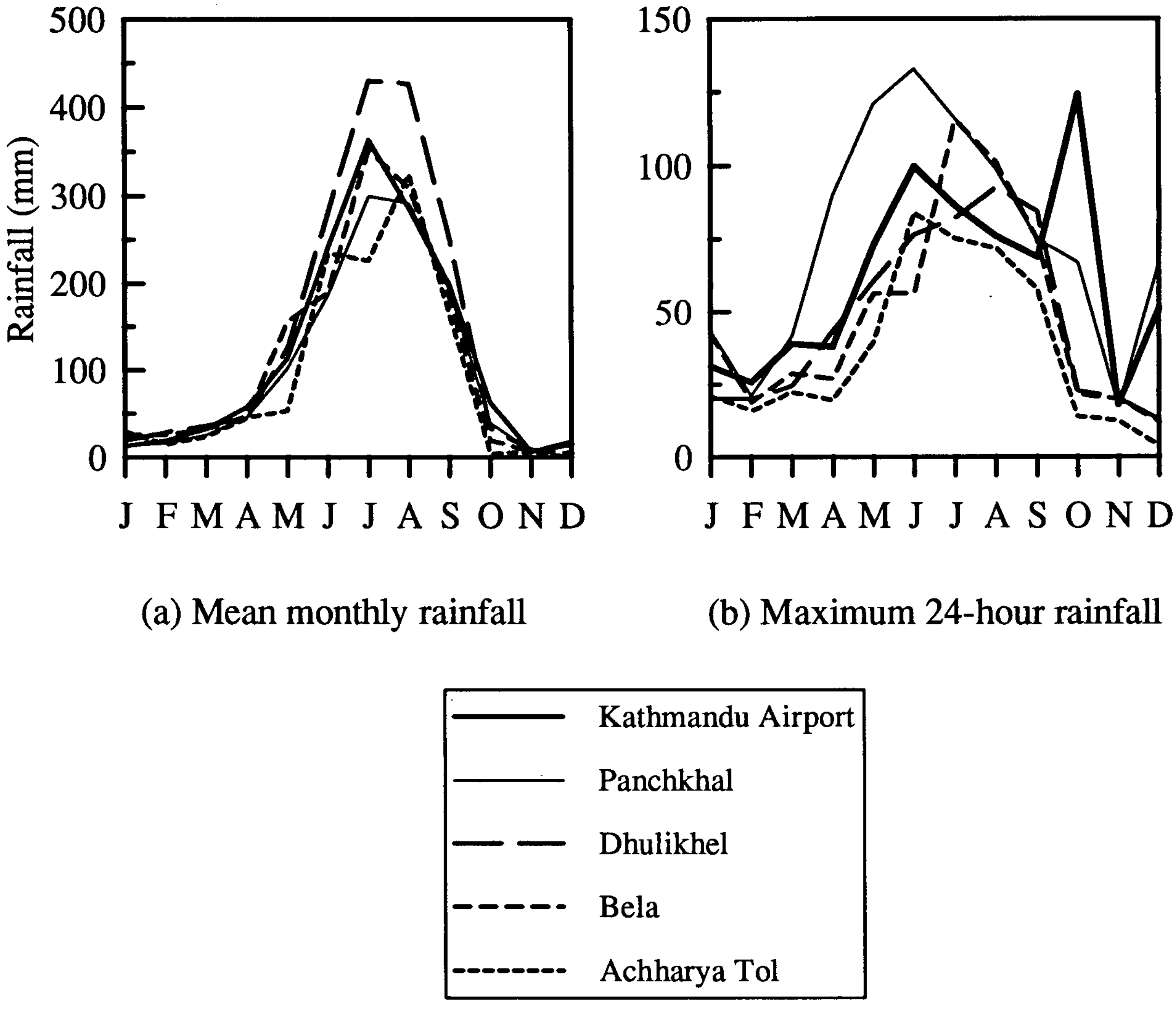


Figure 2.4 Mean monthly rainfall (a) and maximum 24-hour rainfall (b) at Kathmandu Airport (1968-1990), Panchkhal (1978-1985 and 1988-1994), Baluwa (1993-1994), Bela (1990-1994), and Dhulikhel (1990-1994).



Presumably, this suggests that heavy June rainfall can occur but it is infrequent and has not happened in the Jhikhu River basin during this period of study (1990-1994).

Figure 2.4b contrasts the maximum 24-hour rainfall measured at all five sites during the periods of record. Though the mean precipitation in June is lower than in July on average at all sites, this figure reveals a tendency for the highest 24-hour precipitation to occur in June. These comparisons hint at patterns which will be more fully examined in Chapter 4. A striking result in Figure 2.4b is the heavy post-monsoon rainfall measured on October 20, 1987 at the Kathmandu Airport. Finally, all of these descriptive rainfall statistics are summarised in tabular form in Appendix A2.

Temperature

Temperature data for the three valley-bottom climate stations are presented in Figure 2.5. Figure 2.5a shows the mean maximum and mean minimum temperatures and Figure 2.5b shows the extreme maximum and minimum temperatures. Though the data are taken from different periods, they provide a consistent characterisation of the valley-bottom temperature regime: April through September have mean monthly temperatures well above 30°C, temperatures frequently exceed 35°C and, during the monitored periods, the minimum has rarely gone below freezing.

Figures 2.5c and 2.5d present the equivalent temperature data for the two high-elevation sites and provide the mean result from the Kathmandu airport for comparison. The mean maximum monthly temperature at the high-elevation sites is several degrees cooler than at the valley-bottom sites. During the indicated periods, the temperature rarely exceeded 35°C and went below freezing especially at the Kathmandu station.

Summary statistics taken from these monthly results are given in Table 2.3. Not unexpectedly, elevation influences the mean annual temperature. The high-elevation sites show a slightly lower average mean annual temperature than the valley-bottom sites. However, the lower elevation sites

Figure 2.5 Mean-monthly and extreme-monthly maximum/minimum temperatures at (a) three low-elevation sites (Panchkhal, 1978-1994; Baluwa, 1993-1994; Bhimsenthan, 1993-1994) and (b) three high-elevation sites (Kathmandu airport 1968-1990;, Bela, 1990-1994; Bhetwaltok, 1993-1994).

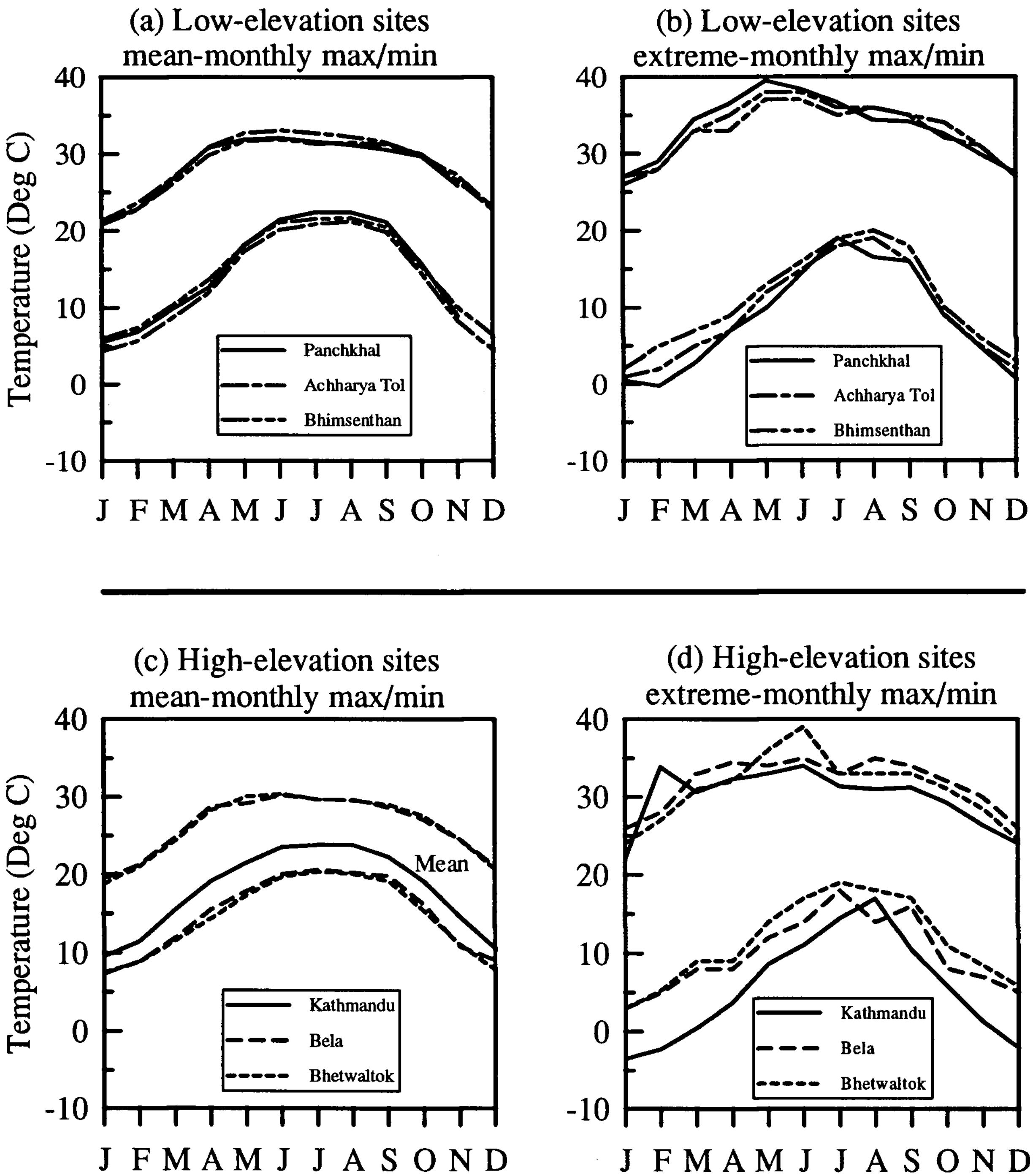


Table 2.3 Descriptive temperature statistics from the six climate stations.

Site	Elev. (m)	Mean Annual	Mean Daily Max	Mean Daily Min	Extreme Daily Max	Extreme Daily Min	Period of Data
Low Elevation							
Panchkhal (flat)	865	21.2	28.1	14.2	39.5	-0.2 (1989)	78-94
Baluwa (north-facing)	865	21.0	28.8	13.1	38.0	1.0	93-94
Bhimsenthan (south-facing)	895	21.2	28.0	14.4	37.0	2.0	93-94
High Elevation							
Kathmandu Airport	1336	17.9	n/a	n/a	34.0	-3.5 (1978)	68-86
Bela (north-facing)	1254	20.6	26.2	14.9	35.0	3.0	90-94
Bhetwaltok (south-facing)	1300	20.3	26.1	14.5	39.0 (Jun 9 92)	3.0	93-94

appear to have lower minima providing evidence for inversions. The annual extremes and mean monthly temperatures are comparable at all sites. There does not appear to be a large effect on temperature due to aspect at these sites.

2.2 Study catchments

A total of six smaller catchments and sub-catchments in the lower regions of the Jhikhu River basin are the focus of this study. Other catchments have been examined as part of the larger study not included in this thesis. Some of these catchments are nested as illustrated in Figure 2.6. The topography of these six study catchments is contrasted in Table 2.4. Two sources of topographic data are used in this study's analyses. A topographic map at 1:20 000 scale was produced in 1990 for the entire basin and a detailed digital topographic map at 1:5 000 scale was produced in 1994 for a cross-

Figure 2.6 Locations of the nested catchments, the hydrometric stations, and the erosion plots.

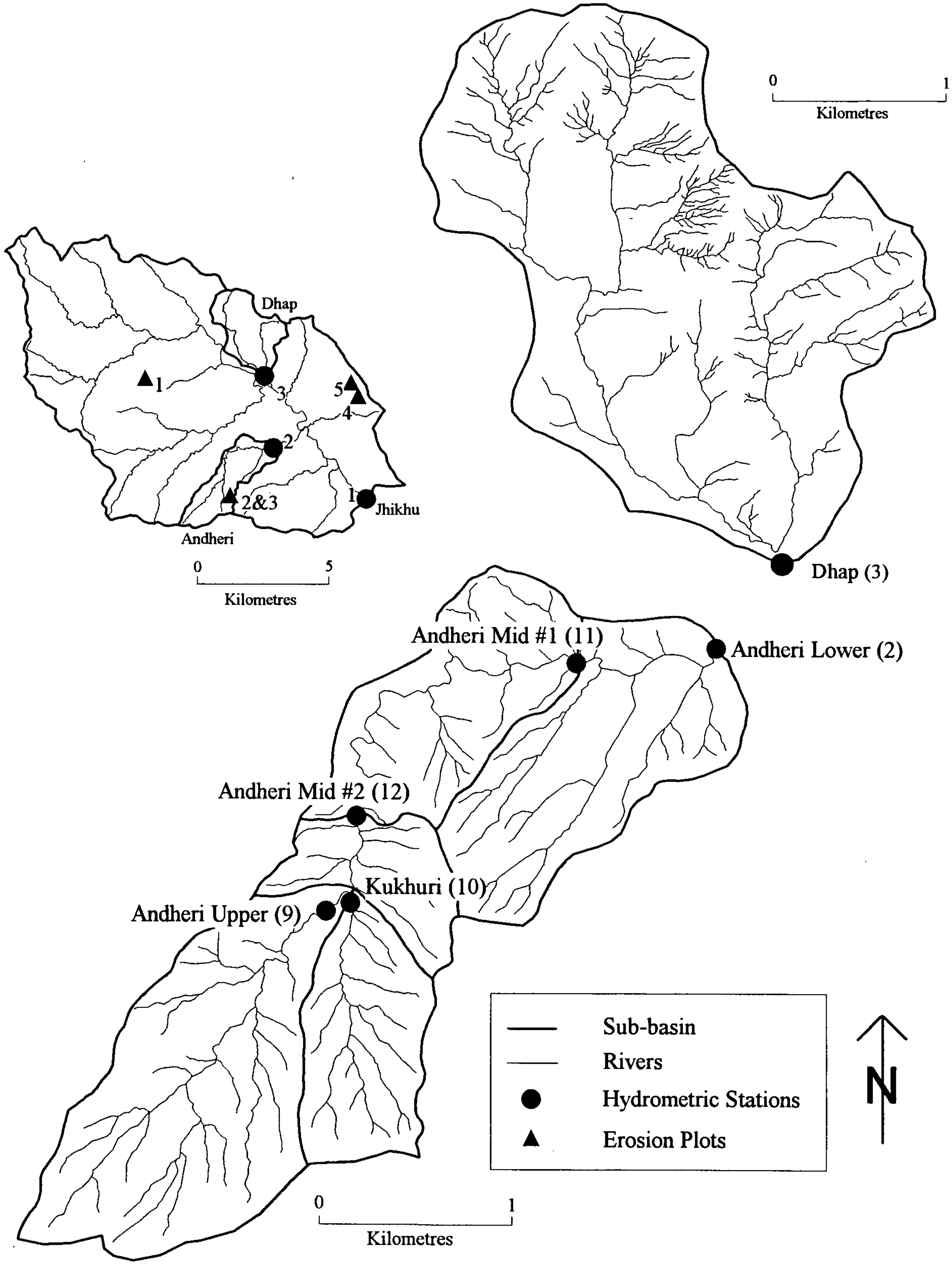


Table 2.4 Topography of the six study catchments based on 1994 1:5 000 mapping. Data for the Dhap catchment are taken from 1990 mapping at 1:20 000 scale.

	Dhap	Andheri	Andheri Mid #1	Andheri Mid #2	Upper Andheri	Kukhuri
St. No.	3	2	11	12	9	10
Area (ha)	558	532	401	299	178	72
Slope (°)						
0-10	73.2%	19.2%	16.6%	11.2%	9.5%	10.3%
10-20	20.2	25.4	24.4	22.7	22.0	21.9
20-30	5.9	38.2	39.2	43.1	42.9	43.6
≥30	0.8	17.2	19.8	23	25.6	24.2
Elev. (m)						
800-1000	98.3%	24.8%	15.2%	0.0%	0.0%	0.0%
1000-1200	1.7	34.9	31.8	28.9	14.3	27.7
> 1200	0.0	40.3	53.0	71.1	85.7	72.3
Aspect						
Flat	35.4%	6.3%	5.2%	3.4%	3.2%	3.2%
N, NE, NW	9.8	53.1	53.5	56.3	63.8	51.1
E	7.3	9.54	9.1	9.6	12.9	0.9
S, SE, SW	36.4	15.8	17.1	14.7	6.6	22.3
W	11.1	15.3	15.1	16.0	13.5	22.5

Note: numbers represent percentage of total area.

section of the Jhikhu River valley, containing the Andheri River study catchments. All digital topographic data have been incorporated into a Geographic Information System to produce quantitative information on elevation, aspect, and slope (see section 3.3.4). The results for the Jhikhu basin appeared earlier in Table 2.1.

The landuse of these six catchments is presented in Table 2.5. Mapping was carried out in 1990 at 1:20 000 scale for the entire Jhikhu River basin and these results appeared in Table 2.2.

Table 2.6 summarises the features of these streams in terms of channel slope and stream order at the hydrometric station (Leopold *et al.* 1964) and their estimated bankfull discharge (Dunne and Leopold 1978). The streams in these catchments are contrasted in profile in Figure 2.7.

Table 2.5 1990 landuse distribution of study sub-catchments within the Andheri basin, mapped at 1:20 000 scale. (Total area based on 1994 1:5 000 photogrammetric map.)

	Dhap	Andheri Lower	Andheri Mid #1	Andheri Mid #2	Andheri Upper	Kukhuri
St. No.	3	2	11	12	9	10
Area (ha)	558	532	401	299	178	72
khet	24.6%	6.8%	8.7%	8.4%	8.9%	8.2%
bari	36.8	33.1	41.1	51.3	53.8	55.4
forest	20.9	32.3	24.4	22.0	22.5	17.9
shrub	3.8	14.6	11.3	7.2	4.3	6.1
grassland	7.6	8.0	9.0	7.4	6.9	8.3
other	6.3	5.3	5.4	3.7	3.7	4.1

Note: numbers refer to percentage of total area.

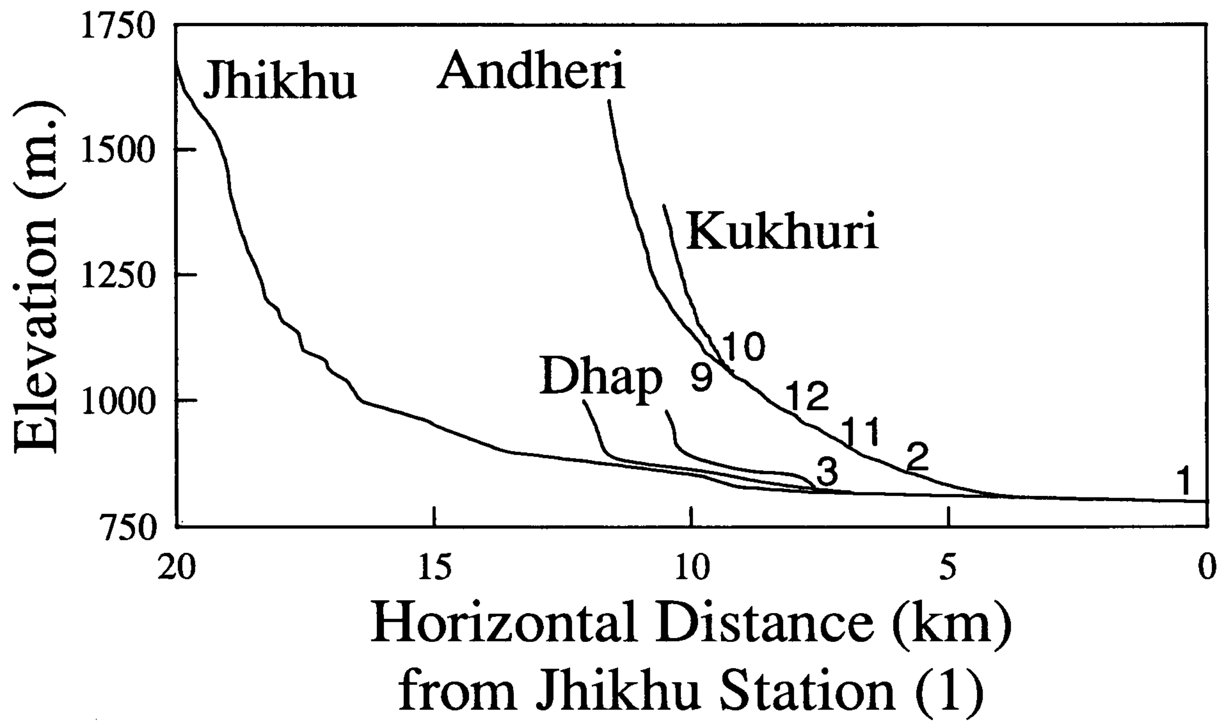
Table 2.6 Slope, order, and bankfull discharge of the study streams at each hydrometric station.

Station	Order	Slope (°)	Bankfull Discharge (m^3/s)
1	6	0.3	85
2	4	1.9	25
3	5	1.0	20
9	3	5.1	13
10	2	6.6	5
11	3	2.1	unknown
12	3	4.8	unknown

Andheri catchment

The Andheri catchment is characterised by intensively-managed cultivated uplands and degraded, often-gullied, red soils in the lowland. It is north-facing with a moderate temperature regime. Station 2 is situated at 850 m near the Andheri River's confluence with the Jhikhu River.

Figure 2.7 Elevational profiles of the study streams (vertical scale is exaggerated by 10 times).



Note: numbers denote hydrometric stations

Kukhuri catchment

The Kukhuri River catchment forms part of the headwater area of the Andheri catchment. This catchment is dominated by well-managed rainfed cultivated steeplands with only a small red-soil component. The Kukhuri River is monitored at 1060 m at station 10, 40 m upstream of its confluence with the Andheri River.

Upper Andheri catchment

Along with the Kukhuri River catchment, this catchment forms the headwaters of the Andheri River. Though the characteristics of these catchments are generally similar, the Kukhuri catchment is proportionately steeper and its irrigated land is consequently of lower productivity. A relict landslide (occupying about 1% of the basin) along with some smaller pockets of mildly-degraded red soils are located in the northwestern portion of the catchment. This upland section of the Andheri River is monitored at Station 9 at 1060 m about 200 m upstream of its confluence with the Kukhuri River (station 10).

Mid-Reach Andheri catchments

Stations 11 and 12 are hydrometric stations located between the headwater area (stations 9/10) and the mouth (station 2) of the Andheri River. These monitoring positions better isolate the transition in this basin between the steep, intensively-managed headwaters and the gullied, red-soil, partly-abandoned lowland. Specifically, station 12 (elevation 1020 m) includes all of the Upper Andheri and Kukhuri sub-catchments along with a portion of degraded forest along the Andheri River. Station 11 (elevation 880 m) includes all of the station 12 drainage as well as extensive forest and degraded shrub land and a small amount of the gullied lowland. These are referred to as the Andheri Mid #1 (station 11) and Andheri Mid #2 (station 12) catchments.

Dhap catchment

The Dhap River catchment, largely flat and south-facing, provides a strong contrast to the characteristics of the catchments within the Andheri catchment. Dominated by red soils, its land is often in a degraded condition. Its drainage is composed of two distinct units - one in a steep location near the river's confluence with the Jhikhu River and the other flatter and more distant. This affects hydrological behaviour at its mouth accordingly. This river is monitored at station 3 at 825 m, 675 m upstream of its confluence with the Jhikhu River.

3. Methods

Methods used in the study are described according to field and laboratory approaches. A selection of procedures used for data synthesis is presented in the chapter's final section.

3.1 Field methods

3.1.1 Climate

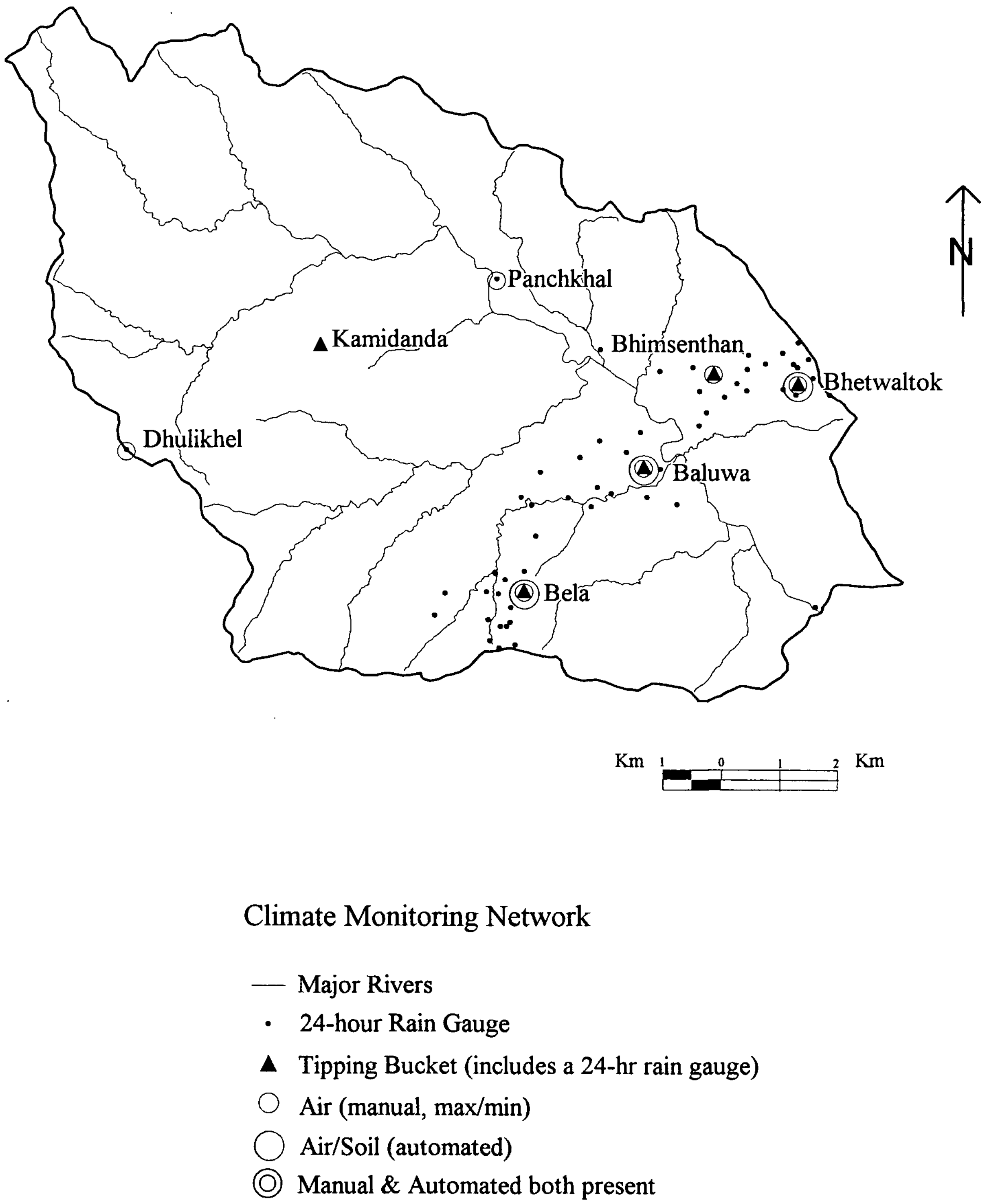
Climate measurements carried out in this study consist of rainfall and temperature using both manual and automated instruments.

Rainfall

Figure 3.1 shows the locations of all rainfall monitoring stations in the study area. At these locations, a mix of storage and recording gauges has been in place from three to seventeen years with most records being of a three- to five-year duration. Appendix A3 provides a summary of the gauges, including gauge number, location, and elevation. Most gauges are located between 850 and 1350 m elevation.

Measurement of rainfall intensity has been made at five sites for three years using recording rain gauges (tipping buckets - Middleton and Spilhaus 1953) complete with pulse data loggers. Rainfall resolution is 1.0 mm at the two monitoring sites within the Andheri Basin (Baluwa and Bela) and 0.25 mm at the other three sites (Bhetwaltok, Bhimsenthan, and Kamidanda). The tipping buckets were installed on a permanent table, one metre from ground level, and have a circular opening of eight inches (324.3 cm^2). Generally, they were visited monthly, though during the rainy season this frequency was increased. Files were converted into ASCII format and manipulated as described in section 3.3.3. The calibration for each tipping bucket was checked twice annually. Sampling frequency varied from 2 to 10 minutes in the earlier period of monitoring (depending on the resolution of the tipping mechanism) and was fixed throughout at 2 minutes for subsequent monitoring.

Figure 3.1 Lay-out of monitoring network for rainfall and temperature within the Jhikhu River basin.



To assure data continuity, a 24-hour rain collector was installed nearby each tipping bucket. Occasionally, the automated gauge record is incomplete as a result of data logger malfunction; in these instances, the supplementary gauge is used to complete the data record (though the short-term rainfall-intensity result clearly is lost).

Two types of storage gauges were installed for measuring rainfall over 24 hours and were visited daily at 7:00 am local time. The first is of the type used by the Department of Hydrology and Meteorology of HMG. It has an opening of eight inches (324.3 cm^2) which stands 1.5 m from the surface. The rain flows directly into a cylinder calibrated for the opening. Four of these rain gauges have been in place in the Jhikhu River basin during the study period.

The second rain collector was custom designed using off-the-shelf ABS (hardened plastic). This collector was produced inexpensively so that over 50 could be installed in the field. Its opening is four inches (81.1 cm^2) and it sits 55 cm from ground level. This compares well with the standard gauge of the Atmospheric Environment Service (of Canada) which has a 64.5-cm^2 opening, sitting 30.5 cm off the ground (Storr and Ferguson 1972). The custom gauge has a straight 5-inch-long entranceway, tapered at the bottom, and a storage capacity equal to a total rainfall of 250 mm (double that of the AES standard gauge). The rainfall reading (mm) is made by measuring the volume of water in the storage bottle (ml) and then applying a conversion factor of 0.1233 to account for the size of the collector's opening.

The catches from these three gauge types have been compared at seven locations to test for consistency across gauges as shown in Table 3.1. The catch ratio for each measurement at each test site has been calculated for all storms and the results appear in Appendix A3. The well-known negative bias associated with wind exposure of a gauge (Brown and Peck 1962) should be responsible for most of this variability. It is to be expected that the custom gauge best represents rainfall because of its smaller opening and its installation closer to the ground. Keller (1972) pointed out that a rain gauge in a network in uniform terrain with the highest catch should be the gauge least affected by wind. McGuinness and Vaughan (1969) observed a seasonal change in rainfall and snowfall catch and determined that it was in fact a wind effect due to seasonal wind regimes. They also found a large difference in the ability of different instruments to cope with the wind effect. The design of the custom gauge minimises wind bias which serves to increase the catch of the custom gauges relative to the two "standard" gauges. The averages and distributions of all catch ratios at each site are given in Table 3.1 and suggest that the standard gauges *underpredict* rainfall by an average of 20.5% (0.258/1.258) using the six comparisons which fall in the tight range of 1.23-1.29 having an average of 1.258. (A catch ratio of 1.258 means that 0.258 mm out of each 1.258 mm is not measured by the standard instruments; this represents an *underprediction* of 20.5% and can be corrected using a multiplier adjustment of 1.258 on the rainfall measured by the standard instruments.) As a result of this finding, all measurements from the standard gauges have been increased by 25.8% from that measured.

Table 3.1 Comparison of catch ratios of the rain gauges at seven test sites.

Test Site	Location	Gauges Installed			Catch Ratio		
		Custom/Tipping Bucket			Custom/HMG		
		N	x	σ	N	x	σ
1	Baluwa	111	1.28	0.18			
2	Bela (1)	58	1.00	0.083			
3	Bhimsenthan	78	1.23	0.17			
4	Kamidanda	95	1.44	0.13			
5	Bhetwaltok	82	1.24	0.30	104	1.29	0.24
6	Dhulikhel				70	1.27	0.21
7	Bela (2)				93	1.24	0.19

It is expected that the wind bias is variable depending on wind speed. Measurements of wind speed within the study area are unavailable. However, observations during the study period suggest that only infrequently is wind speed significant during heavy rain. As a result, the effect of wind speed is neglected in adjusting rainfall records.

Further examination of Table 3.1 indicates that the catch ratios at Sites 2 and 4 are very different from the 1.258 average. Site 4 (catch ratio of 1.44), and the tipping bucket in particular at this site, is exposed to a higher degree of wind than at the other sites and as a result the catch ratio at this site is higher than the average catch ratio at the other sites. At Site 2, the custom rain gauge is installed on a small ridge which effectively raises its point of installation above the ground. As a result, both the custom and standard gauges experience a similar wind bias at Site 2 and the catch ratio is unity. These two anomalies are not used to calculate the average catch ratio.

The adjustment is applied to every measurement of the tipping bucket regardless of rainfall intensity. The bias associated with the moderate- and high-intensity rainfall dominates the aggregate bias, here called the catch ratio. Since moderate- and high-intensity rainfall are of the greatest interest in this study, it is reasonable to adjust all rainfall intensities consistently by the overall catch ratio.

Temperature

Air temperature was monitored using a combination of manual and recording devices. These sites are shown in Figure 3.1 and are summarised in Table 3.2. Temperature was measured manually at a total of six locations. In each case, the max-min thermometer was installed in a standard Stevenson's screen (Middleton and Spilhaus, 1953). Five of these were maintained by this study and provide a record of the daily maximum and minimum air temperatures during the past four years. The sixth site was maintained by HMG and provides a daily record of maximum and minimum temperature covering 17 years.

Automated temperature monitoring, recording every 10 minutes, was begun in 1992 at three sites as shown in Figure 3.1. In these cases, both air and soil temperature (depth of 20 cm) are measured. These sites were chosen to reflect the characteristics of north-facing, south-facing, and valley-bottom microclimates as summarised in Table 3.2.

Table 3.2 Installation information of temperature measurements.

Location	Aspect	Elev. (m)	Installation Date	Type
Baluwa	Flat	865	May 29, 1992	air; manual
Baluwa	Flat	865	Jun 12, 1992	air/soil; automated
Panchkhal	Flat	865	Nov 1970	air; manual
Bhimsenthan	Flat	895	May 30, 1992	air; manual
Bhetwaltok	South	1300	Jun 6, 1992	air; manual
Bhetwaltok	South	1300	May 27, 1993	air/soil; automated
Bela	North	1255	Jan 1, 1990	air; manual
Bela	North	1255	Jun 12, 1992	air/soil; automated
Dhulikhel	North	1545	Jun 1, 1989	air; manual

Note: Automated measurements are sampled at 10-minute intervals.

3.1.2 Stream measurements

Flow measurements or suspended-sediment sampling, or both, were carried out at seven hydrometric stations during 1992-1994 as shown earlier in Figure 2.6. These measurements were challenging because the floods are generally of short duration and most occur at night following afternoon and evening convectional showers. A monitoring team was trained for each station to improve measurement success. Bridges were constructed at five of these cross-sections (stations 1, 2, 3, 9, and 10) to take discharge measurements at high flow. Flow measurements were made using Price AA current meters. At low flow, readings were taken by wading in the stream and recording the flow velocity at frequent lateral intervals (Buchanan and Somers 1969). Due to the very brief nature of high-flow conditions and to prevent damage to the meter, flow measurements of the surface were taken and estimates made of the average velocities at three lateral positions in the stream cross-section. Following an approach modified from Hoyt (1912), a conversion factor was applied to the flow velocity of the surface. Rating curves have been constructed for each station using the three years of flow measurements and are discussed later in Section 3.3.1.

Event and annual hydrographs have been constructed using both automated and manual records of gauge height (stage). Manual records consist of daily (7:00 am) measurements throughout the years 1992-1994 and flood measurements when possible. Manual measurements form the entire record of stage for stations 3, 11, and 12. Automated readings provide the large majority of the flow record at the other four stations and are augmented when necessary with the manual record. At each of stations 1, 2, 9, and 10, an automated monitoring system was installed in 1992. The equipment consisted of a pressure transducer installed near the gauge, a data logger, and a 12-volt power supply. A two-minute sampling interval was selected during most of the study period.

Samples of suspended sediments were taken during flood events at all stations. A DH-48 depth-integrating sediment sampler (Guy and Norman 1970) was used at stations 1, 2, 3, 9, and 10 while dipping-bottle samples were taken at stations 11 and 12. When safe to do so, the rivers were waded in order to sample the thalweg. For safety reasons, sampling at higher flows was carried out at a position at or near the bank. These streams are steep and well-mixed when in flood, permitting this varied approach.

Sampling frequency was changed according to station and flood size. In the steeper catchments such as stations 9, 10, and 12, as many samples as possible were taken - generally up to ten samples per flood. At stations 1, 2, 3, and 11, between 5 and 15 samples were taken per flood. At Station 1, as many as 30 samples are available for some floods.

3.1.3 Erosion plots

Five erosion plots were built in 1991 and then monitored throughout 1992-1994. Some features of the plots are summarised in Table 3.3 and their locations are indicated in Figure 2.6. Each plot contained two terraces connected by a steep terrace riser. In each case, the cropping practice was the same: maize during the rainy season and either millet or wheat during the dry period. The farmers were encouraged to manage the plots in the same way that they managed their other fields. Each plot was on red soils because it is widely accepted that red soils are more difficult to manage and erode at

Table 3.3 Characteristics of erosion plots in the study.

Plot No.	Elev (m)	Aspect	Hillslope Angle (°)	Area (m^2)	Upper Terrace Slope/Length (°/m)	Terrace Riser Height (m)	Lower Terrace Slope/Length (°/m)	USDA Soil Type
1	1240	NNE	30	70	18/4.3	1.6	18/5.0	Haplustalf
2	1240	NNW	27	68	23/10	0.8	23/3	Rhodustalf
3	1240	NNW	27	64	23/9	0.8	23/4.2	Rhodustalf
4	1305	SW	22	108	12/6	1.0	11/6	Rhodustalf (degraded)
5	1260	SSW	25	100	8/10	5.0	15/9	Ustochrept (truncated Rhodustalf)

a greater rate than non-red soils (Turton et al. 1994).

Erosion and runoff were measured on an event basis. Three drums were located in series at the outlet of each plot. The soil and water mixture in the drums was sampled after each erosion-causing storm event. The methodology used to achieve this evolved during the study period. For each drum, the total height of soil and water was recorded. The water column was sampled and drained off to leave behind the eroded soil which had settled to the bottom of the drum. The height of this soil was also recorded and this material sampled. Using these measurements and the samples, and knowing the dimensions of the drums, total erosion and total runoff were calculated for each storm event.

3.1.4 Soil properties

In the field, a selection of soil properties was measured including compactness and infiltration rate. In addition, a complete profile description was recorded at 20 sites.

A penetrometer was used to estimate surface-soil compactness. The instrument was used at ten locations within a field and the results averaged for the entire field. The penetrometer was inserted into the surface using roughly the same force for the surface (0-15 cm) and the subsurface (15-40 cm) soils. The value noted was the highest value reached while the penetrometer was being pushed downward in each vertical section. Soil moisture content and bulk density were measured concurrently in most cases. The penetrometer measurements provide a relative index of the compactness of agricultural fields in the study area. This index can be easily qualitatively calibrated to other quantitative measures of compaction.

Infiltration rates of surface soils were measured using double-ring infiltrometers following Booker Agriculture International Limited (1984). For each measurement, three sets of infiltrometers were installed and monitored simultaneously. The test was run for 4-6 hours, though in clay-rich soils this often had to be extended to up to 10-12 hours.

Soil profile descriptions were recorded at all sites where infiltration was measured. At each site, the depth and type of each horizon down to the parent material was noted. For each horizon, the following soil parameters were determined (Booker Agriculture International Limited 1984):

- colour
- texture (of the fraction $\leq$ 2 mm in size)
- structure
- consistency
- porosity
- presence of roots
- horizon transition
- coarse-fragment content (percentage of sample > 2 mm in size)
- moisture content

In addition, the landuse, physiographic position and topography of the site were recorded. The indigenous soil classification was also determined for the surface horizon (see Chapter 7).

3.1.5 Soil movement

A collection of techniques was employed to provide spatial estimates of soil movement.

Erosion and accumulation pins were installed to indicate change in soil level at specific spatial locations. Surveys provided information on the spatial variation of erosion and deposition across an area.

Bamboo pegs were used in *khet*, *bari*, and in gullies to assess rates of soil loss and accumulation. In the *khet* where they were used to measure soil accumulation, between 4 and 12 accumulation pins were installed in each individual field. In the first year, pins were installed at entranceways and exits to the fields to estimate deposition and scouring occurring there and to relate these areas to the average field values. It was found that these edge effects can be significant but are generally confined to the perimeter of the field due to the complex routing water takes in the fields. Therefore in subsequent years, pins were placed in only the centre of *khet* fields. For each pin, an average of all four sides was taken of the soil height relative to the notch showing the original soil level.

In the *bari*, soil pins were used to estimate soil accumulation in permanent and temporary drainage ditches. In each case, three pins were installed - at the beginning, the middle, and at the end of the ditch length. All pins were placed in the lateral centre of the ditch. These pins were also measured on all four sides.

Finally, in gullied land, pegs were installed near active gullies to estimate rate of change of gully dimensions. For each monitored gully, about five to ten pins were installed and maintained as permanent control points. They were installed flush with soil level to make them invisible to passers-by. Detailed records were kept of the relative locations to facilitate quick relocation of the pins, to have many lines from which to measure the gully sides, and to cope with pins lost to gully growth.

Survey techniques were used on several occasions to record the spatial variation of soil erosion and deposition. Surveys of surface erosion and mass wasting were carried out after several major events during 1992-1994. At its most-detailed level, the entire basin was examined on foot for evidence of erosion and deposition. For each example found, its location was noted on the aerial photograph and the following characteristics were recorded:

- type of erosion
- cause
- volume of material moved (estimate)
- description of eroded material
- connection (if any) to other observed erosion

Where deposition was observed, the volume and type of material involved were noted.

Later in the study, surveys of stream deposition were carried out to quantify changes in sediment storage within the bed of the Andheri and Kukhuri Rivers. Rather than attempting a complete inventory over time of bed storage, locations were chosen to monitor bed stability and changes in bed storage over time. The following observations and measurements were made at these points of reference:

- photographs
- rate of sand-bar accretion/loss using bamboo pegs
- description of sediment sizes present
- grab sample of fine sediment (for colour)

This information was used to evaluate the extent of storage within the bed of the Andheri and Kukhuri Rivers.

3.1.6 Mapping

Topography, resource attributes, and landuse have been mapped variously at 1:50 000 (1947), 1:20 000 (1972, 1990), and 1:5 000 (1994) within the Jhikhu River basin. For this study, the 1:20 000 topographic base map with 50-metre contours is used for overall assessments within the Jhikhu basin and the 1:5 000 topographic base map with 10-metre contours is used for detailed evaluations within the Andheri basin. The 1990 landuse was mapped using photo interpretation and follow-up field verification (Schmidt 1992). In 1994, the 1:5 000 map was developed from the 1990 map using analytical photogrammetry techniques. The landuse was updated by field checking to yield a 1994 landuse map for use with this 1:5 000 topographic map. Both maps were converted for use in a Terrasoft Geographic Information System.

Landuse mapping used in this study follows six categories (Schmidt 1992):

bari	cultivated rainfed
khet	cultivated irrigated
forest	trees with a crown cover of more than 10% and a height greater than 2 m
shrub	trees less than 2 m in height or with a crown cover of 1-10% if greater than 2 m
grassland	uncultivated with less than 1% crown cover
other	outcrop; built-up areas.

Forests in the Middle Mountains are heavily coppiced and harvested but still maintained as "forests" hence the low value of 10% crown cover to distinguish forest and shrub classes. Note that forest, shrub, and grassland definitions are not tied to litter or surface cover.

A new legend is developed in this study to evaluate land degradation. Its three classes are:

moderately degraded

- little or no vegetation with minor gullies; or

- forests with less than 25% crown cover and no understorey vegetation; or

- shrub with crown cover less than 25%

severely degraded

- heavily gullied with little or no vegetation

productive

- active *bari*; active *khet*

- built-up areas

- forests with more than 25% crown cover **or** with good understorey vegetation

- shrub with crown cover greater than 25%.

The 25% crown cover value distinguishing forests between the productive and moderately degraded classes recognises that many forests in the study area are in a moderately degraded state (*i.e.*, 10-25% crown cover).

3.1.7 Interviews and Questionnaires

Throughout the period of fieldwork, constant contact was made with the local farmers to improve understanding of their knowledge about their environment. Of particular interest were the techniques they employ to manage their agricultural landscape and the rationale on which these approaches are based. A great deal of this fact-finding was informal and completely unstructured. However, several attempts were made to formalise this part of the study using interviews and questionnaires. A complete list of the interviews which were carried out is provided in Table 3.4.

Table 3.4 Topics examined for farmer indigenous knowledge.

Year	Interview Type	Subject	No.
1991	unstructured	Perceptions, attitudes, and approaches	5
1992	semi-structured	Soil classification	12
1992/3	structured	*Khet*-accumulation management	32
1993	structured	Soil classification	11
1993	structured	*Bari*-erosion management	21
1993	structured	Irrigation-dam management	32

Interviews were unstructured, semi-structured, and structured. Unstructured interviews were carried out only in the first year of the study to improve overall understanding. Semi-structured interviews were used to pursue a more narrowly-defined subject and to allow the farmer to reveal as much of her or his knowledge as possible. Structured interviews were used to evaluate farmer approaches for specific subjects after unstructured and semi-structured techniques were exhausted. These enquiries consisted of questions which could be answered quantitatively. Questions were written into formal questionnaires so that the results could be compiled easily on a spreadsheet. Questionnaires were brief, taking at most ten minutes to complete. Typically, they were translated to the farmer by a Nepali staff member who also recorded the farmer's response. An example of each questionnaire appears in Appendix A4.

3.2 Laboratory methods

3.2.1 Stream Sediment Samples

Analysis of stream suspended sediment was carried out in the field headquarters and at the University of British Columbia. Before filtering, both the conductivity and the pH were measured using a Hanna HI 9025 meter. The samples were filtered (generally overnight) through a pre-weighed Whatman 40 filter (medium - 0.008-mm mesh). Some clay-rich samples with a high amorphous content were filtered twice. Each filter paper was air dried and then sent to Kathmandu from the field where it was oven-dried and weighed.

Further analyses of the suspended sediment were carried out at the University of British Columbia. The Munsell colour designation of all samples was noted first before any destructive analyses took place. Chemical analyses carried out on these sediments were limited to phosphorus, carbon, and pH due to the small sample sizes generally available. Phosphorus was measured as orthophosphate with a Lachat instrument. Total carbon was determined with the Leco Analyser (Lavkulich 1978). pH was measured using a Radiometer Copenhagen PHM62 Standard pH Meter.

A sub-sample of no more than 3 g of sediment was taken manually from a thoroughly mixed sample. Sediment particle-size distribution was determined by first dry-sieving this sub-sample to 0.250 mm. In each case, the sediment was separated into the following size classes:

1.4 - 2.0 (mm)
1.0 - 1.4 (mm)
0.710 - 1.000 (mm)
0.500 - 0.710 (mm)
0.355 - 0.500 (mm)
0.250 - 0.355 (mm)

The size distribution of the remaining sample (though not less than 1.5 g) was determined using a Sedigraph 5100 Particle Size Analysis System. The two sets of results were reconciled to the original sample using a spreadsheet.

3.2.2 Stream water samples

Stream water samples were analysed in Kathmandu in the Water Laboratory operated by the Department of Hydrology and Meteorology (HMG). Conductivity, pH, sediment concentration, and dissolved sodium, potassium, calcium, magnesium and orthophosphate contents were measured. Conductivity and pH were measured in the same way as they were in our field laboratory. Sediment concentration was virtually nil because filtering was normally carried out in the field before sending the sample for water analysis. Dissolved phosphorus was measured as orthophosphate. Sodium and potassium were analysed using a flame photometer. Calcium and magnesium were measured by titration.

3.2.3 Soil samples

Soil analyses were carried out on soils from upland *bari*, surface and cumulic soils from irrigated *khet*, and soil horizons samples taken from soil pits dug nearby where measurements of infiltration capacity were taken. Depending on the type of soil sample, a variety of physical and chemical parameters was determined.

Soil chemical analyses included pH, total carbon, available phosphate, exchangeable cations, cation exchange capacity, and base saturation (Lavkulich 1978). The Leco Analyser gave total carbon for a 0.5-g sub-sample through complete combustion. Available phosphorus was measured as orthophosphate using a Lachat Autoanalyser. Exchangeable cations (Ca, Mg, K, and Na) and cation exchange capacity were determined using ammonium acetate extraction and atomic adsorption spectrophotometry.

Physical parameters included particle-size analysis and colour. Particle-size distribution was determined using a hydrometer and Stokes' Law (Lavkulich 1978). The coarse fragment content was calculated from dry sieving to 2 mm. Colour was determined according to the Munsell colour system.

3.3 Data synthesis

To prepare the data for detailed analysis, some basic assimilation procedures were used. Four important examples are:

- Development of stage-discharge relations
- Parsing of automated data.
- Reconstruction of rainfall record from tipping-bucket record.
- Use of a geographic information system to integrate spatial data

3.3.1 Stage-discharge relations

Stage-discharge relations have been developed at five hydrometric stations: Jhikhu River below Bhendabaribesi (station 1), Lower Andheri River (station 2), Dhap River at Shree Rampati (station 3), Upper Andheri River above Kukhuri River (station 9), and Kukhuri River at Andheri River (station 10). For each point on the stage-discharge relation, individual velocity measurements are combined to yield an estimate of total flow at the recorded gauge height. Total flow is determined by first measuring flow velocity and depth at a selection of lateral points in the stream cross-section. At each lateral point, at least one velocity measurement is taken at a vertical position chosen to represent the average velocity over the entire depth at that lateral position as described by Buchanan and Somers (1969). If the lateral slice is less than one metre in depth, a vertical distance of 0.6 of the depth below the surface is acceptable. If the depth is greater than one metre, two measurements are recommended - one each at 0.2 and 0.8 of the total depth. Where the 0.6 or 0.2/0.8 method has been successfully carried out, the entire flowrate is determined by addition knowing the area of each slice (using stream depth and the amount of the stream width represented by the measurement at that lateral position).

As explained in subsection 3.1.2, many flow measurements cannot be carried out in this standard way. Instead, a flow measurement is made at the stream surface which is at a higher point in the flow than the 0.6 and 0.2/0.8 methods suggest. In these instances, a correction factor (CF, modified from Hoyt 1912 based on comparison of surface and 0.6 measurements taken at medium flows) has been applied to the calculated velocity ($V_{surface}$) as follows:

$V = CF \times V_{surface}$ where

depth < 1 m CF = 1
depth $\geq$ 1 m CF = 1 - (depth/20)
(depth does not approach 20 m)

Once the flows are calculated and summed for each measurement, the stage-discharge pairs are assembled in an x-y plot. Linear regression using a logarithmic transform is used to develop relationships of discharge as a function of gauge height. The five stage-discharge relations which are used in this study are provided in Appendix A5.

3.3.2 Automated data

Automated data from the twelve data loggers in this study were parsed using in-house algorithms. Typically, long periods pass with little or no change in data reading. This applies to river stage, rainfall, and air/soil temperature. Data parsing follows the general principle of retaining only the first and last readings within an allowable, user-defined tolerance. Thus, when a gap in the parsed record exists (other than data gaps due to equipment error etc. which were appropriately flagged), it is known that the "missing" data fall between the values bounding them subject to the tolerance applied by the parsing algorithm.

Table 3.5 shows the tolerances used to parse all automated data. The value of zero for the rainfall data indicates that only non-zero readings were retained and therefore the rainfall record can be reconstructed with absolutely no loss of information. In contrast, the stage and temperature record suffer a small loss in resolution according to the magnitude of the tolerance. The tolerances used in both cases were far smaller than any value which would threaten the integrity of the database.

3.3.3 Tipping-bucket rainfall data

Any tipping-bucket rain gauge records total rainfall during small time periods continuously. No information is retained over timescales smaller than the basic time period of integration. At high

Table 3.5 Tolerances used to parse automated data.

Data Type	Tolerance
Stage, station 1	6.6 cm
Stage, station 2	3.0-4.4 cm
Stage, stations 9 and 10	2.6 cm
Rainfall	0 mm
Air temperature	0.5°C
Soil temperature	0.8°C

Note: In each case, if the change in reading is less than or equal to the tolerance, then the subsequent reading is not retained.

rainfall rates, this is essentially of no concern but at low rates, especially those falling below the rate of one tip/period, the loss of information can be important. For instance, if one tip is recorded every hour for three hours, did each tip's rainfall occur during one period? two periods? or during some combination of periods up to each entire hour? The tipping bucket does not provide this information so some assumptions must be made to deal with these low-rainfall rates. The assumptions used in this study are as follows:

1) Single tips are averaged over all preceding sample periods (within the same storm) for which no rainfall was recorded. This value is also imposed upon a preceding single tip if it begins the storm record.

2) If more than one tip occurs in a tipping period then the tips are **not** averaged over preceding tip periods regardless of the number of tips recorded in these earlier periods.

3.3.4 Geographic information system

The larger study has integrated all spatial biophysical and socioeconomic data into a Terrasoft Geographic Information System (GIS). The GIS has also been used to derive a digital terrain model for the basins under study. The present study uses this GIS and its database for three applications:

1) Overlay techniques

Land and landuse attributes are overlaid to determine spatial relationships. For example, the soil colour map is overlaid with the digital terrain model to reveal the elevation of red soils. Also, rainfall isohyets are overlaid on the soil colour map to determine the soil colour where rain is heaviest.

2) Area computation

Areas are computed for various physiographic and landuse classes. For example, the area is computed within a basin which is in specific bands of elevation, aspect, and slope.

3) Point data

A variety of point data are determined from the GIS. For example, stream profiles are developed using point data along stream courses.

4.0 Monitoring monsoonal rainfall for studying erosion and sediment transport

4.1 Introduction

In Chapter 2, patterns of local and regional climate were characterised descriptively with a focus on rainfall over monthly and annual timescales. However, rainfall delivery is highly variable in time and space and, in the Middle Mountains of Nepal, these variabilities have the potential to affect profoundly erosion and sediment transport. Patterns of rainfall behaviour important to erosion and sediment transport are therefore evaluated here to address the significance of rainfall to the overall diagnosis of basin sediment dynamics over different spatial and temporal scales. A storm classification is developed for use in the erosion analysis.

In the study area, erosion and sediment transport can respond quickly to changes in rainfall delivery. The landscape and its surface form a highly heterogenous mountainous environment, resulting from both very steep topography and a high degree of site-specific human manipulation. Surface condition changes both temporally and spatially in response to management. Variability in both rainfall delivery and erosion susceptibility interact to yield highly complex basin sediment dynamics.

Rainfall monitoring is a sampling exercise which must pay careful attention to regime variability to be successful in its characterisation. Decades of research examining the mechanics of rainfall measurement have yielded a good understanding of how to sample rainfall effectively at a point. In contrast, understanding how to sample for temporal and spatial variabilities is grossly inadequate, especially in mountainous environments. Logistics, cost, and challenges in measurement all contribute to the paucity of studies.

Some specific questions addressed by this chapter include:

Temporal Variability

a) How do storm-period variables (especially storm intensity, total rainfall, duration, and burst timing) vary between storms?

b) Do these storm-period variables change seasonally?

c) Does the pattern of spatial variability in storm rainfall change seasonally?

d) Does storm frequency change seasonally?

e) How frequently must rainfall be measured to adequately assess storm-period variability?

Spatial Variability

a) How much rain is actually falling over the basin?

b) Where is the rain falling?

c) How accurately does the gauge network monitor rainfall?

d) Are there predictable local and elevational changes in rainfall delivery?

This study pursues answers to these questions using recording and storage rain-gauge data gathered over a variety of spatial and temporal scales. Recording rain gauges have been in place for three years at five different sites (see Figure 3.1). Four of these sites are located to provide results for a 2x2 matrix of high and low elevation and south and north aspect. The fifth gauge is located at high elevation and north aspect, far removed from the sites of the other four. About 25 storage gauges provide spatial resolution of 24-hour rainfall on each of two adjacent hillslopes during the rainy season. The monitoring network on the south-facing hillslope was in place for 1992 only while the north-facing network has been in place during each rainy season of 1992-1994. On each hillslope, the network is divided into a high- and low-elevation cluster each of at least 10 gauges. Eight storage gauges have been in place since 1992 providing uninterrupted measurements of 24-hour rainfall at locations throughout the Jhikhu River basin.

After discussing findings from other research which are useful to this study, three analyses are presented. Analysis of temporal variability focuses on changes in storm-period variables during a storm and across seasons. Spatial variation regionally with elevation and locally within a storm cell and across a hillslope form the focus of the following section. Findings from these two analyses are assembled in the last section to yield a classification approach to addressing the rainfall parameter in studies of erosion and sedimentation.

4.2 Research background

Though there has been a great deal of study about the mechanics of precipitation, there remain large knowledge gaps in topographic patterns of rainfall delivery, especially in the Himalaya. The extent of variability inherent in systems of mountain precipitation, the difficulty of gathering data - including automated data - in the Himalaya, and the common problem of adequate monitoring to address spatial variation are the most common causes for these gaps in understanding. After presenting a review of rainfall behaviour emphasising rainfall delivery at the ground surface, findings from Himalayan studies useful to the present work are highlighted to calibrate the understanding developed in other regions and to provide a context for this study's data and results.

4.2.1 Patterns of rainfall delivery

Spatial patterns

Although a wide variety of parameters affects rainfall delivery and its spatial distribution as measured at the ground surface, it is the effect of elevation which has received perhaps the greatest interest. Henry (1919) outlined the early studies (of the 19th century), discussing examples from around the world of changes in precipitation with elevation. He pointed out that there is typically a zone of maximum precipitation - generally below 1000 m in the tropics and between 1400 m and 1500 m in the temperate regions. He recognised that for mountains to cause an increase in precipitation, their axis cannot be parallel to the direction of the winds bringing the storm rainfall and that the steeper the slope, the greater the rate of change of precipitation. Givone and Meignien (1990) recognised this relation in establishing an array of 14 recording gauges perpendicular to the mountain range under study. They examined the detailed meteorological features of the rainfall before studying the influence of topography on it. They found that instability triggered at the footslope of the mountain yielded the heaviest hourly totals at low elevation with the heaviest daily totals occurring at the top of the range. Henderson (1993) examined elevational effects on storm total-rainfall in the Southern Alps of New Zealand and found the maximum rainfall to occur at 10 to 20 km upwind of the elevational maximum. These findings underscore the importance of carefully selecting the storm-period variables under consideration and the range of elevation for which extrapolation is acceptable.

Smith (1989) described the four most likely mechanisms of orographic precipitation: smooth, forced ascent; seeder-feeder mechanism; diurnally-forced convection; and triggered convection by forced ascent or blocking. A common aspect is that precipitation enhancement occurs on the upwind slope and can be so reliable as to be used as a crude indicator of regional wind direction. Unfortunately, despite significant study of precipitation change with elevation, comparatively little is understood about the specific mechanisms involved. He suggested that this lack of understanding must change if we are to better predict spatial variability in mountainous terrain.

The rainfall-elevation effect, however, is far from alone in shaping spatial patterns of rainfall delivery. Spreen (1947) realised this and included slope, exposure, and orientation as independent variables important to rainfall spatial variability. Spreen's ability to predict precipitation locally increased dramatically when these other factors were also considered ($R^2=55\%$ elevation only; $R^2=94\%$ all factors). Importantly, he found that in steep mountainous terrain, these non-elevational factors dominate locally. Sinclair (1993) blamed this lack of "orographic resolution" on the inability of elevationally-driven approaches to predict rainfall spatial variation in an extreme event.

These studies have one thing in common: they examine spatial variability over large scales (>100 km^2). In the Middle Mountains, and certainly in many other mountainous areas of the world, though the average rainfall over many storms may vary spatially in a predictable way, individual events may not. This temporal variability over a fixed spatial scale is a topic rarely discussed in the literature. There are few examinations of the behaviour of individual cells of limited spatial extent (1 to 10 km^2) in mountainous terrain. For instance, Paturel and Chocat (1993) used measurements from a network with average density of one gauge per 20 km^2 by asserting that this figure corresponds to the smallest convective cell likely to have an influence on the drainage network. They noted and did not explain, however, that a high degree of spatial heterogeneity resulted in their rainfall data.

Temporal patterns

Another common approach to examining dynamics of storm rainfall uses descriptive statistics of myriad storm-period variables. There appear to be as many analyses of storm-period variables as there are authors. For instance as shown in Table 4.1, the definition of a storm (when it is given) is rarely the same from author to author. Minimum total rainfall (R) and time-without-rain (S) requirements are the dominant criteria. How these are applied appears to depend on the nature of available data. For instance, Reid *et al.* (1981) had 24-hour rain data and established the definition of storm on that basis. Tropeano (1991) discussed 280 events in detail but did not present his storm definition. These studies tend to define a storm to accommodate the data available and do not evaluate the appropriateness of the definition chosen. Depending on the goal of the analysis, there exists the potential of introducing an error at a fundamental level.

Table 4.1 Published storm definitions.

Author(s)	Storm Definition
Huff (1967)	$S \geq 6$ h $R_T \geq$ threshold from network
Collinge and Jamieson (1968)	$R_T \geq 25$ mm anywhere in basin
Reid *et al.* (1981)	$R_T \geq 0.5$ mm in 24 hours with a day of $R_T < 0.5$mm on each side
Tropeano (1991)	None provided
Farmer and Fletcher (1972)	$S \geq 1$ h and $R_T \geq 2.5$ mm
Patural and Chocat (1993)	$S \geq 4$ h
Overseas Development Agency (1995)	$S \geq 1$ h

Note: R_T = total storm rainfall (m)
S = length of time without rain before and after a storm (h)

Having established the definition of a storm, there are many approaches to analysing the storm-period variables. Herschfield (1962) presented extensive analyses of storm-period variables and Huff (1967) pointed out the importance of tailoring such analyses to a specific application with specific spatial and temporal scales of concern. Unfortunately, after analysing 261 storms using a quartile-separation approach, Huff (1967) determined that quartile separation does not vary consistently with storm type.

The results of these analyses uncover some interesting temporal dynamics in rainfall behaviour at a point. Farmer and Fletcher (1972) examined convectional, high-elevation burst-rainfall behaviour in Utah finding that over half of storms yielded more than 50% of the storm rainfall in a 10-minute burst. Also, in most storms the period of heaviest rainfall occurred in the first quartile. They used their burst information to define storms for planning purposes in soil erosion and flood protection. Their study illustrates that relevant rainfall statistics ultimately depend upon precipitation mechanisms, in this case semi-desert to desert convectional showers driven by extensive surface heating. Bryant (1991) documented an apparent worldwide maximum envelope of rainfall intensity for any given timescale. Presumably such a relation could help develop an appreciation for the relative severity of different mountain precipitation regimes. Bryant also emphasises the lack of rainfall data over short timescales of less than 5 minutes. Given the many hurdles to adequately measuring storm rainfall distribution in both time and space including the instrumentation concerns reviewed in section 3.1.1, it is not surprising that many researchers have turned to rainfall models for their rain data (*e.g.*, Rodriguez-Iturbe and Eagleson 1987).

Another approach to estimate rainfall in mountainous terrain is to use streamflow data distributed back over the catchment and corrected for evapotranspiration (Danard 1971; Anderson 1972; Ishihara and Ikebuchi 1972; Dingman 1981; Griffiths 1981). Unfortunately, it is for flood prediction in mountainous terrain that storm characterisation is most needed (*e.g.*, Collinge and Jamieson 1968; Dingman 1981).

4.2.2 The Asian Monsoon

The Asian monsoon which brings the rainfall examined in this study occurs because of the seasonal reversal of winds across the Indian subcontinent. Webster (1987) identified the three fundamental driving mechanisms behind the planetary monsoon:

1) the differential heating of the land and ocean creating the pressure gradient which drives the winds from high pressure to low pressure;
2) the rotation of the Earth which introduces a swirl to the winds; and
3) moist processes that store, redistribute, and selectively release the solar energy arriving over most of the tropics and subtropics.

The Asian monsoon is notable for its immense extent and the penetration of its influence beyond tropical latitudes (Barry and Chorley 1992). The potential magnitude of rainfall in this region and both spatial and temporal variability of the monsoon are important to the present study and are discussed in this section in relation to synoptic-scale precipitation mechanisms.

The Asian monsoon is known for its ability to deliver huge quantities of rainfall. In developing the concept of an envelope of maximum possible rainfall in relation to total measurement time (Bryant 1991), the data for all time periods greater than one week came from Asian monsoon measurements in Cherrapunji India. The highest 24-hour rainfall ever recorded in the Ganges basin was 823 mm (at Nagina in Uttar Pradesh), in the Brahmaputra basin it was 1036 mm (at Cherrapunji) and in Nepal it was 539.5 mm at Tistung (Dhital *et al.* 1993).

The mechanisms responsible for these extreme rates of rainfall delivery include cyclonic storms near the Bay of Bengal, various types of low-pressure (widespread across the Subcontinent), and orographic mechanisms due to complex topography and, at times, extreme relief (Takahashi and Arakawa 1981). The variety of large-scale effects and the contrasts in topography over this vast region result in considerable spatial variation in rainfall delivery across the Subcontinent.

Because the coastal cyclonic storms generally do not adequately penetrate the Subcontinent to reach the Middle Mountains near Kathmandu, it is the monsoon depressions (areas of moderate low-pressure covering tens to hundreds of thousands of square kilometres) originating near the Bay of Bengal which bring most of the precipitation to the study area during the period of the southwest monsoon. The area is prone to thunderstorms (Takahashi and Arakawa 1981), likely triggered by the suite of orographic effects resulting from the area's complex topography. The Middle Mountains possess adequate relief (in contrast to the Siwalik and Mahabharat Ranges to the southwest) to cause smooth forced ascent and to trigger conditional and convective instabilities. Also, convection is triggered by upslope winds and the considerable diurnal heating of slopes (Barry and Chorley 1992). Undoubtedly, these effects may all be present in addition to topographically-created preferred pathways.

Superimposed on the large-scale regional spatial variability in mountain precipitation are significant local variations. For example, Upadhyay and Bahadur (1982) studied rain gauge data in the Dehang catchment in the Brahmaputra basin and found that correlation between adjacent stations became negligible at about 35 km. Dittman (1970, in Domroes 1979) found that there was "no systematic connection" between the daily totals of rainfall for five gauges - located in a mixture of valley bottoms and ridge tops - within a few kilometres of each other in the elevation range of 1860-2130 m near Jiri, Nepal. LRMP (1984) suggested that rainfall intensity is higher at lower elevations. Despite the extent of these important local differences, they are poorly researched (Bruijnzeel and Bremmer 1989) and, unfortunately, the overall density of rain gauges is also low - in Nepal, 1 in 490 km^2 in 1984 (Department of Hydrology and Meteorology 1984). The World Meteorological Organisation recommends that in mountainous regions of tropical zones rainfall monitoring stations be installed in altitude zones of 500 m per zone and with a minimum density of 1 station for 100-250 km^2 (World Meteorological Organisation 1981). Given the emphasis on valley-bottom gauge sites in Nepal and the other factors mentioned above, there is considerable uncertainty about actual precipitation rates at ungauged mountainous locations.

Orography causes total precipitation generally to increase because of the relation between temperature and saturation vapour pressure. But since less moisture reaches still higher (and colder) elevations, precipitation declines (Upadhyay and Bahadur 1982). This behaviour has been observed in, for example, the Canadian Coast Range (Loukas 1994). In the eastern part of the Ganges-Brahmaputra basin, a decrease in rainfall with elevation has also been observed (Bruijnzeel and Bremmer 1989). In his work in the High Mountains, Ries (1991) found rainfall to be inversely proportional to elevation between 2000 and 3300 m. Rainfall intensities were found to be greater in the valleys than on the hillslopes. Unfortunately. these authors do not report how well gauge catch biases were controlled in their studies.

Although the Asian monsoon demonstrates considerable predictability, temporal variability can be significant. Das (1987) illustrated the annual arrival date of monsoon rains across the Indian subcontinent. Near Kathmandu where the study area of the present research is located, the initial monsoon burst typically comes in the second week of June. This start date is defined by an increase in the moisture content of the atmosphere and a sustained increase in rainfall (Das, 1987). Although 80% of annual precipitation falls during the monsoonal months of June, July, August, and September, there is a variable pulse alternating between active and break periods (Barry and Chorley 1992). This wet-season variability in monsoonal rainfall delivery is similar to the widely-recognised variability in tropical rainfall (Jackson 1989). Although breaks in the Asian monsoon are most common in August and September and last on average five days, they may occur at any time during the summer and can last as long as five weeks.

Rainfall delivery in the Middle Mountains shows a nocturnal maximum. Winkler, Skeeter, and Yamamoto (1988) found this for hourly precipitation in the United States, particularly at high intensities. This behaviour is likely related to regular diurnal cooling of convective showers (Shaw 1972).

4.3 Definitions

How storm-period variables are defined strongly influences how effectively they can be used in this study's diagnosis of basin sediment dynamics. The storm and seven storm-period variables are defined in this section. In each case, the choice of spatial and temporal scales is guided by the application to erosion and sediment transport of interest here (100 m^2 to 10 km^2 in particular).

4.3.1 Storm

In quantitatively representing storm rainfall-intensity data, the continuous record of rainfall is first divided into distinct events. After storms have been delineated, storm-period variables can be quantitatively extracted. Two steps are applied in defining a storm. In the first step, a minimum "time-without-rain" or storm separation time (S_{MIN}) is used and is applied to the beginning and end of a period of rain. Because storm events will later be related to flood events, this approach is convenient because it creates a storm characterisation which parallels that of the floods. In the second criterion, "storms" of inconsequence for sediment dynamics are filtered out through a minimum total-rain constraint (R_{MIN}).

At what value should S_{MIN} be set? Two practical considerations narrow the range initially:

- avoid combining storm rainfall arising from distinctly separate rainfall events and
- avoid resolution effects of the tipping bucket rain gauge.

The first of these suggests that S_{MIN} should be less than the time it takes for a synoptic scale event to come and go - no less than about half a day and generally much more. To assess the quantitative extent of the resolution effect, we divide the poorest resolution (1.258 mm - adjusted) by the lowest intensity of consequence for erosion in a storm event, about 10 mm/h. With these numbers, we expect 7.5 minutes to occur between measurements by the instrument even under continuous rain. If we make S_{MIN} less than 7.5 minutes, we will create separate storm events as a result of this resolution limit.

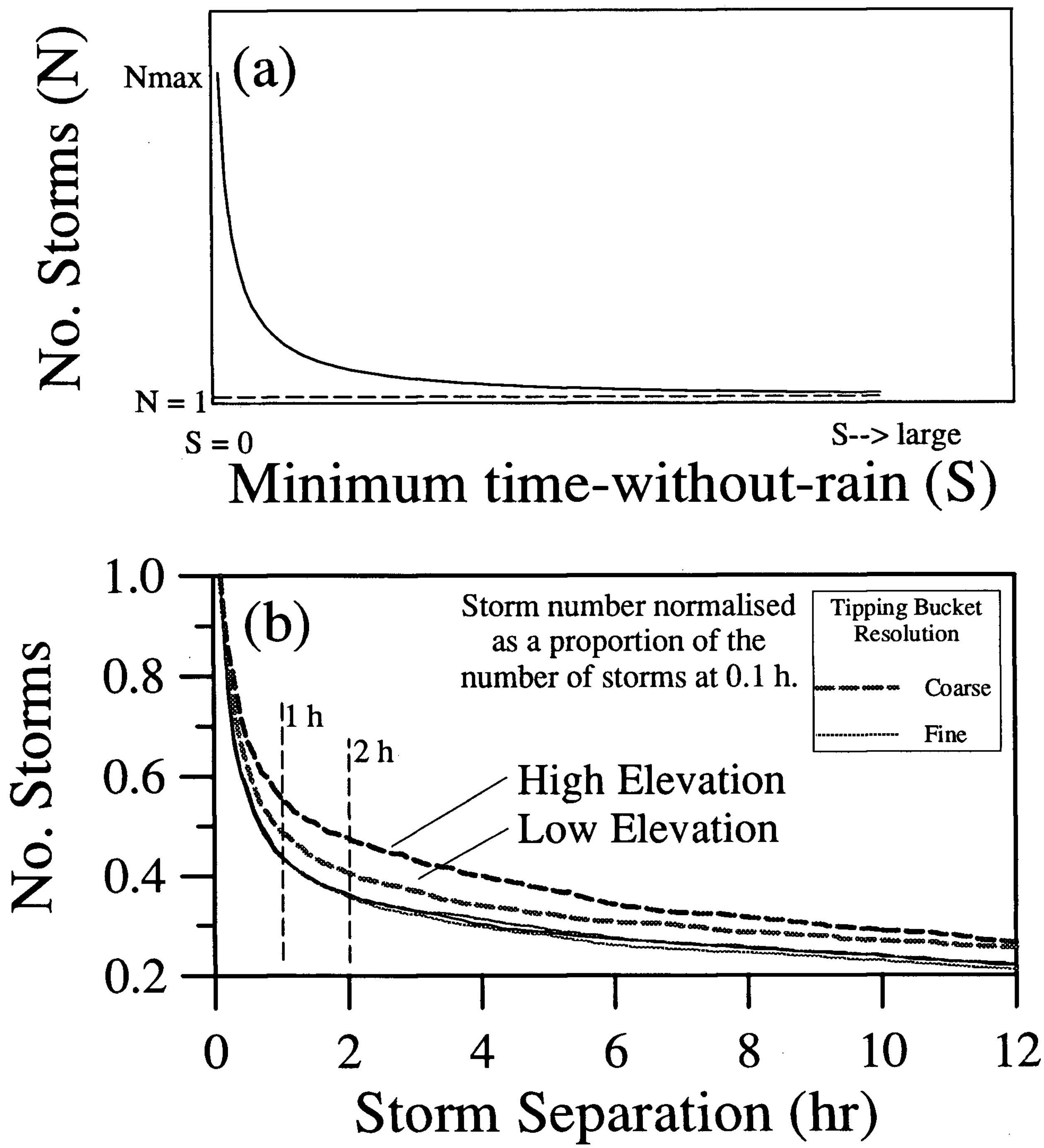
To fix this variable's timescale within this "operating range", consider the variation in the number of storms (N) as a function of S_{MIN}. As illustrated in Figure 4.1a, as S_{MIN} becomes large, N becomes small and eventually reaches unity. Conversely, as S_{MIN} becomes small, N will grow large up to a maximum related to the length of the record and the propensity for and the frequency of rainfall in the specific location.

The continuous data for all five recording gauges in this study have been subjected to this sensitivity analysis and the normalised results are presented in Figure 4.1b for the range S_{MIN}= 0.1 to 12 hours. This graph confirms the intuitive trend illustrated in Figure 4.1a. Additionally, between S_{MIN}= 1 and 2 hours, a major change develops in N. In other words, as S_{MIN} is reduced from 12 to 2 hours, little change in total number of storms results, but when the criterion is varied further to 1 hour, a large increase occurs. This is the lumping together of separate flood-causing convective bursts which we set out to avoid.

We can get further help in choosing S_{MIN} within this range by also considering the flood events which result from these storms. Ideally, S_{MIN} should be chosen to avoid unnecessary splitting and lumping so that all the rainfall that contributes to a certain flood event gets accounted for in an individual storm. In these headwater areas, it takes typically only a few hours for a flood to rise and return to a small percentage of its peak flow. If S_{MIN} is significantly less than these few hours, then undesirable storm splitting will occur. Specifically, in this case, it is best to use the highest value in the range being considered, namely S_{MIN} = 2 hours.

Having divided the continuous rainfall record into discrete events, a minimum-size criterion (R_{MIN}) is applied to the results. Storms of less than 3 mm are excluded from further analysis because they are unimportant to erosion and in addition, the measurement of single-tip and double-tip storms can be unfavourably affected by resolution limitations of the instrumentation. The combined application of these criteria yields, typically, 80 storm events per year at each of the five sites. It is these storms which are the subject of the analyses in the following sections.

Figure 4.1 Number of storms in relation to (a) generalised minimum-time-without rain, and (b) specific minimum-time-without-rain at the five study locations.



4.3.2 Storm-period variables

Appropriate storm characterisation underpins any examination of the effect of rainfall on erosion and sediment transport. Storm-period variables must be extracted from the rainfall record so that rainfall aspects most germane to erosion will be quantitatively and comparatively expressed. For example, it is known (Hudson 1981) that rainfall intensity plays an important role in initiating surface erosion, but what is the best expression of this storm-period variable? Which timescale(s) is most appropriate?

Short-term rainfall intensity and total rainfall are the two rainfall characteristics which most strongly shape the character of the erosion process (see Chapter 5). High-intensity bursts are effective at initiating surface erosion at the plot scale as a result of the kinetic energy they possess. Antecedent moisture conditions (influenced by prior rain activity) can also greatly affect the ability of these bursts to cause surface erosion. Large rainfall volumes (usually over a long period) shift the emphasis within the sediment budget from surface erosion at the plot scale to slumping, streambank erosion and bed scouring (often farther downstream) due to large, channelised flows.

Several storm-period variables are proposed to address surface erosion. A characteristic of tropical and subtropical rainfall is heavy burst rainfall lasting only a few minutes. Several minutes of rainfall at high intensity can cause damaging surface erosion on sloping agricultural fields. In choosing a timescale to characterise this intensity, the resolution of the recording rain gauge is the major constraint in accurately quantifying the short-term rainfall intensity. In this study, most measurements of rainfall intensity are for two minutes, though 5-minute and 10-minute intervals have also been used. If this short-term intensity timescale is set smaller than ten minutes, the intensity parameter cannot be calculated for all the storms. Further, if it is set too close to the resolution of the instrument, then the intensity parameter will be undesirably affected by how the instrument randomly measures the event. For these reasons, the maximum rain that falls in a ten-minute period of a storm

(I_{10}) is measured for each storm.

The timing of the peak 10-minute burst (T_{10}) and antecedent moisture conditions can both greatly influence the erosivity of the burst. For this reason, two other storm-period variables are considered:

T_{10} The start time of the peak 10-minute rainfall intensity relative to storm start

S The period (hr) before a storm since the end of the previous storm ("period-without-rain")

Together, these variables provide a good relative indication of the antecedent moisture conditions as I_{10} begins.

Several storm-period variables are defined to address the effect of large amounts of storm rainfall. Since total storm rainfall (R_{TOT}) and duration (T_{DUR}) are frequently cited in other studies these are also considered in this analysis. In these steep headwater catchments, the flood-causing rain of a storm often does not occur over the duration of the storm (sometimes it is delayed as long as ten hours). It appears that the bulk of the rainfall of most storms occurs over a period of about one hour. What timescale best represents this characteristic? As the value becomes larger, more storms will not be characterised because of inadequate duration. As the value is made smaller, it will not properly represent the total-flood-causing-rainfall concept. One hour is chosen and I_{60} is defined as the maximum amount of rainfall occurring in a 60-minute period of the storm. Consistent with T_{10}, T_{60} is defined as the start time of the peak 60-minute rainfall intensity.

4.4 Storm-period variables

This section describes the temporal variability of rainfall by examining storm-period variables in the study area and assessing the seasonal change in the distribution of their characteristics. To make the storm classification relevant to the observed geomorphic thresholds for erosion over contrasting spatial scales, findings from Chapters 5 and 8 are brought in to the quantitative discussion which follows.

4.4.1 Distributions

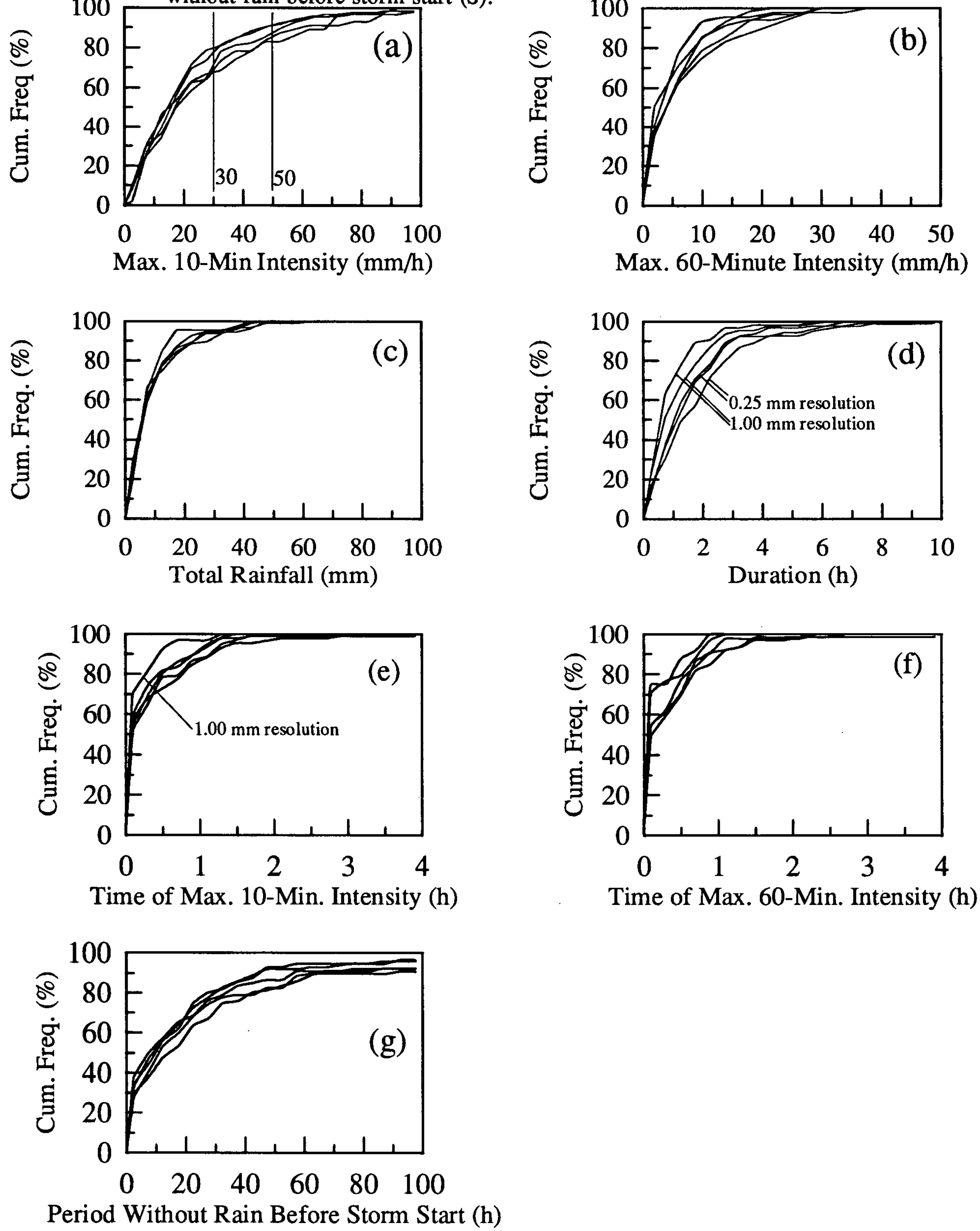
Seven storm-period variables - total rainfall (R_{TOT}), event duration (T_{DUR}), maximum 10-minute (I_{10}) and 60-minute (I_{60}) rainfall intensities, within-storm timing of 10-minute (T_{10}) and 60-minute (T_{60}) peak intensities, and the rain-free period before each storm (S) - have been determined for all the events at the five recording rain gauges. Distributions of these variables are discussed on both annual and seasonal bases. Cumulative frequency diagrams are used to examine gross trends and similarities. Occurrence frequencies by class are examined for statistical differences. Class intervals for frequency distributions follow Conrad and Pollak (1950).

Figure 4.2 shows the cumulative frequency distributions of the seven studied storm-period variables. These cumulative plots exaggerate similarities and highlight only large differences. All these plots indicate a preponderance of storms at the low-value end of the distributions. This is consistent with the field observation that the majority of storms is not flood-producing.

Figures 4.2a and 4.2b show the cumulative frequencies of I_{10} and I_{60} in terms of percentage of total occurrences for each of the five recording rain gauges within the Jhikhu River basin (1992-1994). Figure 4.2a reveals a consistent pattern across all gauges: about 75% of storms have a maximum 10-minute rainfall intensity of less than 30 mm/hr. In Chapter 5, this value is found to represent a threshold for initiation of significant surface erosion. Only 10% of all storms exceed 50 mm/hr, a minimum threshold (of I_{10}) determined in Chapter 8 to be required for significant basin soil loss to occur (see also section 4.6). I_{60} exhibits the same coherent pattern, the values being correspondingly lower. R_{TOT} (Fig 4.2c) shows more variability between sites with 75% of all storms delivering less than 15 mm and only 10% of all storms bringing more than 25 mm.

Although storm duration is often cited in studies describing storm characteristics, the distributions of T_{DUR} given in Figure 4.2d reveal the inadequacy of this storm-period variable for this

Figure 4.2 Cumulative frequency distributions of storm-period variables (1992-1994) at the five study locations: (a) maximum 10-minute intensity (I_{10}), (b) maximum 60-minute intensity (I_{60}), (c) total rainfall (R_{TOT}), (d) duration (T_{DUR}), (e) start of maximum 10-minute rainfall intensity (T_{10}), (f) start of maximum 60-minute rainfall intensity (T_{10}), and (g) period without rain before storm start (S).



purpose: the result is sensitive to the resolution of the instrumentation. Whereas T_{10} (Fig 4.2e) is also sensitive to gauge resolution, T_{60} is not because the effect of gauge resolution is lost over the longer period. Figures 4.2e and 4.2f show that burst rainfall occurs very soon after the beginning of a storm. For instance, in half of all storms the 10-minute and 60-minute peak intensities begin in the first 15 minutes of the storm.

Figure 4.2g shows how many hours without rain precede storms. About 50% of all storms follow only 12 hours without rain. A further 25% follow 12-24 hours without rain. The final 25% can follow long periods without rain, often of many days. This timescale has important implications for surface erosion, especially if the storm rainfall arrives abruptly on dry ground.

For the variables not sensitive to the measuring instrument, Table 4.2 summarises the ranges of the variables in the three classes: 0-75%, 75-90%, 90-100%. These distributions provide an overview of the nature of storms in the study area, one which will be useful in section 4.6 when a storm classification system is described and applied to these data.

Table 4.2 Frequency of occurrence of four storm-period variables in three classes.

Percentage Occurrence	R_{TOT} (mm)	I_{10} (mm/h)	I_{60} (mm/h)	T_{60} (h)	S (h)
First 75%	0-15	0-30	0-7.5	0-0.5	0-17
Next 15%	15-25	30-50	7.5-15	0.5-1	17-34
Last 10%	≥25	≥50	≥15	≥1	≥34

The distributions shown cumulatively in Figure 4.2 were tested for differences using a Chi-Squared Goodness of Fit analysis for the five storm-period variables not sensitive to the measuring instrument. Occurrence frequencies were classified using a five-class system with the class boundaries established so that each class contained about 20% of all occurrences. For each of the five variables, three tests were carried out. In the first, the distributions at all five sites were tested in a combined 5 x 5 test with 24 degrees of freedom. In the other two, occurrences from the high- and low-elevation sites were pooled to form two groups which were tested in a combined 5 x 2 test with 9 degrees of freedom. Only R_{TOT} showed a significant difference ($0.90 < P < 0.95$). Aspect appeared to drive this difference ($0.95 < P < 0.975$) though no consistent trend between the two distributions pooled by elevation was observed.

4.4.2 Seasonal distributions

Figures 2.3 and 2.4 demonstrated that averages and extremes of total monthly rainfall vary during the year suggesting that storm characteristics might change seasonally. The data on storm-period variables are used to determine quantitatively how storm characteristics change seasonally.

The majority of the annual rainfall occurs during the months of June through September with a distinct dry season from November to April. During May and June, the rains first start to arrive while the land surface is desiccated and the cultivated fields generally bare. This period is known as the pre-monsoon season. During the months of July, August, and September, vegetative cover is well developed - this season is termed the monsoon season. The date of onset of the monsoon season is variable but in this study, the end of the pre-monsoon season is determined to be June 30, followed by a transition season of 19 days' duration (from July 1-19) at the end of which the "monsoon" season begins. The choice of these dates is made on the basis of stream suspended-sediment regimes (see section 5.4.2) so in a sense, this is to some degree a "land-surface response" monsoon definition rather than a strictly hydrometeorologic one.

For consistency, the same seasonal definitions are used to characterise both the rainfall and sediment regimes. Before continuing, it had to be decided whether the 19-day transition season - designed to facilitate the analysis of sediment dynamics - will be included with the pre-monsoon season or with the monsoon season.

A sensitivity analysis using three options was evaluated for demarcating the end of the pre-monsoon and the beginning of the monsoon season: (midnight) June 30, July 10, and July 20.

Initially, data from the two gauges on the north-facing hillslope were used to assess the sensitivity of all the variables to changes in the date separating the seasons. I_{10} was the most important to surface erosion and therefore was used as the key indicator in examining the data from all five sites. The seasonal difference in I_{10} was the greatest using June 30. As the separation date advanced, the differences tend to decline at all five sites suggesting a dilution of real seasonal differences as "monsoon" storms of July 1-19 are added to the "pre-monsoon" storm population. Hence, in this seasonal analysis, the pre-monsoon season ends on June 30 (midnight) and the monsoon season begins on July 1.

A second set of Chi-Squared Goodness of Fit analyses containing two parts is carried out on these seasonal storm data. In the first, the analyses carried out for the combined data are repeated for the separate seasonal groups. These tests examine differences *within* seasons. In the second, differences *between* seasons are examined by pooling the data within each season in different ways to yield five tests for each variable: all sites (24 degrees of freedom), high elevation, low elevation, north aspect, and south aspect (9 degrees of freedom). To limit the accumulation of Type I Error, only differences limited to 0.5% *should* be considered significant $[(1-0.005)^{25} = 0.882]$ though all differences within 10% are discussed.

The within-season analyses revealed no important differences within either season. The test using data pooled by elevation resulted in a difference in T_{60} at 90% though no consistent cause or result of this difference was evident.

Differences between seasons were the most statistically important of all the results. Of the differences observed, the results for S were the strongest. The high-elevation and north-aspect groupings showed differences of 99% and 97.5% respectively while the result for the seasonal contrast for the south aspect pool was 90%. Consistently, S was higher in storms of the pre-monsoon season. This is an important difference because a longer period without rain before the start of a storm suggests drier conditions and can point to more erodible surface soils.

The test results suggest that T_{60} comes earlier in pre-monsoon storms: differences in south-facing pooled data were significant at 97.5% and in low-elevation pooled data at 90%. Early arrival of a storm's heavy rain should increase its erosivity. If combined with a longer pre-storm dry period, the effect can be important.

Consistent with the non-seasonal analyses, some differences were found in R_{TOT}. Not surprisingly, R_{TOT} for the monsoon storms was shifted toward higher values. All distributions showed this characteristic. The seasonal contrast using all five sites was significant at 90% and it was at the south-facing sites where this effect was the greatest (99.5%).

In summary, the similarities between seasons far outweigh the differences. Storm characteristics in the study area are conducive to surface erosion as heavy rain can fall over dry ground throughout the year. The seasonal contrasts suggest that the pre-monsoon storm regime is somewhat more liable to generate surface erosion, exacerbating a situation where the surface soil is already vulnerable to erosion due to its bare condition.

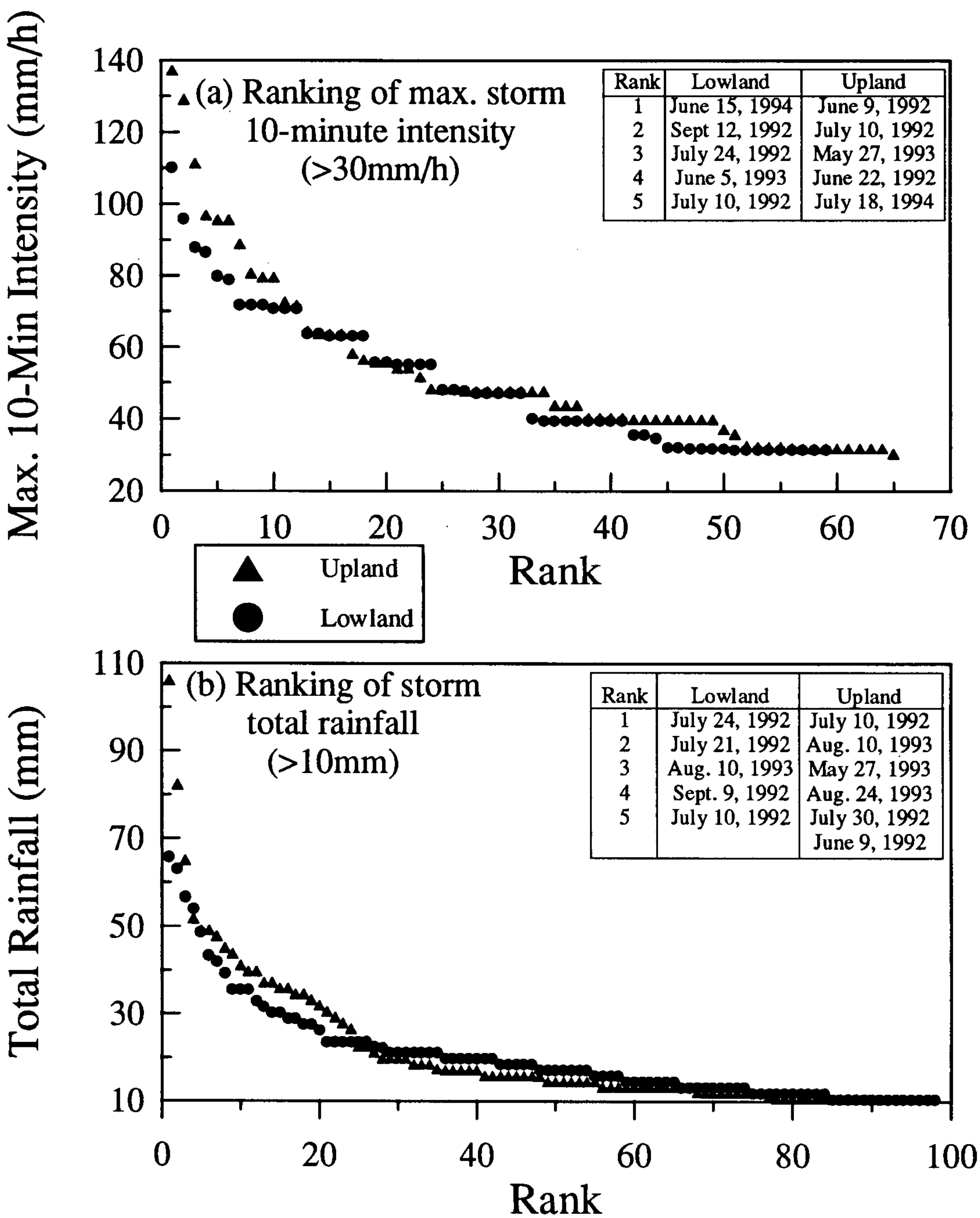
4.4.3 Event ranking

Rainfall

Figure 4.3 illustrates the ranking of the largest monitored storms within the Andheri basin by R_T and I_{10}. Though the previous section showed that storm-period variables are not significantly different between the upland and lowland, these distributions reveal them to be slightly larger in magnitude at the upland recording rain gauge location. These distributions also reveal that there is little correspondence between the upland and lowland areas for the rankings of the largest events - only two events appear in the top five for both the upland and lowland areas. Only the July 10, 1992 event appears in all categories, suggesting that it is a significant event of the study period.

Though the three-year record is inadequate to justify the development of intensity-duration-frequency relations, these rankings are useful to illustrate the relative magnitude of the major

Figure 4.3 Ranking of largest monitored storms in upland and lowland of Andheri basin by (a) I_{10} and (b) R_T.



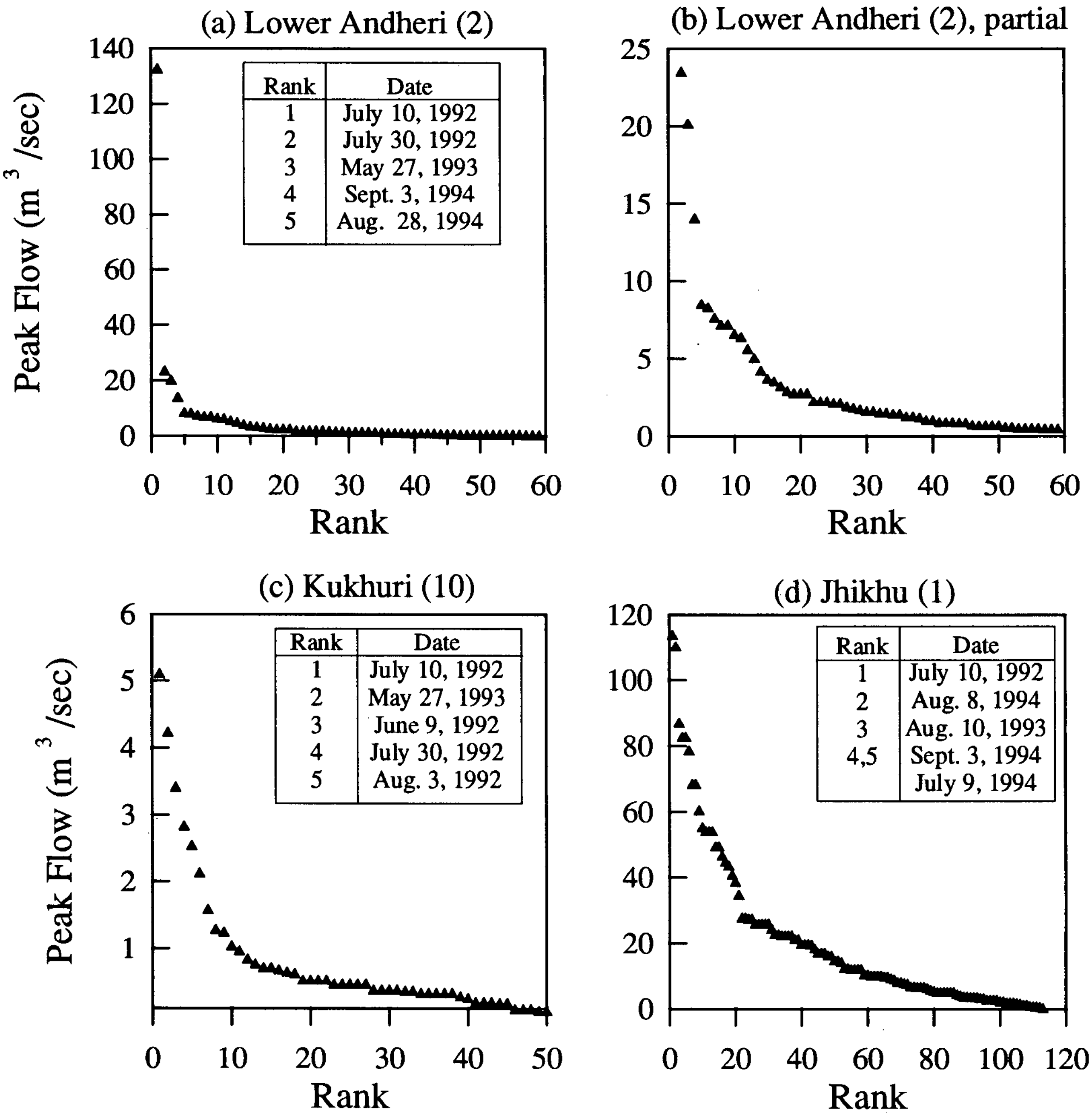
monitored storm events. The upland experienced two or three events noticeably heavier (with respect to both R_{TOT} and I_{10}) than all the other events at both the upland and lowland stations. Overseas Development Agency (1995) report a maximum measured rainfall intensity of 144 mm/hr (for one minute) from a three-year monitoring study at several nearby locations.

High-flow

A ranking of high-flow peaks at Khukuri, Lower Andheri, and Jhikhu stations is presented in Figure 4.4. The continuous nature of the data from Khukuri and Jhikhu suggests that these distributions represent events with low return period of perhaps less than three years. The result for Lower Andheri stands in stark contrast suggesting that the return period of the flood event of July 10, 1992 is significantly higher than that of the other events during the study period. The local farmers indicated that a flood event like that of July 10, 1992 had not been experienced in over ten years. Though it is difficult to provide a confident estimate of this event's return period, it may be reasonable to consider that it was a ten-year flood event. This event was the highest measured at all three scales providing further confidence in this estimate. With analysis of the subsequent three years' data, this estimate can be improved.

Though the five biggest events at the Khukuri and Lower Andheri stations exhibit some consistency, the rankings of the high-flow events at these two stations shows no relation to that of Jhikhu (except for the July 10, 1992 event). These changes in ranking with scale hint at spatial variability in the rainfall-runoff process. In addition, a comparison of the flood rankings at Khukuri/Andheri to the rainfall rankings provided in Figure 4.3 suggests that it is the large total-rainfall events of the *upland* that are most able to shape the high-ranking events of Lower Andheri station. Rainfall is an important control on the flood regime but it is clearly not the only important control. These comparisons will be useful in Chapter 8 where individual events are examined further.

Figure 4.4 Ranking of monitored floods at (a) Lower Andheri, (b) Kukhuri, and (c) Jhikhu stations.



4.5 Spatial variation

The effect of elevation over three different scales (1, 10, and 100 km^2) and local variation within individual storm cells (1 km^2) are examined using 24-hour rainfall measurements. The 100-km^2 analysis (the Jhikhu River basin) uses data from long-term climate stations. The 10-km^2 (hillslope) and 1-km^2 (storm cell) analyses use data from the detailed wet-season rain-gauge network (see section 3.1.1).

4.5.1 Elevation

Over the spatial scale of the Jhikhu basin (100 km^2), how does elevation influence rainfall? Rainy-season (June-September) data from eight long-term monitoring stations within the basin are presented in Figure 4.5a. The graph suggests that total June-September rainfall increases with elevation, perhaps at a rate of about 0.5 mm/m. These data are also plotted monthly in Figures 4.5b through 4.5e: the same trend is evident in each month. The data are too few to justify further quantitative analysis.

Data from the detailed north-facing study basin in Figure 4.6a show that on the Andheri hillslope (5 km^2), June-September rainfall declines with elevation, driven by the behaviour during June and September. The two groups, separated elevationally at 1150 m, were tested using the Mann-Whitney U-Test. In June and September, the rainfall in these two groups is significantly different (September: 95%, $P=0.014$; June: 99.9%, $P=0.0001$). Reporting on rainfall dynamics in the Likhu basin near Kathmandu, Overseas Development Agency (1995) found that the areas which are the first to receive a system are also the areas with the higher rainfall. This is generally the case on this hillslope: systems arrive in the Jhikhu River valley and move up into the Andheri sub-basin. The shoulder months also exhibit a tighter pattern suggesting that wind effects may be minimised during this period. The variability in rainfall measured over the hillslope during July and August may be attributed largely to the negative bias of wind. The high measurements at Gauge 19 (1182 m) situated

Figure 4.5 Effect of elevation on rainy-season rainfall at eight monitoring stations distributed across the Jhikhu River basin (100 km^2; 1992-1994): (a) June-September, (b) June, (c) July, (d) August, and (e) September.

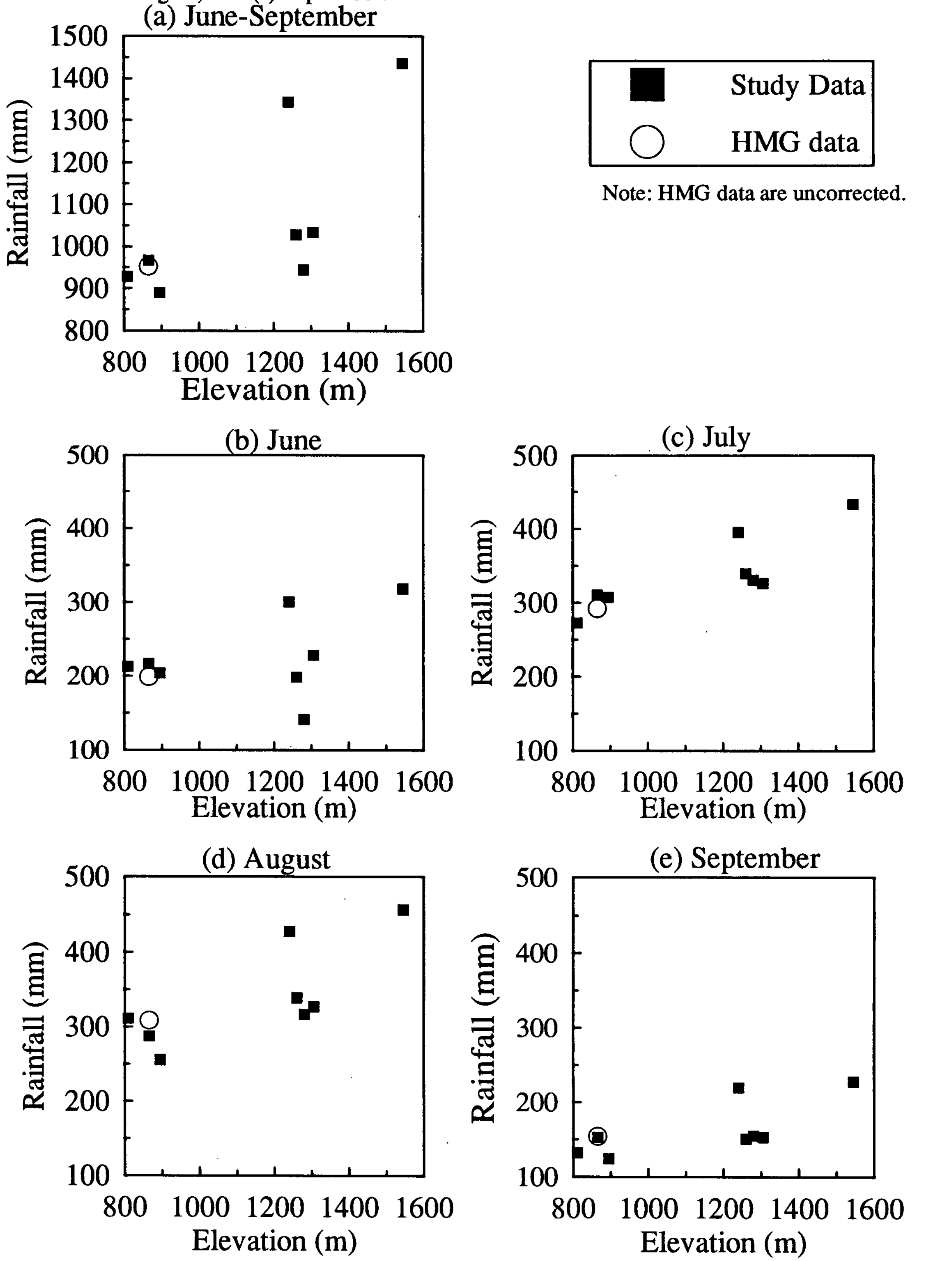
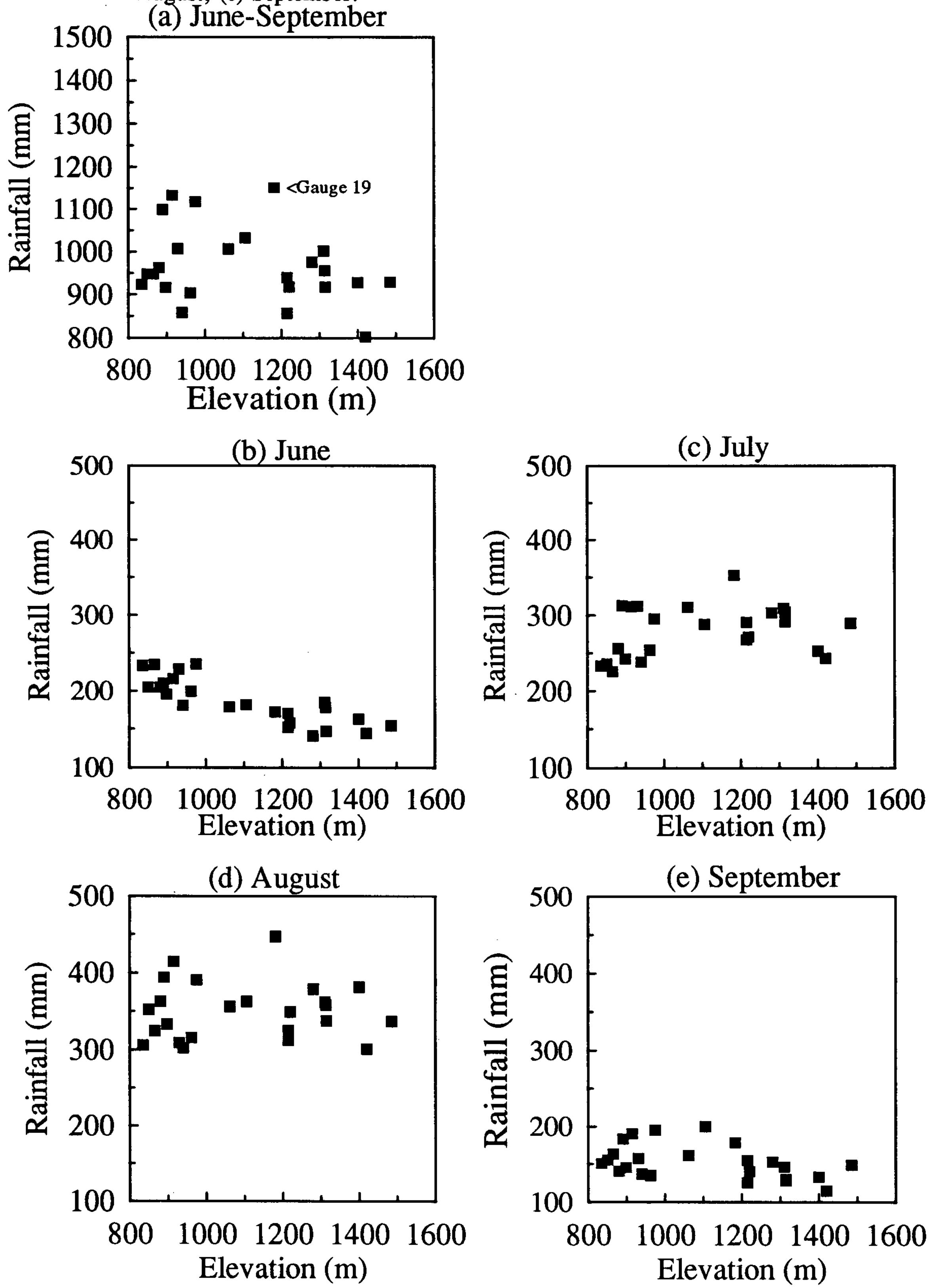


Figure 4.6 Effect of elevation on rainy-season rainfall at 20 monitoring stations located on the Andheri basin hillslope (10 km^2; 1992-1994): (a) June-September, (b) June, (c) July, (d) August, (e) September.



at the break in slope below the Kukhuri sub-basin (10) suggests that there may be a mid-slope maximum - perhaps due to a modest exhaustion effect - but the data are too few to confirm or refute this hypothesis.

Data are available from 1992 for the south-facing hillslope and are presented monthly in Figures 4.7a through 4.7c. The July data are too few to infer any trend in rainfall with elevation on the hillslope. In contrast, data for August reveal a strong increase with elevation, one which experiences no exhaustion upslope. This contrast to the north-facing hillslope could be due to the abrupt nature of the south-facing slope.

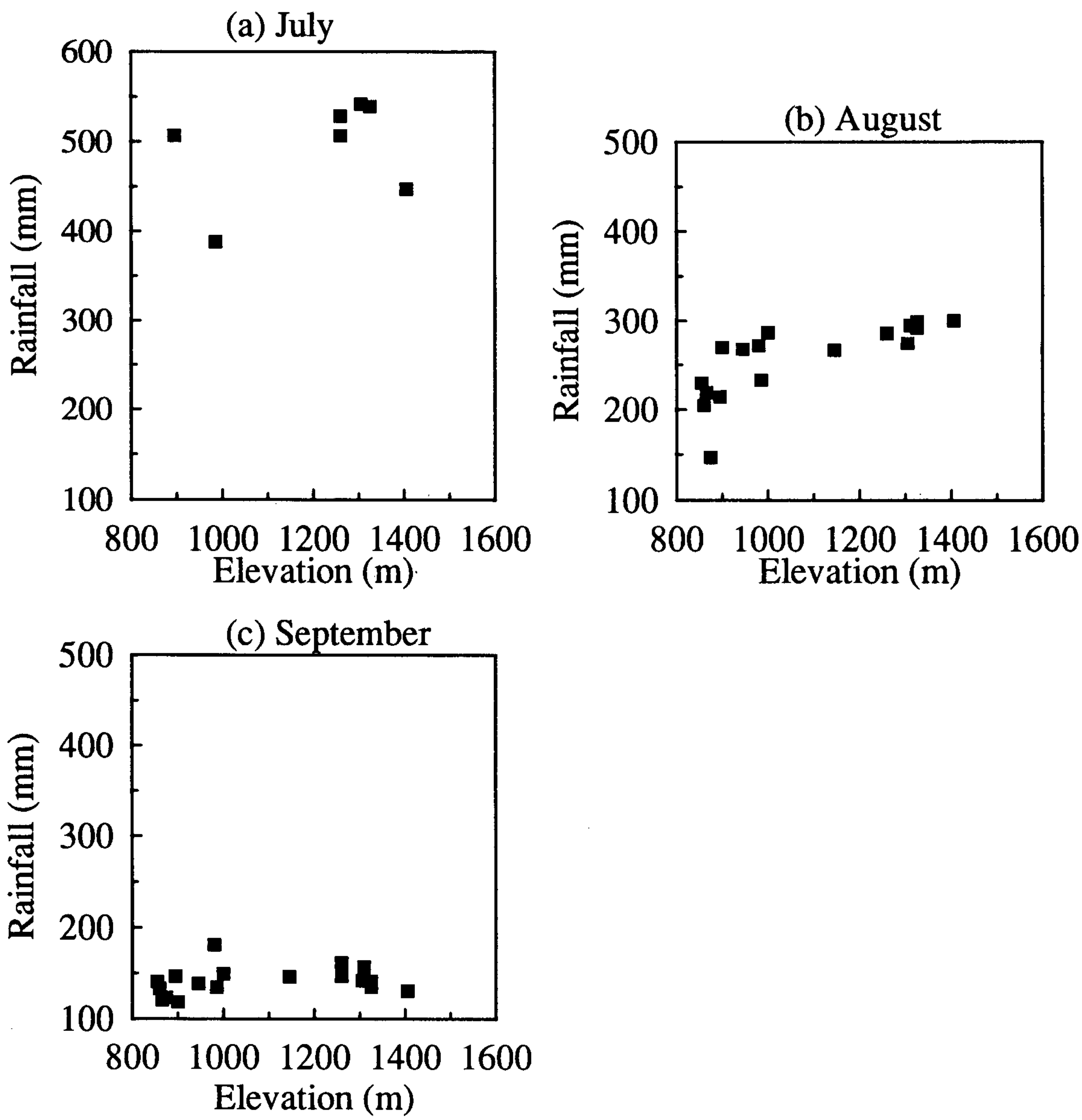
These findings have important implications for rainfall monitoring in these mountainous regions. Spatially, measured rainfall can vary by 50% on a 5-km^2 hillslope reflecting the combination of real spatial variability of rainfall and the variability due to gauge performance as affected by wind patterns. Real rainfall spatial variability is dependent on the elevation of the slope and on topographic peculiarities of the area especially in relation to prevailing patterns of the region whereas the variability due to gauge performance is undoubtedly affected by seasonal changes in wind strength, a well known control on rainfall catch - unstudied here.

4.5.2 Storm cell

The rain-gauge clusters located on the Andheri hillslope are used to examine the variability in rainfall delivery within a storm cell (1 km^2). The monthly changes in total rainfall revealed in the last section suggest that elevation may affect within-storm spatial variability; because the elevation of these clusters is contrasting, the extent of influence of elevation can also be investigated.

The 24-hour rain-gauge network, in place for three rainy seasons on the Andheri hillslope, has yielded hundreds of days of rainfall data, each day's data comprising simultaneous measurements at up to 30 locations. The gauge locations form two clusters. One cluster is over steep, intensively-managed agricultural land in the headwater Kukhuri basin. The other cluster is over the lower reaches

Figure 4.7 Effect of elevation on total rainfall at 18 monitoring stations located on the south-facing hillslope (10 km^2; 1992): (a) July - only 7 data available, (b) August, and (c) September.



of the Andheri basin where bare and heavily-gullied, red soils prevail.

To examine the variation of rainfall within a storm cell, only the daily 24-hour measurements which derive from *individual* storm events are considered. Initially, following the storm definition developed in section 4.3.1, only storms with an average of at least 3 mm of rainfall (from either the upland or lowland rain-gauge cluster) are used. To remove the data for which more than one storm contributes, the detailed record from the tipping bucket within each rain-gauge cluster is used. Eight discrete 24-hour periods contain two distinct events (none contains three); the rainfall for these events cannot be known. In addition, storm rainfall cannot be known for the five events which straddle the measurement time (7:00 am) and are followed immediately by a 24-hour period with a storm (or storms). After removing other data, 90 events remain for consideration.

For each of these 90 storm events, eleven well-distributed gauges are chosen from each cluster. The mean rainfall and its variance are determined from these data for each event in each cluster individually and for the two clusters combined. These descriptive statistics are then tested for significant difference. Both parametric (t-test, 95%) and non-parametric (Mann Whitney U Test) tests are applied due to the uncertainty of the underlying distribution. In most cases, the two tests agree. When the result from one test is at a lower confidence limit, then the result from the other test is used to rule on the difference. In one case only did the two tests outright disagree: for this data pair, it is assumed that no significant difference exists.

Using the results from the statistical tests, the data are divided into three groups. Basin events occur where there is no significant difference between the data from the two clusters. Where significant differences are found, the events are termed as either upland or lowland depending on which has a greater mean rainfall. Finally, the coefficient of variation is calculated for each event. The average of the coefficients of variation for all events within each of the three event-area classes (basin, upland, lowland) is presented in Table 4.3. Also, for ***all*** rainfall over each area (the upland, the lowland, and the entire basin) the average coefficient of variation is determined regardless of the

Table 4.3 Spatial variation within a storm cell and distribution of events according to lowland, upland, and basin area-events for storms of $R_T \geq$ 3mm and $R_T \geq$ 10mm.

Areal Extent	Events Included	Average Coefficient of Variation	Number of Events	Percentage of Total Events
$R_T \geq$ 3 mm* ; 90 events				
low-elevation cluster only	lowland	0.283	22	24%
high-elevation cluster only	upland	0.480	26	29
entire basin	basin	0.459	42	47
low-elevation cluster only	all	0.445	88**	100
high-elevation cluster only	all	0.426	90	100
entire basin	all	0.594	90	100
$R_T \geq$ 10 mm; 63 events				
low-elevation cluster only	lowland	0.244	20	32%
high-elevation cluster only	upland	0.307	14	22
entire basin	basin	0.328	29	46
low-elevation cluster only	all	0.338	63	100
high-elevation cluster only	all	0.332	63	100
entire basin	all	0.459	63	100

* The events with > 3 mm include those with ≥ 10 mm.
** Two upland events yielded no rain in the lowland hence CV cannot be calculated.

event designation (as "upland", "lowland", and "basin").

The lowland events (CV=0.28) show less variability than do their upland counterparts (CV=0.48). The upland cluster sits in steep topography and the resulting variability is evidenced in Table 4.3, this despite the fact that the gauges of the lowland cluster are more widely dispersed than those in the upland. The variability of the basin events (CV=0.46) is similar to that of the upland cluster. Not surprisingly, rainfall for all the events over each area type shows generally more variability than do the area events when considered on their own.

About half of these events provide basin coverage with the other half split between the upland and the lowland. Though it was not possible to select this set of storm events to be representative of the entire record, there are 90 events and as such it may be reasonable to assume that the double-event (and triple-event) days which were removed have the same distribution.

The entire set of events considered above includes many events of low R_T (though greater than 3 mm). Events with $R_T < 10$ mm over both the upland and lowland areas are rarely flood-producing and are therefore of limited interest in this study. These events are removed from the data set, the summary statistics are recalculated, and the results appear in the bottom half of Table 4.3.

The spatial variability within a cluster is reduced when only the larger events ($R_T \geq 10$ mm) are considered. Variability in the upland remains higher than in the lowland. For each area type, the variability is always higher if the entire data subset is included rather than exclusively the local events. Note also that there are far fewer large upland events than large lowland events. By subtraction, there are proportionately far more small (3 to 10 mm) upland events (15) than there are equivalent lowland events (2).

The previous section described changes in monthly rainfall on the north-facing hillslope in terms of elevational differences and possible exhaustion and wind-bias effects. Though the exhaustion mechanism may be present and the wind bias mechanism is certainly present, it is clear from the findings of this section that 22% of high-rainfall events ($R_T \geq 10$ mm) bring a significantly lower rainfall to the lowland hence hillslope exhaustion is not an appropriate explanation for *all* storm events. Convection is strongly "cellular" in this region at times bringing rainfall to one area but not to the other (50% of cases) and at other times, bringing rainfall to the entire hillslope, *perhaps* with an exhaustion effect. The mechanism for this elevational difference remains open to speculation. Do hillslope exhaustion effects operate during most storms and cause there to be less rainfall over the upland? Does the local, convective nature of showers in this region mean that storms arriving via distinct topographic pathways bring characteristic levels of rainfall?

In Table 4.4, the large ($R_T \geq 10$ mm) events are stratified according to season. Basin events, though common during the monsoon season (49%), occur infrequently during the pre-monsoon

Table 4.4 Seasonal distributions of spatial variation within a storm cell and distribution of events according to lowland, upland, and basin area-events for storms of $R_T \geq 10$ mm total rain.

Areal Extent	Events Included	Coefficient of Variation	Number of Events	Percentage of Total Events
Pre-monsoon season; 9 events				
low-elevation cluster only	lowland	0.282	5	45%
high-elevation cluster only	upland	0.252	4	37
entire basin	basin	0.346	2	18
low-elevation cluster only	all	0.366	11	100
high-elevation cluster only	all	0.328	11	100
entire basin	all	0.585	11	100
Monsoon season; 45 events				
low-elevation cluster only	lowland	0.230	15	29%
high-elevation cluster only	upland	0.330	10	19
entire basin	basin	0.326	27	52
low-elevation cluster only	all	0.331	52	100
high-elevation cluster only	all	0.331	52	100
entire basin	all	0.433	52	100

season. In other words, the pre-monsoon season shows a greater propensity for local rain. However, the spatial variability of the local pre-monsoon events is equivalent to those of the monsoon season.

Figures 4.8 through 4.10 illustrate the rainfall delivery over the Andheri basin hillslope for representative basin, upland, and lowland storms. Figure 4.8a occurred on July 10, 1992 (transition season) and Figure 4.8b shows a basin event which is typical of the monsoon season. Although it was an upland event, it brought heavy rainfall to the entire basin to be the most significant event of the study period. Figures 4.9 and 4.10 contrast upland and lowland events of the pre-monsoon and monsoon seasons. Upland storms like the one presented in Figure 4.9a are infrequent but when they

Figure 4.8 Rainfall isolines for storm rainfall over Andheri basin for (a) an upland event during the transition season which was also the heaviest event of the study period and (b) a basin event typical of the monsoon season.

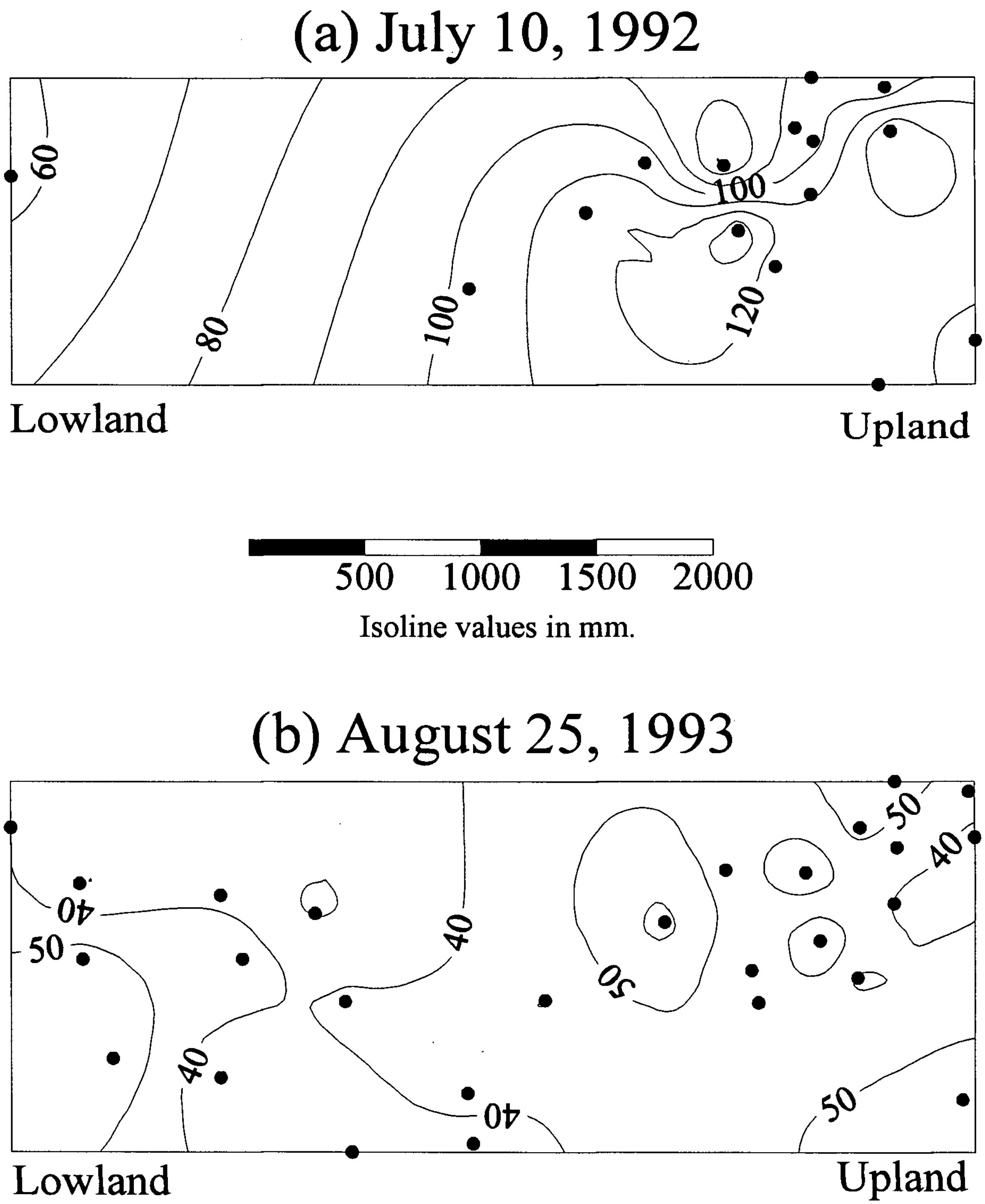


Figure 4.9 Rainfall isolines for storm rainfall over Andheri basin for upland events during the (a) pre-monsoon season and (b) monsoon season.

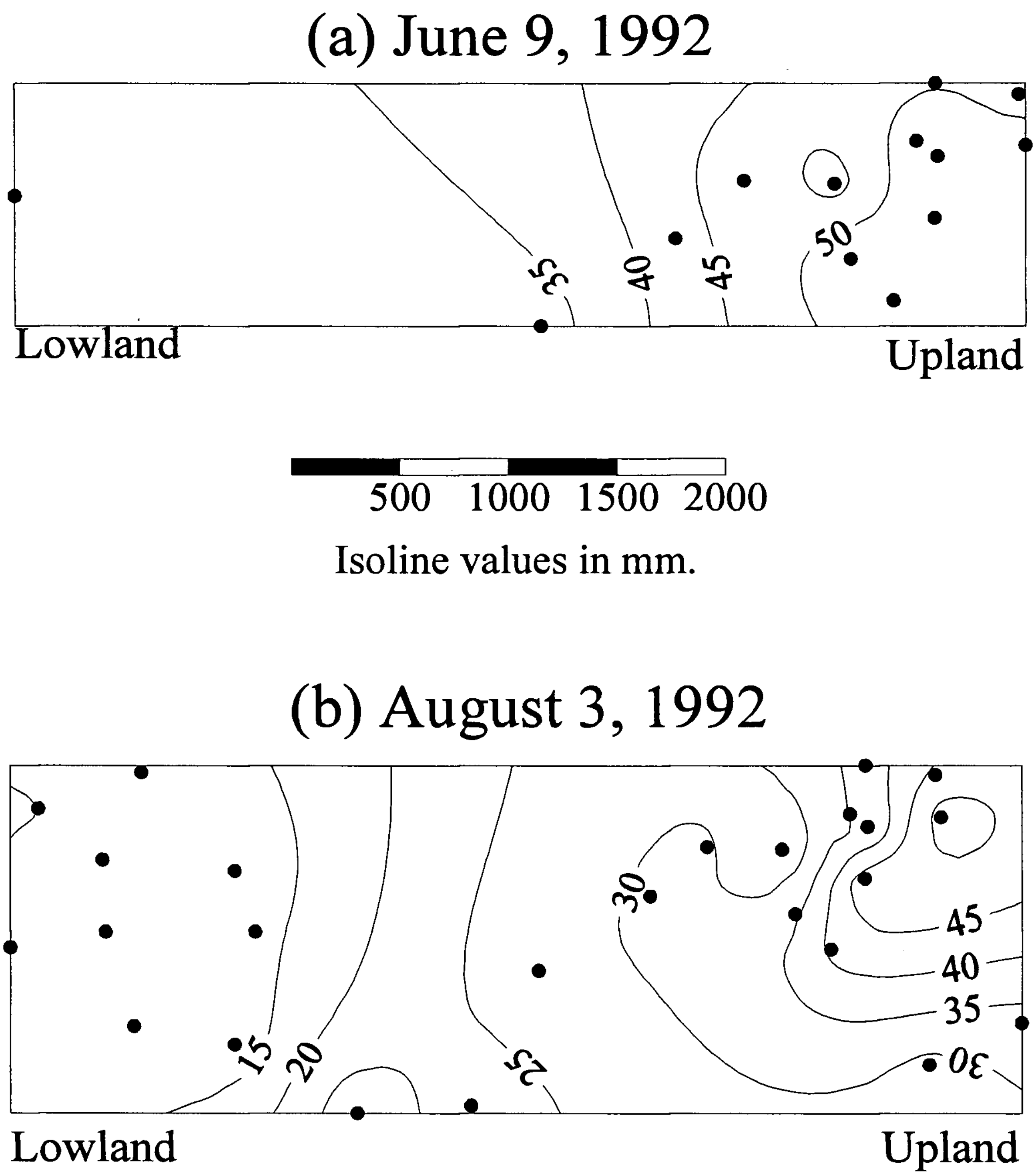
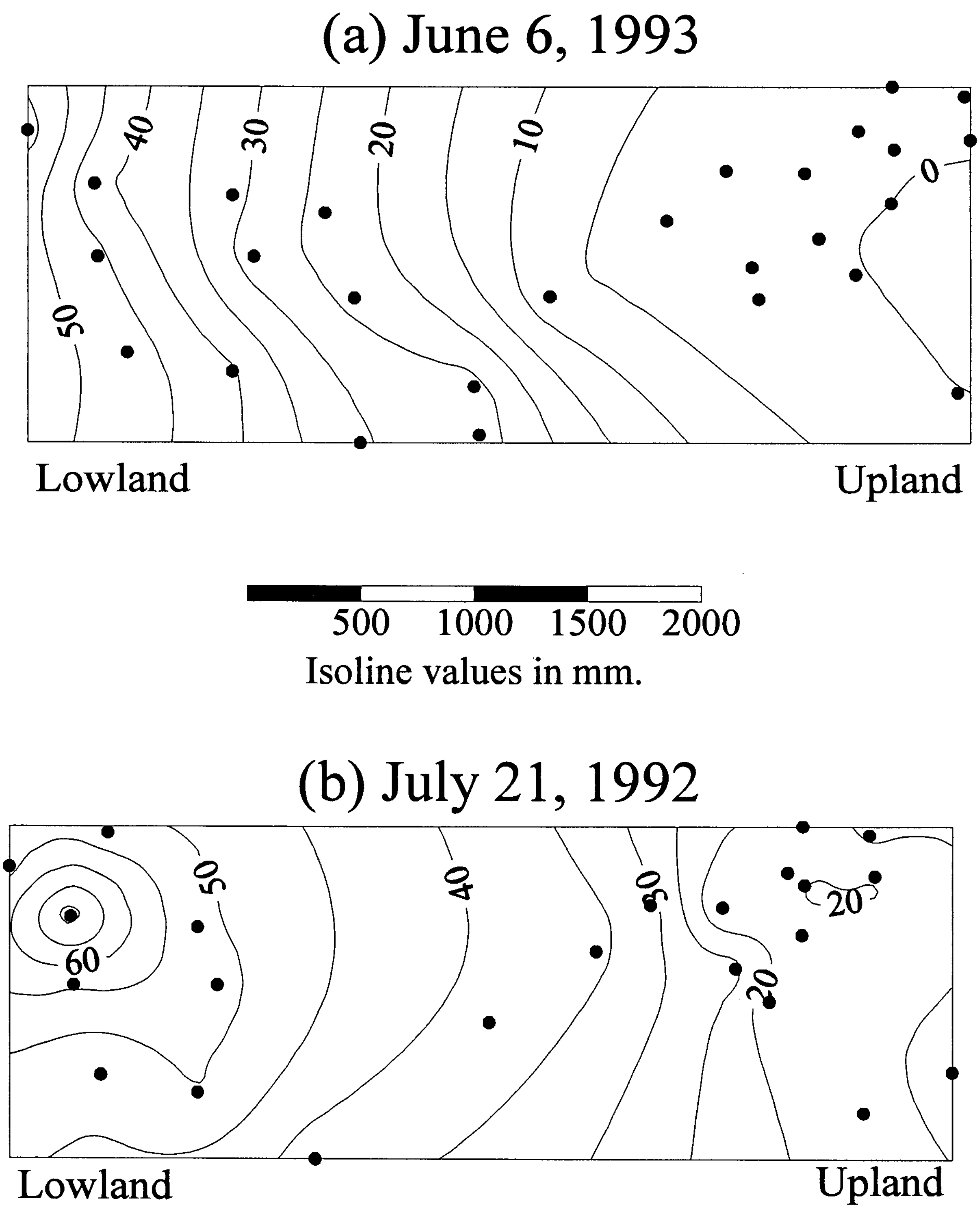


Figure 4.10 Rainfall isolines for storm rainfall over Andheri basin for lowland events during the (a) pre-monsoon season and (b) monsoon season.



occur, they are a major threat to upland soil erosion. Lowland pre-monsoon storms (Figure 4.10a) appear to be more frequent in occurrence.

An important application of these data involves the determination of how accurately point measurements represent the areal average. This is especially important when attempting to construct basin water budgets. To investigate this representativeness, the following equation

$$E = (t)\,(s)\,(n)^{-0.5}$$

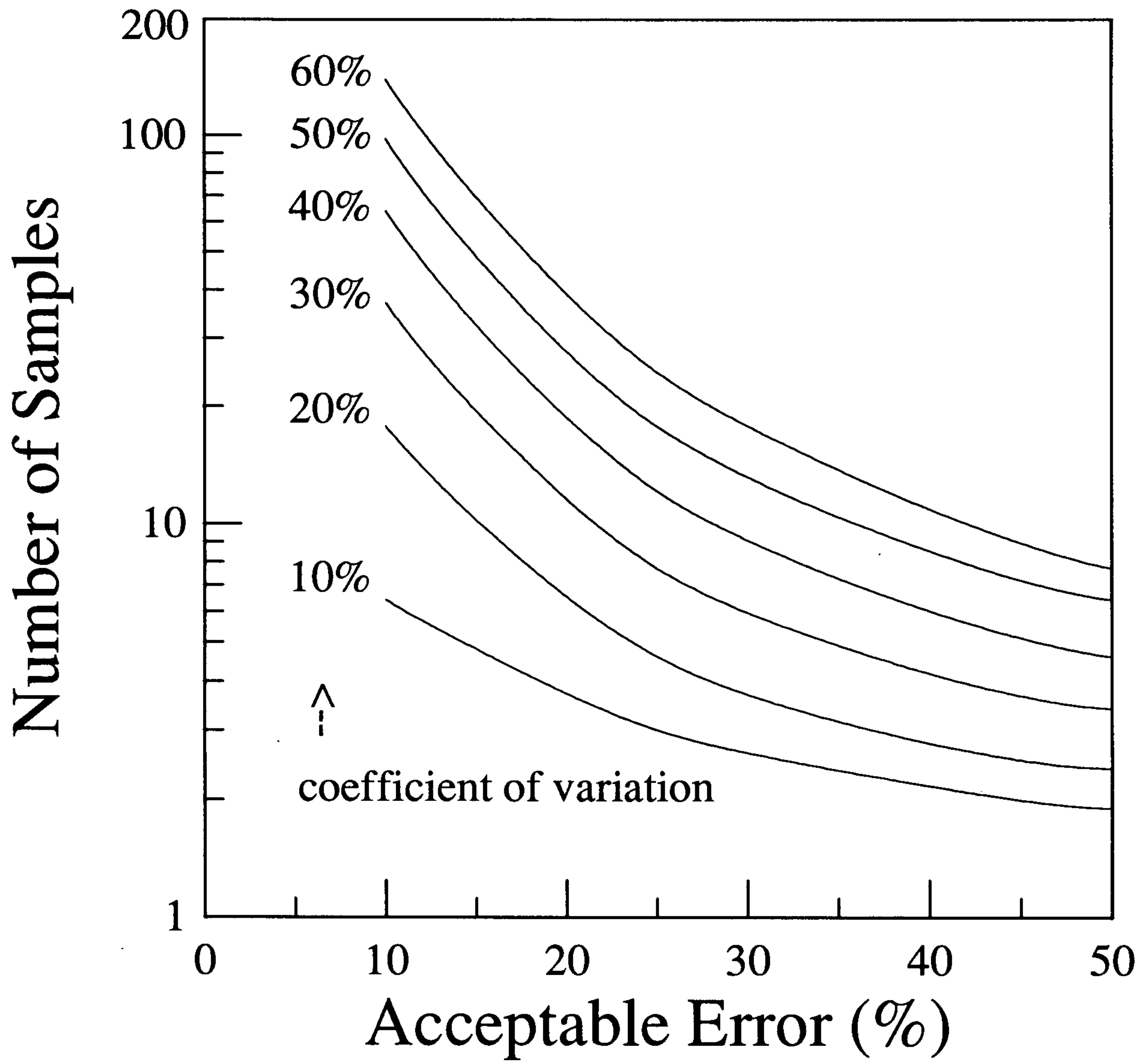
(Cochran 1977) relating realised error (E) to the standard error (s) and size (n) of the sample is used (t is the appropriate value from student's t-distribution). This equation is solved for the relative or acceptable error (AE=E/x, where x is the sample mean) to give

$$n = (t)^2\,(CV)^2\,(AE)^{-2}$$

where CV is the coefficient of variation (s/x) and t is a function of n. This equation is solved iteratively to yield the results which appear in Figure 4.11.

Figure 4.11 combined with Table 4.4 indicates the number of rainfall monitoring sites required to achieve a specified level of relative error for upland, lowland, and basin events of the pre-monsoon and monsoon seasons. For example, with a coefficient of variation of 38% (monsoon season) and 56% (pre-monsoon season), in the order of 100 monitoring sites are required to measure basin rainfall (for storms of $R_T \geq 10$ mm) to a confidence of within 10%. If the gauge requirement were limited to, say, 10 sites a level of error of 30% would result. The coefficient of variation of the lowland (0.23 to 0.28) and upland (0.154 to 0.196) events is smaller so fewer gauges are required for the same level of relative error: 10% requires 10-40 monitoring sites, 20% requires 5-20, 30% requires 3-6, and 50% requires 2-4, depending on which area/season combination is under consideration. A 10% level of error appears unworkable for most applications due to the excessive monitoring requirements - a level of error of 30% appears to be the most practical, if acceptable in the management or research application. Certainly, if only one gauge is installed in the basin, the data will essentially tell nothing reliable about storm rainfall delivery within a basin. This result casts

Figure 4.11 Number of rainfall monitoring sites required in relation to the relative error for a range in coefficient of variation.



serious concerns on the value of data from thinly-spread (in valleys) HMG gauges, for example.

4.6 Integration

The previous sections examined separately spatial and temporal variability in rainfall delivery as measured throughout the study site. This section attempts to integrate these findings to serve two purposes. The first provides guidelines for those attempting to measure rainfall in the Middle Mountains. The second establishes a quantitative reference framework to be used in subsequent chapters in the diagnosis of erosion.

4.6.1 Classification

A storm classification system is proposed based on R_T and I_{10} because these are the storm-period variables most important to surface erosion (plot scale, on-site) and mass wasting (larger scales, off-site). Findings from later chapters are combined with insights from section 4.4.1 to yield thresholds. In Chapter 5, a 30 mm/h threshold is observed for significant surface erosion at the plot scale (similar to Hudson (1981) who described a 25 mm/h threshold). In Chapter 8, it is shown that serious basin-scale sediment output corresponds roughly to storm events with I_{10} exceeding 50 mm/h and $R_T \geq 30$ mm. Events with $R_T < 10$ mm rainfall yield insignificant basin sediment output. Table 4.5 illustrates the class thresholds of each of these parameters and how their combinations are used to derive three storm classes: minor, intermediate, and major.

For all five recording rain gauges, storm-period variables have been analysed to determine storm type for every storm and the resulting distributions appear in Table 4.6. Despite the changes in elevation and aspect and the differences in data gaps from gauge to gauge, there is a striking consistency in the five distributions. A large majority (77%) of all events is minor (either $R_T < 10$ mm or $I_{10} < 30$ mm/h), of little consequence for flood generation. One in five events is intermediate and likely causes floods. The erosional consequences of these events focus on *either* surface erosion

Table 4.5 Definitions of minor, intermediate, and major storm classes in relation to total rainfall and peak 10-minute rainfall intensity.

<table>
<tr><td colspan="2"></td><td colspan="3">Peak 10-minute Rainfall Intensity (mm/h)</td></tr>
<tr><td colspan="2"></td><td>0-30</td><td>30-50</td><td>≥50</td></tr>
<tr><td rowspan="3">Total Rainfall (mm)</td><td>3-10</td><td colspan="3">Minor</td></tr>
<tr><td>10-30</td><td></td><td colspan="2">Intermediate</td></tr>
<tr><td>≥30</td><td></td><td></td><td>Major</td></tr>
</table>

Table 4.6 Distribution of storm events in three storm classes (minor, intermediate, major) at five sites.

Site	Total	Minor	Intermediate	Major
North facing; high elevation	211	75.4 (159)	20.9 (44)	3.8 (8)
North facing; low elevation	211	76.8 (162)	19.0 (40)	4.3 (9)
South facing; high elevation	200	78.5 (157)	19.0 (38)	2.5 (5)
South facing; low elevation	173	78.0 (135)	18.5 (32)	3.5 (6)
Outside detailed study area	229	75.1 (172)	21.4 (49)	3.5 (8)
Overall average	n/a	**76.8%**	**19.7%**	**3.5%**

(if $I_{10} \geq 50$ mm/h) or on slumping and stream bank/bed erosion (if $R_T \geq 50$ mm) but not both. The major events are erosive in terms of *both* surface erosion and mass wasting as a result of their high intensity and high volume. These events are infrequent, occurring in about 3% of all storms (1 in 33).

Table 4.7 presents the seasonal distribution of storm class at all sites. On average, 38% of all storms occur in the pre-monsoon period whereas 62% occur during the monsoon season. The natural variability around these trends is potentially enhanced by the unequal distribution of data gaps at the sites. Though the storm class distribution within each season varies from site to site, it is remarkably

Table 4.7 Seasonal distribution of storm events in three storm classes (minor, intermediate, major) at five sites for 1992-1994 data.

Site	Percentage of All Events Occurring Within Each Season		Percentage of Season's Events Occurring Within Each Class					
	P	M	Pre-Monsoon (P)			Monsoon (M)		
			Min	Int	Maj	Min	Int	Maj
North facing; high elevation	30.3 (64)	69.7 (147)	76.9 (45)	20.9 (15)	2.2 (4)	74.2 (117)	20.8 (25)	5.0 (5)
North facing; low elevation	43.1 (91)	56.9 (120)	70.3 (70)	23.4 (19)	6.3 (2)	79.6 (89)	17.0 (25)	3.4 (6)
South facing; high elevation	42.0 (84)	58.0 (116)	83.3 (70)	16.7 (14)	0.0 (0)	75.0 (87)	20.7 (24)	4.3 (5)
South facing; low elevation	31.2 (54)	68.8 (119)	72.2 (39)	22.2 (12)	5.6 (3)	80.7 (96)	16.8 (20)	2.5 (3)
Outside detailed study area(high elev)	41.9 (96)	58.1 (133)	72.9 (70)	24.0 (23)	3.1 (3)	76.7 (102)	19.5 (26)	3.8 (5)
Overall, High Elev.	38.1	61.9	75.8	21.3	2.9	77.3	18.9	3.8
Overall, Low Elev.	37.8	62.2	75.2	21.4	3.4	77.4	18.8	3.8
Overall	**37.7**	**62.3**	**75.1**	**21.4**	**3.5**	**77.2**	**19.0**	**3.8**

consistent. In fact, the integrated average of all sites yields essentially the same distribution for each season - 76.8% minor, 19.7% intermediate, 3.5% major (and obviously the same as the non-seasonal distribution). Observed differences in the storm class distributions were tested for significance using a Chi-Squared Goodness of Fit test. Annual and seasonal distributions were tested by site, elevation, and aspect and each test showed no significant difference (90%). In addition, seasonal differences in these categories were found not to be significant. The significant differences in storm-period variables found in section 4.4.1 are insufficient to persist after storm classification. It is the temporal change in storm characteristics at a site that provides the important difference geomorphically. The minor events rarely cause a change in streamflow important to erosion. The intermediate events are significant but tend to be easily managed. It is the major events, because of their combined high intensity and high volume which are seriously damaging.

While these differences are statistically nonsignificant, the small differences in measured occurrence of *major events* may be important if they persist at other times. Due to their importance in initiating erosion, a slight systematic departure in frequency of occurrence of major events may make some sites more prone to erosion. For instance, at the low-elevation site, 6.3% of pre-monsoon storms, 3.4% of monsoon storms, and 4.3% of all storms are major storms in contrast with the 3.5% average overall. If important, these concerns would need consideration in light of total storm frequency (Table 4.8).

4.6.2 Storm Frequency

In the previous section, conclusions were reached about overall and seasonal distributions of events within the study site. This section seeks to extend those findings by examining the annual and seasonal frequency of occurrence of storms within the basin during the three-year study period.

Table 4.8 presents the total number of storm events at each site for each year (1992-1994) as recorded by the tipping buckets. These figures are not exact averages due to the presence of data gaps of variable extent at most sites. Because these data gaps are generally small, the estimates form reasonable approximations, completed using adjacent 24-hour measurements and inference from the nearest recording gauge (with data). Sites had between 68 and 87 events per year with most sites having between 70 and 80. The overall mean is 77.5 events/year.

In Table 4.9, the seasonal distributions by storm class (from Table 4.7) are applied to the average annual event frequency (77.5) to yield expected annual storm frequencies in the study area. On average, of the 77.5 events which occur each year, 48.0 of them occur in the monsoon season while the remaining 29.5 occur in the pre-monsoon season. Only 17.8 of these are non-minor; of the major events, one will occur in the pre-monsoon season of almost every year while one or two should occur each year during the monsoon season. We also expect almost ten intermediate storms during the

Table 4.8 Number of storms in each year (1992-1994) at each site as given by recorded data.

Site	Total Annual Number of Storms			
	1992	1993	1994	Mean
North facing; high elevation	71	87	79	79.0
North facing; low elevation	71	68	72	70.3
South facing; high elevation	70	74	78	74.0
South facing; low elevation	72	83	78	77.7
Outside detailed study area; high elevation	85	87	87	86.3
Overall mean	73.8	79.8	78.8	**77.5**

Table 4.9 Expected average seasonal storm frequency by class (minor, intermediate, major) within the study area.

	Minor	Intermediate	Major	Total
Pre-monsoon season	21.9	6.2	1.0	29.2
Monsoon season	37.2	9.2	1.8	48.3
Both seasons combined	59.0	15.7	2.8	77.5

Note: Frequencies of occurrence for combined seasons are based on an averaged distribution, hence do not identically equal the sum of the two seasonal distributions presented.

monsoon season and about six intermediate events during the pre-monsoon season.

4.7 Summary and conclusions

The specific quantitative findings from this chapter are listed in this section followed by the main conclusions derived from these detailed results.

4.7.1 Summary of quantitative findings

The findings from this chapter can be grouped around four topics: temporal variation, spatial variation, storm classification and frequency, and guidelines for monitoring and analysis. In making these observations, a storm is defined as delivering at least 3 mm of rainfall and being separated by at least two hours from other rainfall.

Temporal variation

1) Storm-period variables

- Peak 10-minute and 60-minute intensities begin within the first 15 minutes in half of all storms.
- In 25% of all storms:
    - the peak 10-minute rainfall intensity exceeds 30 mm/hr;
    - more than 15 mm total rainfall is delivered; and
    - more than 24 hours without rain precedes the storms.

2) Seasonal effects

- Storm characteristics are similar between the pre-monsoon and monsoon seasons: they deliver both high-volume and high-intensity rainfall capable of causing severe erosion.
- In comparison with monsoon storms, pre-monsoon storms:
    - deliver less total rainfall;
    - are shorter in duration;
    - occur after longer periods without rain;
    - show a delayed occurrence of peak rainfall.

Spatial variation

Spatial variation was assessed as a function of elevation and storm cell variability in terms of total rainfall (over specific time periods) and in terms of storm-period variables:

3) Storm-period variables

- Systematic differences in storm-period variables are not evident between elevation and aspect; differences observed relate to narrow combinations of season and storm characteristic.

4) Elevation

- Over the scale of 100 km^2, wet-season rainfall (June-September) increases with elevation; the trend is insensitive to season.
- Over the scale of a hillslope (10 km^2) rainfall variation shows a trend to increase with elevation though marked exceptions are observed:
  - total pre-monsoon-season rainfall decreases with elevation;
  - total monsoon-season rainfall shows a midslope (1050-1150 m) maximum.

It is not clear the extent to which these elevation differences are due to hillslope exhaustion and due to the local "cellular" nature of convection.

- Over a hillslope (10 km^2), total variation in rainfall can exceed 50% in a month; a large proportion of this variance may be due to increased wind bias in measurement over complex topography.

5) Storm cell

- About half of all hillslope storm events deliver significantly different total rainfall within contrasting 1-km^2 upland and lowland subregions;
- Hillslope-wide events are uncommon during the pre-monsoon season;
- Low-rainfall events (3 mm $\leq R_T <$ 10 mm) are highly variable especially in the mountainous, high-elevation terrain where CV=0.48;
- Lowland and upland high-rainfall events ($R_T \geq$ 10mm) demonstrate reduced variability.
- High-rainfall "area" events (isolated over either the lowland or upland) occur more frequently at low elevation than at high elevation and together constitute more than half the total number of hillslope events.

Storm Classification and Frequency

6) Storm classification

- A matrix classification using I_{10} and R_T provides a convenient basis for classification because its basis is compatible with the rainfall-induced variation in character of erosion:
- Minor events deliver R_T < 10 mm *or* have I_{10} < 30 mm/h;
- Major events deliver $R_T \geq 50$ mm *and* have $I_{10} \geq 50$ mm/h; and
- Intermediate events form the remainder of the storms.

7) Storm distributions

- Annually, 76.8% of all storms are minor events; 19.7% are intermediate events; and 3.5% are major events.
- Storm-class distributions are insensitive to aspect, elevation, and season.
- Of the wet-season storms, 37.7% occur during the pre-monsoon season and 62.3% occur during the monsoon season.

8) Storm classification and frequency

- Annually, an average of 77.5 storms were recorded across all five sites: 59.0 minor events, 15.7 intermediate events, and 2.8 major events on average across all sites.
- Only 2.8 major storm events are expected annually (1.0 pre-monsoon; 1.8 monsoon).

Guidelines for monitoring and analysis

9) Field Instrumentation

- When measuring rainfall intensity for erosion studies in the Middle Mountains, use a minimum resolution of 0.25 mm and a sampling frequency not exceeding 2 minutes; maintain these constant during the monitoring period.
- To measure mean storm rainfall over a fourth-order tributary basin, data from one gauge is inadequate; in the 5.3-km^2 study basin, 2 to 4 gauges are needed to limit the allowable error to 50% and about eight gauges are required for a maximum allowable error of 25%.

- Maintain duplicate instruments at many sites, especially when different types of instrumentation are used and breakdown can cause gaps.

10) Analysis

- A storm definition based on a two-hour minimum period without rain respects the inherent characteristics of rainfall in the Middle Mountains and R_{MIN} = 3 mm eliminates gauge resolution effects.
- I_{10} and I_{60} best reflect rainfall characteristics affecting surface erosion and mass wasting respectively (provided the sampling frequency is $\leq$ 5 minutes).
- S and T_{60} provide useful relative indices of antecedent moisture conditions.

4.7.2 Conclusions

These findings suggest this chapter's three principal conclusions:

- *Seasonal storm characteristics*

Storms of the pre-monsoon and monsoon seasons deliver equivalent high-intensity, high-volume rainfall capable of causing severe erosion. However, in comparison with monsoon storms, pre-monsoon storms deliver less total rainfall, are shorter in duration, occur after longer periods without rain, and show a delayed occurrence of peak maximum 60-minute rainfall intensity. Spatially, pre-monsoon storm cells are smaller than monsoon storms. These conclusions suggest that the erosivity of storm rainfall in these two seasons should be equivalent but the timing of pre-monsoon storms may enhance the relative erodibility of the land surface during this season's significant storms in contrast with the monsoon season.

- *Spatial variability*

Over a hillslope (10 km^2), variation in total rainfall often exceeds 50% in a month. This variability is driven by a combination of wind bias (due to instrument limitations and complex topography), local storm-cell structure, and hillslope exhaustion. This conclusion raises severe concerns about the usefulness of rainfall data derived from single gauges, notably when these gauges are not within the catchment of concern. The data may provide useful information regarding broad regional trends but they do not provide any reliable information on synoptic-scale flood-producing storm rainfall.

• *Storm distribution*

Under a three-class storm classification system designed for this study of erosion and sediment transport and using class divisions based on maximum 10-minute rainfall intensity and total rainfall there is no significant difference in the distributions of storm classes between site, aspect, and elevation within either season. Annually, an average of 77.5 storms was recorded across all five sites. Of these, an average of 2.8 *major* events (more than 50 mm/hr maximum 10-minute intensity *and* greater than 30 mm total rainfall) occurs: 1.0 event during the pre-monsoon season and 1.8 events during the monsoon season.

5. Diagnosing headwaters controls on erosion and sediment transport

5.1 Introduction

Factors which shape the erosion regimes of the study catchments are examined diagnostically to evaluate their relative effects on sediment dynamics. A wide assortment of geomorphologic, hydrologic, and agricultural techniques is available for measuring rates of erosion over widely-contrasting spatial and temporal scales. Data from erosion plots are used here to evaluate the effect of individual storms at the plot (100 m^2) scale during all seasons. The sediment-rating-curve technique is used to examine the combined effects of all erosion processes operating within the catchments during individual flood events over various spatial and temporal scales. By contrasting the behaviours of catchments of different character and over different seasons, dominant causes are inferred. Erosion-pin measurements and erosion surveys provide corroboration of the findings. The diagnosis provides a foundation for the sediment-budget analysis in Chapter 8.

Rainfall is obviously the precursor to erosion in this region. Rainfall intensity patterns of the pre-monsoon season are strikingly similar to those of the monsoon season. However, pre-monsoon storms tend to be of shorter duration and have longer dry periods between them than do monsoon storms. More rainfall occurs at lower elevations in the study area yet peak rainfall intensity tends to be somewhat higher at higher elevation. These distinct patterns evident in the rainfall regime will be examined more closely for their relation to observed patterns of sediment dynamics.

Having established how rainfall behaves in the study area, it is now possible to attempt a diagnosis using erosion and sediment-transport data from this study. The evaluation begins with an examination of surface erosion from cultivated fields at the plot scale. Findings are tested and conclusions extended by examining stream suspended-sediment regimes over contrasting spatial scales and basin character.

5.2 Research background

A wide variety of methods has been used to study patterns of fine-sediment transport, including erosion plots (Mutchler *et al.* 1988), stream hydrometric stations (Gregory and Walling 1973), soil-profile development (Harden *et al.* 1979), tracers (Bovis 1982), erosion pins, and erosion surveys (ASCE 1975). Each approach focuses on specific processes and spatial and temporal scales. Erosion plots and stream hydrometric stations are the two techniques used in this chapter so a review of these two tools forms the focus of this section. Himalayan studies of direct relevance to this study are also reviewed.

5.2.1 Behaviour of fine-sediment erosion and transport

Erosion plots

Erosion-plot soil-erosion research has a long history in agriculture and the Universal Soil Loss Equation (USLE) represents the most-comprehensive application of this work (Wischmeier and Smith 1978). This equation predicts average annual sheet and rill erosion and was developed using data from over 10 000 plot-years' data from standard plots of 72.6 ft (22.1 m) in length and 9% slope throughout the United States Midwest (Wischmeier 1976). It represents the major controls on plot-scale erosion using six parameters: rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover and management (C,P). The Universal Soil Loss Equation (USLE) is useful in that it explicitly recognises all the controls on soil loss operating at the plot scale. For conditions within the range of parameters studied, it provides a convenient and accurate assessment of soil erosion for management.

Several attempts have been made to improve upon the USLE. The Revised Universal Soil Loss Equation, RUSLE, (Renard *et al.* 1991) uses modified USLE factors and computerised algorithms. Unfortunately, like the USLE, outside of the conditions for which the equation was developed, it is often not useful. Increasing computer capabilities have led to the development of complex mathematical predictors which model the successive detachment, transport, and deposition processes within small catchments. The Water Erosion Prediction Project (WEPP) model (Laflen *et al.* 1991; Risse *et al.* 1995) is the modern replacement to the USLE, building on earlier attempts like the Chemicals, Runoff, and Erosion for Agricultural Management Systems (CREAMS) model (Foster 1988). These mathematical models are limited in their application in developing countries because of their high data requirements.

Despite the limitations, researchers have attempted to extend use of the USLE to other regions. The Soil Loss Estimator for Southern Africa (SLEMSA) was developed in Zimbabwe based on the USLE model (Wendelaar 1978 in Elwell 1984). Narayana *et al.* (1983) used the USLE and river, reservoir, and soil-loss data to estimate an average annual rate of erosion for India as 16.4 tonnes/ha. They used work by Babu *et al.* (1978) in developing an R-factor map of India based on climate records. Low (1967) proposed an estimator of soil loss for developing countries based on easily-obtained mean terrain attributes. Elwell (1984) stresses that countries which attempt to determine local USLE factors face an onerous task and often lose interest in prediction techniques believing that development costs are well beyond their resources.

In situations where a quantitative prediction of soil erosion is not directly necessary, erosion plots can be efficiently used to diagnose patterns of sediment production over small spatial scales (< 1 ha). For example, Lal (1982) studied the effect of terraces on sediment production and delivery in small basins (4 ha) in Nigeria and found that while terraces are effective at reducing the delivery of soil from the plot, they do not substantially reduce soil detachment. Young and Onstad (1982) looked at the effect of soil characteristics on soil erosion and found that the degree of aggregation, aggregate stability, and the soil clay content most strongly influenced sheet erosion. Pandey *et al.* (1983) and Pathak *et al.* (1984) used plots to assess hydrological aspects of forested and nonforested slopes in the Kumaun Himalaya in India. Pinczes (1982) studied sloping, Hungarian vineyards, finding that erosion rates correlated well to runoff and rainfall intensity for low-intensity rain events and correlated poorly for high-intensity events. Richter and Kertesz (1987) discovered a strongly seasonal pattern of erosion from plots in Germany and Hungary.

Hudson (1981) explained the importance of the kinetic energy of rainfall in determining soil loss from plots. In developing an alternative to the USLE R-factor for use in Africa, he had found that 25 mm/hr represents a threshold of kinetic energy between erosive and non-erosive rain. He pointed out that others went on to modify this concept proposing various combinations of total rainfall, rainfall intensity, and the energy of the storm (Elwell and Stocking 1975; Lal 1976; Morgan 1977). These studies focus attention on specific erosive storms rather than total annual rainfall at a plot.

Plot-basin scale linkage

To address soil loss over larger spatial scales, the concept of a "sediment delivery ratio" has been developed (Glymph, 1954; Maner 1958; Roehl 1962) and applied to erosion data extrapolated spatially over a basin to link the plot to the basin scales. Walling (1983) defined the sediment delivery ratio (SDR) as the ratio of the sediment delivered at the catchment outlet to the gross erosion within the basin on an annualised areal basis. Unfortunately, the SDR is very hard to predict and depends on the sediment sources, the drainage network, relief, slope, soil characteristics, vegetation, and landuse (Walling 1983; Ichim 1990).

The SDR concept is a black-box model which lumps all spatial and temporal variabilities into a single number. Spatial heterogeneities have led to distributed application of the delivery-ratio concept often in conjunction with the USLE. Burns (1979 in Walling 1983) focuses on individual sources and on identifying their separate delivery potentials. With adequate spatial resolution and a thorough diagnosis of the delivery potential of important sediment sources, the SDR concept could accommodate spatial heterogeneity.

The alluvial erosion and storage component of the basin sediment budget is not generally included in the calculation of "gross erosion" (Piest *et al* 1975; Walling 1983) and forms the key weakness of the delivery-ratio concept. Church and Slaymaker (1989) examined landscapes in British Columbia (Canada) responding to glacial disturbance and found an increase in specific sediment delivery downstream due to stream channel bed and bank erosion. Though this has been termed a controversy (Bull *et al.* 1995), it is simply the alluvial component of the basin sediment budget operating over very long temporal scales. This relaxation time of disturbance is also evident over shorter timescales as sediment wedges cascade through a drainage system over decades as a result of anthropogenic disturbance associated with logging activities (Roberts and Church, 1986). Equivalently, it can also occur over short timescales such as the single event.

The problem is further complicated by the size distribution of transported sediment (Walling and Moorehead 1989) and the existence of geomorphic thresholds (Schumm 1977). Considering sediment as a homogeneous material is to create another black box akin to the one associated with spatial lumping of the delivery-ratio concept. This will be considered in detail in Chapter 6. Extreme events occur even for a system in equilibrium and can greatly affect the storage term. The relative importance of extreme versus frequent geomorphic events has been well discussed (Wolman and Miller 1960) and will be addressed in Chapter 8.

The difficulties associated with linking plot-scale measurements to basin sediment yield are clear. An effective approach uses multiple methods covering a wide variety of spatial and temporal scales. In this study, stream sediment sampling to determine stream sediment yield is the other dominant technique used to assess erosion.

Stream sediment yield

Patterns of suspended-sediment transport in streams have long been studied to determine average areal denudation rates for spatial scales that are impractical for the erosion-plot technique (> 1 to 10 ha). The larger spatial scale expands the range of controls under consideration. Campbell and Bauder (1940) popularised the concept of a sediment rating curve to determine the characteristic suspended-sediment concentration for any stream discharge. They identified the straight-line logarithmic relation between suspended load and stream discharge, $C=aQ^b$ where C is suspended-sediment concentration, Q is stream discharge, b is the exponent of the relation (or "slope" on logarithmic coordinates) and a is the coefficient (or y-intercept on logarithmic coordinates). Walling (1974) pointed out that b is normally between 1.0 and 2.0, though smaller values have been reported (*e.g.*, Loughran *et al.* 1986 found $b \simeq 0.68$ for a 170-ha basin in New South Wales). This relation has been exploited extensively for determining total fine-sediment output from basins (*e.g.*, Johnson 1942; Porterfield 1972; Singh and Durgunoglu 1992). Due to the distributed, stochastic nature of sediment production and delivery, the technique of regressing C on Q remains a common approach to estimating basin sediment yield (Shen and Li 1976).

The sediment-rating curve represents the net effect of the interaction of sediment availability (supply) and its movement through a basin (transport) (van Sickle and Beschta 1983). Most basins studied in the literature are supply-limited resulting in suspended-sediment concentrations which often range across two orders of magnitude (Walling 1977a) - the combined event, seasonal, and spatial variation prevented Brown and Krygier (1971) from reaching general conclusions. Analysis of variance and multiple regression are frequently used to identify dominant controls (*e.g.*, Walling 1974, McPherson 1975, Griffiths 1981). Unfortunately, these methods rest on the appropriate choice of independent variables and require that each variable be measurable and expressed quantitatively; in addition, the variables can be confounded (*e.g.*, precipitation and discharge).

Typical reported high values of annual suspended sediment yield range between 100 and 1 000 $t \cdot km^{-2} \cdot yr^{-1}$ for small basins (1 to 10 km^2) (*e.g.*, Nordin 1963; Griffiths 1979; Doty *et al.* 1981; Tropeano 1991). Tropeano (1991) also reported 5 200 $t \cdot km^{-2} \cdot yr^{-1}$ for a 0.75 km^2 basin in northwestern Italy. Church *et al.* (1989) reported almost 20 000 $t \cdot km^{-2} \cdot yr^{-1}$ for sub-basins (0.2 to 400 km^2) in China's Middle Yellow River basin.

Effective use of the rating-curve technique requires that an adequate number of events be sampled, covering a wide range of the controls on sediment yield. In small, especially mountainous basins, flow and suspended-sediment can change rapidly making measurement difficult, increasing error (Walling 1977b), whereas in larger basins more controls can be operating increasing the variability of the net suspended-sediment response. Measurement error and variability in response must be considered when using sediment rating curves to calculate stream event, seasonal, and annual sediment yields (Walling 1977a; Walling and Webb 1981) as discussed in Chapter 8. These concerns are particularly problematic in Nepal (Rakoczi 1985).

A variety of mechanisms controls sediment availability and its transport or retention in a basin. To improve the accuracy of the relation, rating curves can be stratified according to these controls. Ultimately, the relation is established by five primary controls - geology, climate, hydrology, topography, and management (adapted from Griffiths 1981). However, to stratify results effectively, measurable parameters important to the controlling mechanisms are the most useful.

Effective controls on suspended-sediment rating curves can be grouped into four categories:

Hydrology
- stream discharge
- storm-period variables (peak intensity, total rainfall)

Surface response
- topography
- soil characteristics
- surface cover
- antecedent soil-moisture conditions

Scale
- spatial/temporal variability in rainfall/runoff
- travel time
- antecedent flood history

Management

- modification of surface soil/cover
- structures
- water diversion

These controls interact to affect the mobilisation, transport, and deposition of sediment, yielding a spatially- and temporally-heterogenous relation. Measurement difficulties and high variability can make it difficult to isolate the effects of some of these controls. Two common approaches are to stratify by hydrograph stage (rising versus falling limb) and by season. Frequently, a much smaller number of controls change with either season or stage and by examining these stratified rating curves, information can be gained about the importance of certain controls. Most of the literature reviewed in the following discussion uses stratification by season to examine, through inference, the operation of the above controls.

Hysteretic effects complicate analysis of sediment rating curves by desynchronising changes in sediment and discharge. Though this decoupling introduces difficulties in developing an accurate predictive relation, it also provides new information about upstream sediment dynamics which can assist in evaluating the controls. In this discussion, the general importance of hysteresis is indicated when it arises - a complete discussion of the mechanics and consequences of hysteresis for sediment rating curves is given in Chapter 6.

Discharge is generally observed to be the strongest single control on suspended sediment. Higher flows possess a greater ability to carry sediment, especially the larger size classes. Discharge can also induce a change in riparian sediment supply. Sidle and Campbell (1985) suggested that high flows in a gravel-bed stream break the surface armour allowing the fines to be flushed out before re-armouring again at or near the peak flow. Paustian and Beschta (1979) studying forested basins in the Oregon Coast Range found that over 30% of the winter sediment output of gravel-bed streams was stored in the bed. Discharge-induced supply contributes to the well-known clockwise hysteretic behaviour described in Chapter 6. At higher flows, the stream is also able to access sediment supplies not frequently available. Sidle and Campbell (1985) observed a steeper sediment-discharge relation at higher flows - that is, a stronger relation of C to Q. These in-stream supply dynamics compelled Van Sickle and Beschta (1983) to propose the partitioning of supply among several compartments accessed at different levels of streamflow.

Some authors prefer to use rainfall instead of discharge as the independent variable. Griffiths (1981) derived regional relations for large basins in South Island New Zealand concluding that mean rainfall is the best predictor of suspended sediment output (6 basins of 4-100 km^2, 27 basins of 100-1680 km^2). He reached similar conclusions for North Island basins (Griffiths 1982). Griffiths (1981) noted the dominance of precipitation found in other climatic regions (semiarid, arid, subhumid, tropical). Walling (1974) used multivariate analysis to assess the effect on suspended sediment on an event basis of three rainfall parameters (15-minute intensity, total rainfall, storm kinetic energy) and found them to have a strong relation. Unfortunately, because discharge and precipitation are confounded in small basins, it is difficult with this approach to determine the relative importance of storm-period variables to suspended-sediment output.

Burt (1989) stressed that although topography can be a strong control on suspended sediment, it is in the sub-basin scale where it is most important. In the headwaters, topography influences how fast runoff is concentrated into a powerful stream. In very small basins (scale depends on the climate), there is inadequate flow to be competent in transport. In very large basins, tributary inflows are desynchronised reducing the effect of topography. It is in the mid-sized tributary basins where topography can exercise the greatest effect on the flow regime. Tropeano (1991) echoed these ideas pointing out that basin lag time is also a function of basin shape and dimensions - lag time is therefore considerably shorter in headwater basins.

Surface condition - expressed through surface cover and soil characteristics - is important in determining the quantity of sediment available for transport. Because most systems are supply-limited (van Sickle and Beschta 1983), this effect can be large. Tropeano (1991) found suspended sediment output from a 6.8-km^2 basin in Northern Italy to be greatest in the summer resulting from recently-ploughed fields. Walling (1974) also attributed a seasonal change in response in a British basin to a decrease in vegetative protection during winter. With bare ground, storm-period variables - especially short-term versus long-term rainfall intensity - become important to sediment production.

Infiltration rate and soil moisture conditions affect runoff and its ability to entrain material. Surfaces with low permeability - *e.g.*, built environments - encourage shorter times of concentration resulting in higher peak flows and greater sediment production. Wood (1977) pointed out that long periods without erosion can cause fines to be in greater supply due to weathering and biological activity. He also suggested that desiccated surfaces may favour drying and crumbling which cause fines to be more readily entrained during the onset of precipitation. Conversely, fines may be harder to entrain when wet, especially if the surface is hydrophobic or clay-rich. Findings of Chapter 4 indicated that antecedent moisture conditions of surface soils during the pre-monsoon season should be drier than those of the monsoon season - the difference may contribute to seasonal erodibility of cultivated soils in the study basins.

Spatial- and temporal-scale interactions modify the sediment response measured at a point. Scale influence has already been mentioned in terms of headwater hydrology. Variability in rainfall input and a heterogeneous surface response add further spatial-scale influences to the sediment-discharge relation (Porterfield 1972). This effect is lost in very small and very large basins (scale depending on the climate). Studies often find that total output is dominated by sediment production from a limited area of the basin (*e.g.*, Tropeano 1991 found that 30-50% of total tributary input came from 8% of the land area, dominated by badlands). Also, Sidle and Campbell (1985) pointed out that the sediment response of small basins can be dominated by one source such as a landslide (*e.g.*, Brown and Krygier 1971).

Antecedent flood history can modify the supply regime. Many authors have noted seasonal, inter-event, and intra-event exhaustion patterns (Colby 1964; Arnborg *et al.* 1967; Walling and Teed 1971; Wood 1977; Beschta 1978; Walling and Webb 1982). Beschta (1978) observed the seasonal shift after the annual peak flow had occurred. Walling and Webb (1982) found sediment output to increase strongly with "recovery period" (defined as the time between successive events). Wood (1977) found that sediment exhaustion within individual events depends upon the length and severity of the event. Arnborg *et al.* (1967 in Wood 1977) suggested that the entrainment of sediment deposited on the bed during the recession stage of a previous flood also results in this differential supply regime.

In large basins, the different travel times of water and sediment can modify the sediment-discharge relation. This spatial-scale effect results in a counterclockwise hysteresis loop, in contrast to the clockwise loop commonly found from the effects of supply exhaustion.

Watershed management can reduce or enhance the effects of most of the controls described above. Anderson (1981) found that landuse variables accounted for 30% of the variance in sediment rating curves for 61 basins in California. Management comes in many forms; the two of most interest to the present study are structures and modification of surface conditions.

Roads are one of the most familiar modifications made to a managed watershed. In British Columbia and the USA Pacific Northwest, the increase in sediment production resulting from construction of forest access roads is well documented (Brown and Krygier 1971; Megahan and Kidd 1972; Beschta 1978; Reid *et al.* 1981; Reid and Dunne 1984; Anderson and Potts 1987). Other structures such as reservoirs and diversion dams can also strongly modify the downstream sediment-discharge relation.

In agricultural basins, perhaps the greatest effect from management is the surface modification brought about by cultivation and other agricultural activities. Loughran (1986) studied a 1.7-km^2 managed basin in New South Wales, Australia (forestry/agriculture) and found that 93% of sediment output derived from vineyards (60% of the area) and only 7% came from the forested land (30% of the area). Using erosion plots, he was able to attribute the difference to the absence of a surface cover on cultivated fields. Though output from sloping agricultural fields can be high, it is important to remember that typically only one-third to one-half of the amount eroded from the surface actually leaves the basin (Walling 1983). For example, Imeson (1974) examined an 18.9-km^2 basin in England and found that because only a third of the soil eroded from the bare agricultural fields actually left the basin, the river channels were an important sediment source accounting for over 35% of the total basin output. Presumably, in steepland agricultural basins like those in Nepal, the effect of surface-cover modification is pronounced. This is discussed further in the following section.

5.2.2 Quantitative Himalayan data

Himalayan soil-erosion research has evolved from brief and superficial assessments of the dominant causes of erosion, to measurements of the rate of erosion over limited spatial and temporal scales, to the current focus on combined measurements of precipitation and landuse variables important to erosion and sediment transport. Several good overviews exist (Carson 1985, Ramsay 1986; Bruijnzeel and Bremmer 1989). This review focuses on studies specifically designed to measure erosion rates in the Middle Mountains and other research designed to explain the causes.

Early research on erosion in the Himalaya sought to explain the causes of observed erosion using inference from very limited data. In particular, research was focused on determining whether erosion was natural in origin or caused primarily by farming activities. Laban (1977) estimated erosion due to mass movements by counting landslides from an aircraft and noting their association with land use. His results led him to conclude that about 75% were from natural causes and 25% were induced by human activity. Using a geomorphological analysis initiated as a result of catastrophic rainfall during October 1968 (500 mm in 24 hours), Starkel (1972) estimated surface lowering in the Darjeeling Himalaya to be of the order of 60 to 70 $t \cdot ha^{-1} \cdot yr^{-1}$ over the prior century. Mass movements resulting from extreme rainfall events dominated this rate of surface denudation, and there was not a direct relation between the amount of mass wasting on forested versus nonforested slopes. According to Carson (1985), both Sastray and Narayana (1984) and Winiger (1983) found that terracing and related farming practices have a stabilising influence on steep slopes as long as farming is economic; otherwise, slope degradation can occur at a greatly accelerated rate until natural rates resume.

Attempts at measuring rates of erosion in the Himalayan region have been based largely on erosion plots and stream sediment yields as summarised in Tables 5.1 and 5.2 respectively. The

Table 5.1 Surface erosion rates as determined by field studies using erosion plots within or near the Middle Mountains.

Source	Details of Study	Scale (m^2)	Erosion Rate $t \cdot ha^{-1} \cdot yr^{-1}$
Erosion Plots			
Laban (1978)	Middle Mountains	n/a	
	grassland		10-20
	overused grassland		20-50
	seriously eroded, gullied		200-500
Mulder (1978)	Kathmandu Valley	10	
	densely forested		0.34
	well-managed pasture		9
	steep, overgrazed		35
DSCWM (1991)	Shivapuri	15	
	terraced; cultivated;		
	mulched/nonmulched; steep		6-32
Sherchan *et al.* (1991)	Pakhribas	18	
	cultivated terrace; (various treatments)		18-35
Upadhaya *et al.* (1991)	Kulekhani	90	
	terraced; cultivated;		
	5% and 10% slopes;		0.8-7
Ries (1994)	High Mountains	14	
	traditional cultivations		1-9
Overseas Development Agency (1995)	traditional cultivations	76-536	3-13
	degraded shrub	25-95	6-22
	degraded forest	71-85	0-19
	grassland	30-69	< 1
	- based on extrapolations from partial sampling during 1992/3.		

Note: Bruijnzeel and Bremmer (1989) summarise other early Himalayan measurements.

results from erosion plots indicate that at the spatial scale of less than 100 m^2, annual erosion rates vary on cultivated land and on non-gullied shrub/forest land from 1 to 35 t/ha. The low annual rates reported by Upadhaya *et al.* (1991) at the DSCWM Kulekhani site (most fall between 1 and 3 t/ha) may be due to measurement discontinuities and the gentle slopes of the plots. Laban (1978) summarised his measurements and a variety of earlier field measurements concluding that 10 to 20 t/ha was a reasonable estimate of annual surface erosion for well-managed cultivated or grazing land, rising to 20 to 50 t/ha if overused and increasing locally to 200 to 500 t/ha if seriously eroded and

Table 5.2 Surface erosion rates as determined by field studies using check dams and hydrometric stations.

Source	Details of Study	Scale (km^2)	Erosion Rate $t \cdot ha^{-1} \cdot yr^{-1}$
Accumulation behind Check Dams (all sites within Middle Mountains)			
Laban (1978)	overgrazed grassland	0.13-0.25	22
	gullied, overgrazed grassland - parallel-dipping phyllitic schists - 30% trap efficiency - 70% SDR		29
Laban (1978)	overgrazed scrubland	0.18	43
	severely gullied - weakly consolidated granites and migmatites - 50% trap efficiency -100% SDR	0.11-0.19	125-570
Laban (1978)	degraded, gullied forest - Mahabarhat Lekh; very steep - metamorphic/sedimentary rocks	0.11-0.15	63-420
Basin Sediment Yield			
Ries (1994)	High Mountains:		
	Bamti	0.08	13
	Chhukarpo Low	0.24	30
	Chhukarpo Middle	2.7	7.5
	Chhukarpo Middle	3.7	3.7
	Surma	5.7	4
Kandel (1978)	Middle Mountains 6 basins; mix of forested, cultivated, degraded land	6-585	3-46 (excluding pre-monsoon)
Sharma (1977)	Bagmati	585	46
	Trisuli	4110	19
	Karnali	42 890	51
Ramsay (1986)	some major Nepalese rivers	> 5000	10-70
Williams (1977) in Carson (1985)	Tamur	5770	38
	Arun	34 525	7.6
	Sunkosi	18 985	21
	Saptakosi	59 280	15

Note: Some values based on conversion of 1 mm = 13 t/ha gullied.

Most denudation estimates from suspended-sediment data are for large rivers (5 000 to 50 000 km^2) and generally range from 10 to 70 $t \cdot ha^{-1} \cdot yr^{-1}$. Agricultural erosion rates averaged over larger scales typically result in lower rates due to deposition within the basin. At the large scales assessed in the studies which are summarised in Table 5.2, myriad sediment sources - especially those associated with riparian erosion (Bruijnzeel and Bremmer 1989) - are active making extrapolation to field-scale erosion extremely difficult and uncertain (Ramsay 1986). The sediment sources which contribute to the denudation rates calculated using river measurements are different than those under far narrower consideration in the plot studies. In the High Mountains, Ries (1994) measured annual sediment yield from small basins (0.1 to 6 km^2) of 4 to 30 t/ha; these rates may be more representative of those expected for agricultural basins however this work was carried out in a physiographic region very different to the Middle Mountains.

Many of these studies, unfortunately, are based on significant assumptions in extrapolating their results through space and time. For instance, although many researchers have contended that surface erosion rates are highest in the pre-monsoon period (Overseas Development Agency 1995; Ramsay 1986; Bruijnzeel and Bremmer 1989), data are rarely available to defend this assertion. Impat (1981) found that soil loss was greatest at the beginning of the measurement period in June despite precipitation peaking in August (in Ramsay 1986). Overseas Development Agency (1995) reported that 45-60% of measured soil loss occurred in May (part of the pre-monsoon period) but did not provide details on differences between monsoon and pre-monsoon sampling coverage. The spatial scales of most of these measurements are either very large ($>$ 5 000 km^2) or very small ($<$1 km^2) - processes and sediment sources important in the intermediate scales are rarely evaluated.

Several studies have recently tried to integrate specific measurements of surface erosion with precipitation and landuse measurables over contrasting spatial and temporal scales to reach more meaningful conclusions about catchment-scale processes. Ries (1994) (Table 5.2) provided perhaps the best example: field-scale erosion rates are contrasted with basin sediment yields and rainfall delivery in the High Mountains over consistent spatial and temporal scales. Perino (1993) documented a paired-catchment approach for basins of 2 hectares in size within the Phewa Tal and Kulekhani basins in the Middle Mountains. The complete capture of all runoff (including bedload) in a large structure with detailed hydrometeorologic measurements is combined with manipulation for conservation practices. The low basin output of the first year (1992) - less than 1 t/ha - was attributed to exceptionally low rainfall in the study area. Overseas Development Agency (1995) (Table 5.1) provided detailed measurements of surface cover and rainfall storm-period variables and concluded that the lack of surface cover in May of the pre-monsoon season is a strong control on field-scale soil loss; unfortunately, they failed to relate this to suspended sediment dynamics at larger basin scales.

Despite these recent catchment-scale research efforts, there remain few quantitative data describing erosion in the Middle Mountains over spatial and temporal scales of importance to farming activities and their relation to downstream sediment transport. Specific parameters crucial to understanding the erosion process remain conspicuously absent. These include high-flow sediment samples, rainfall intensity and distribution measurements, and the measurements of sediment storage to address within-catchment variability. Further, measurements remain dominated by monsoon observations, ignoring the pre-monsoon season when it is widely believed transport rates are the highest.

5.3 Surface erosion on cultivated rainfed uplands

Five erosion plots have been monitored throughout 1992-1994 on steep, high-elevation, rainfed, cultivated fields. In this section, the factors which shape surface erosion at this scale are examined. Event, annual and seasonal erosion rates are determined. Event analyses provide insight into the mechanics of the surface-erosion process and strengthen the conclusions from the integrated annual and seasonal analyses.

5.3.1 Controlling factors

The factors which determine surface erosion from the erosion plots include topography (slope length and steepness), soil characteristics, storm-period variables, and management. In the Jhikhu River basin, management is pervasive, greatly influencing all controlling factors except rainfall characteristics. For instance, management affects the rate of surface erosion through cropping practices and soil characteristics such as the organic-matter content.

The topography of the cultivated fields is greatly modified by management through the construction of terraces. The Middle Mountain farmers who cultivate the steeplands have developed a long-standing tradition of terraced agriculture which works to minimise the negative effects for cultivation of the steep topography.

5.3.2 Erosion plots: annual regimes

Table 5.3 presents a summary of the annual rate of soil loss from each of the five erosion plots during 1992-1994. Management practices were held constant across the plots and were characteristic of prevailing management on the rainfed cultivated fields (section 3.1.3). Similarly, the slope of the plots (22°-30°) is typical of much of these cultivated uplands. The results suggest a tremendous range of surface-erosion in these upland fields from almost none to rates exceeding 40 $t \cdot ha^{-1} \cdot yr^{-1}$.

Table 5.3 Annual rate of soil loss (tonnes/ha) from all plots, 1992-1994.

Plot	1992	1993	1994
1	18	4.1	42
2	23	34	6.4
3	38	37	6.9
4	0.1	0.2	2.9
5	0.1	0.3	2.6

The significant plot-to-plot variation in soil erosion is largely a reflection of the huge variation in soil properties across the five plots. In particular, infiltration rate as affected by the texture of the surface soil is a controlling influence on the nature of storm runoff and therefore on the rate of erosion. Soil loss from plots 1, 2, and 3 is over an order of magnitude greater than that from plots 4 and 5 (see also Figure 5.3). Table 5.4 contrasts coarse-fragment content, fine-fraction texture, and infiltration rate for the five plots. Plots 1, 2, and 3 have a much greater tendency for overland flow as a result of the fine surface texture and the consequent reduction in surface infiltrability. In contrast, the surface (and subsurface) of plots 4 and 5 are highly porous, resulting in infrequent overland flow. Although there are differences in clay content of the surface soils between the plots, it is the much larger difference in coarse-fragment content which is the first order effect and sets apart the erosion rates at the two sets of plots.

Plots 1 and 2/3 also differ in their responses largely due to their surface soil characteristics. (Plots 2 and 3 have the same physical characteristics because they are adjacent - see Chapter 3.) Generally, Plot 1 yields less erosion than Plots 2/3. This may be due to the inherent erodibility of

Table 5.4 Surface-soil characteristics of erosion plots.

Plot No.	Surface Horizon (#1) (about 0-15 cm)		Sub-surface Horizon (#2) (about 15-50 cm)		Surface Infiltration Rate	
	Coarse Fragment Content (%)	Texture of Fine Fraction (S/Si/C)	Coarse Fragment Content (%)	Texture of Fine Fraction (S/Si/C)	Initial (10 min)	Final (>4hr)
					cm/hr	
1	1.7	44/35/21	1.1	40/32/28	42	32
2	4.2	37/34/29	3.4	37/33/30	47	16
3	4.2	37/34/29	3.4	37/33/30	47	16
4	45.8	52/37/11	69.3	53/36/11	68	20
5	67.3	39/42/19	39.8	34/40/26	94	51

Fine fraction consists of particles ≤ 2 mm in size. Coarse fragments include large gravels.
S=sand; Si-silt; C=clay.

these two soils: plots 2/3 contain red soils which are highly weathered and of low carbon content (Shah *et al.* 1994) and lack aggregate stability (though direct measurements are unavailable). In contrast, the soil of Plot 1 is better aggregated to resist surface erosion. Also, infiltrability is somewhat higher in Plot 1 than in Plots 2/3 (see Table 5.4) which might further discourage overland flow in Plot 1. The reversal in erosion rates between 1993 and 1994 at these plots was driven largely by storm patterns (not by soil properties) especially in relation to surface cover.

Table 5.4 also shows a large inter-annual variability of erosion from each plot of an order of magnitude. This variability can be investigated further by examining seasonal changes in erosion rate, the subject of the next section.

5.3.3 Erosion plots: seasonal regimes

Within each plot there is also a large intra-annual variability as shown in Figure 5.1. Table 5.5 shows the percentage of each plot's annual erosion which occurs during the pre-monsoon, transition, and monsoon seasons. In most years and at every plot, more than half of the annual erosion occurs in the pre-monsoon season. In fact, often over 80% occurs in the *combined* pre-monsoon and transition seasons, yet only 45% of the annual precipitation occurs during this period. The presence of swelling clays in Plot 1 might explain why a greater proportion of the annual erosion

Table 5.5 Percentage of each plot's annual erosion occurring in the pre-monsoon, transition, and monsoon season, 1992-1994.

Plot No.	pre-monsoon season			transition season			monsoon season		
	92	93	94	92	93	94	92	93	94
1	1	15	31	64	10	57	35	75	12
2	82	100	98	17	0	1	1	0	1
3	60	100	96	39	0	1	1	0	3
4	37	62	100	50	6	0	13	30	0
5	23	74	100	8	4	0	69	22	0

from this plot occurs during the monsoon season (see the end of section 5.3.4).

When the rains first start to arrive in the late spring, in the pre-monsoon season, the land surface is desiccated and the upland cultivated fields bare and vulnerable to erosion. By mid-July, the monsoon season is well under way, normally bringing regular rainfall. The first few weeks of July show erosion-regime behaviour which intergrades between that of the pre-monsoon and monsoon seasons and, in this study, is called the transition season (see section 5.4.2 for more details).

The major seasonal change in surface condition which occurs at the plot is a change in surface cover as weed growth and the summer crop develop. In 1994, measurements were made of average maize stalk height and leaf length to document the seasonal development of the crop within the five erosion plots. The results shown in Figure 5.2 indicate a close correspondence between these basins' erosion regimes and the development of surface cover in the plots especially when compared to each plot's chronological erosion history (Figure 5.1). The farmers also frequently intercrop providing a further protection of the soil from intense rainfall.

Changes in vegetative cover also explain the large inter-annual variation in soil loss at a given plot. Surface cover does not develop immediately but requires rainfall to get started and then takes several weeks to be complete. If damaging rains occur when the surface cover is only partially complete - which is common - then significant losses are likely at the plot in a single event. If the fields have recently been weeded (typically once in either June or July) then further losses can result. Subsequent rains falling on the same ground with a strong vegetative cover (monsoon season) often cause almost negligible surface erosion. As a result, loss from single events dominates annual soil loss. Table 5.6 shows the percentage of each plot's annual soil loss that occurred in the two most-damaging events at each plot and their dates of occurrence. At all plots and in almost all years, over 50% of the annual total occurs in only two events. At plots 2 and 3, the rate is over 80%. These two events typically occur during the pre-monsoon and transition seasons.

Figure 5.1 Soil loss from the erosion plots on an event basis, 1992-1994.

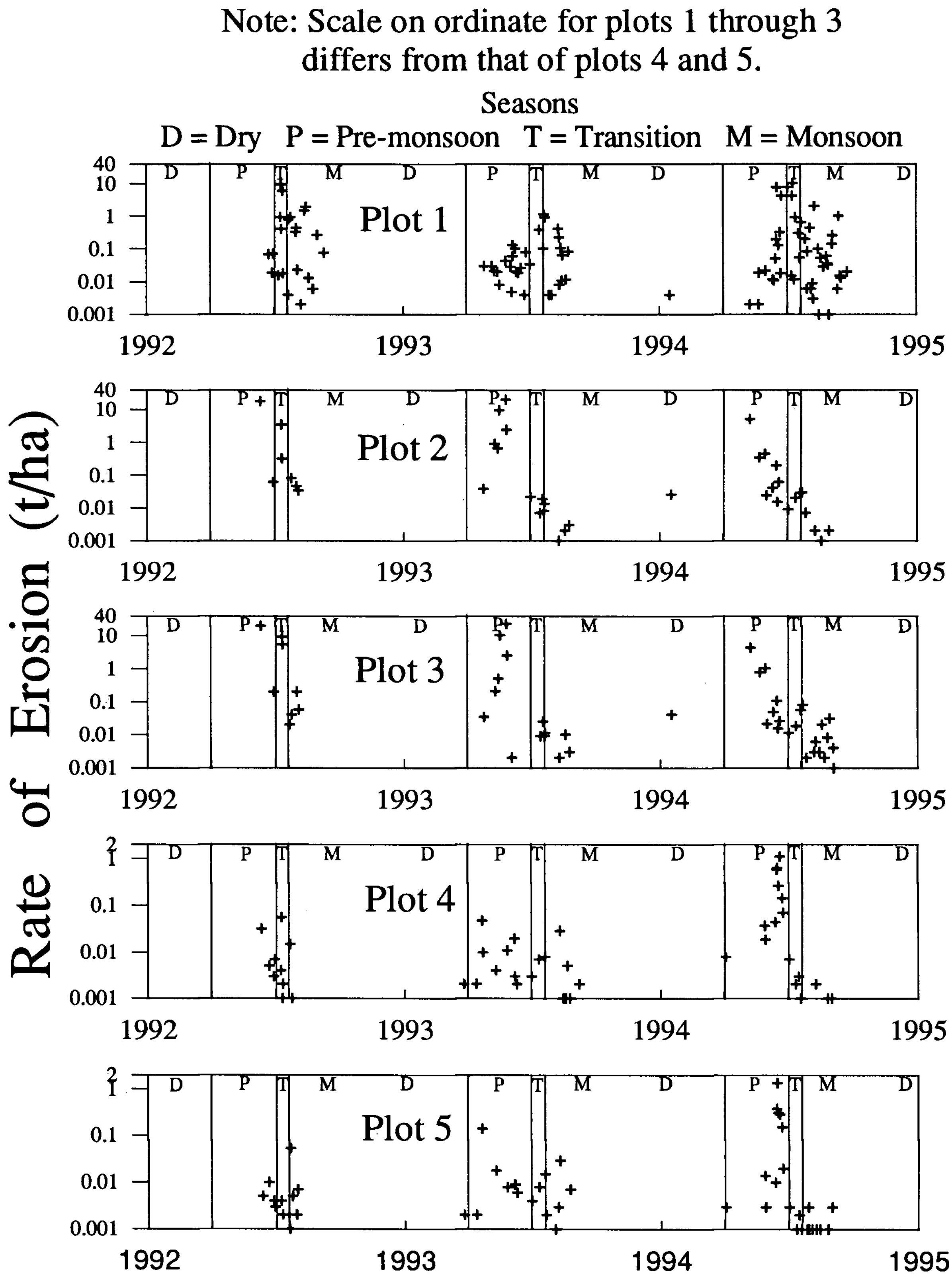


Figure 5.2 Average maximum maize height (a) and maize leaf length (b) at all erosion plots in 1994.

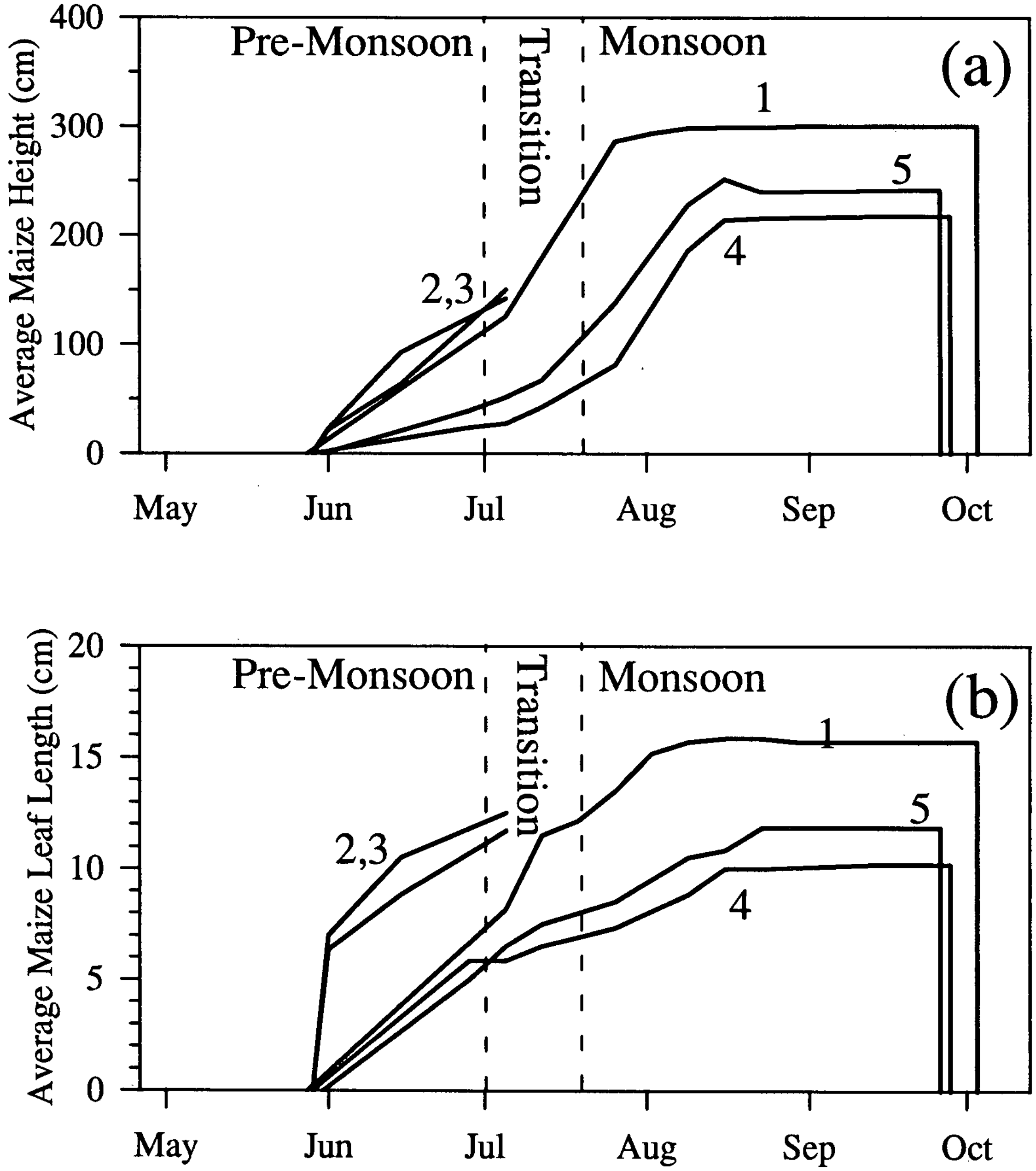


Table 5.6 The percentage of the total annual erosion at each plot which occurred in the two most-damaging events of each year, 1992-1994.

Plot No.	1992	1993	1994
1	55	50	44
	(10/7; 15/8)	(21/7;22/7)	(9/7;2/7)
2	96	88	87
	(10/6;10/7)	(17/5;27/5)	(9/5;30/5)
3	78	91	82
	(10/6;10/7)	(17/5;27/5)	(9/5;30/5)
4	69	40	60
	(9/7;10/6)	(21/4;10/8)	(19/6;15/6)
5	60	57	67
	(21/7;11/6)	(21/4;10/8)	(15/6;17/6)

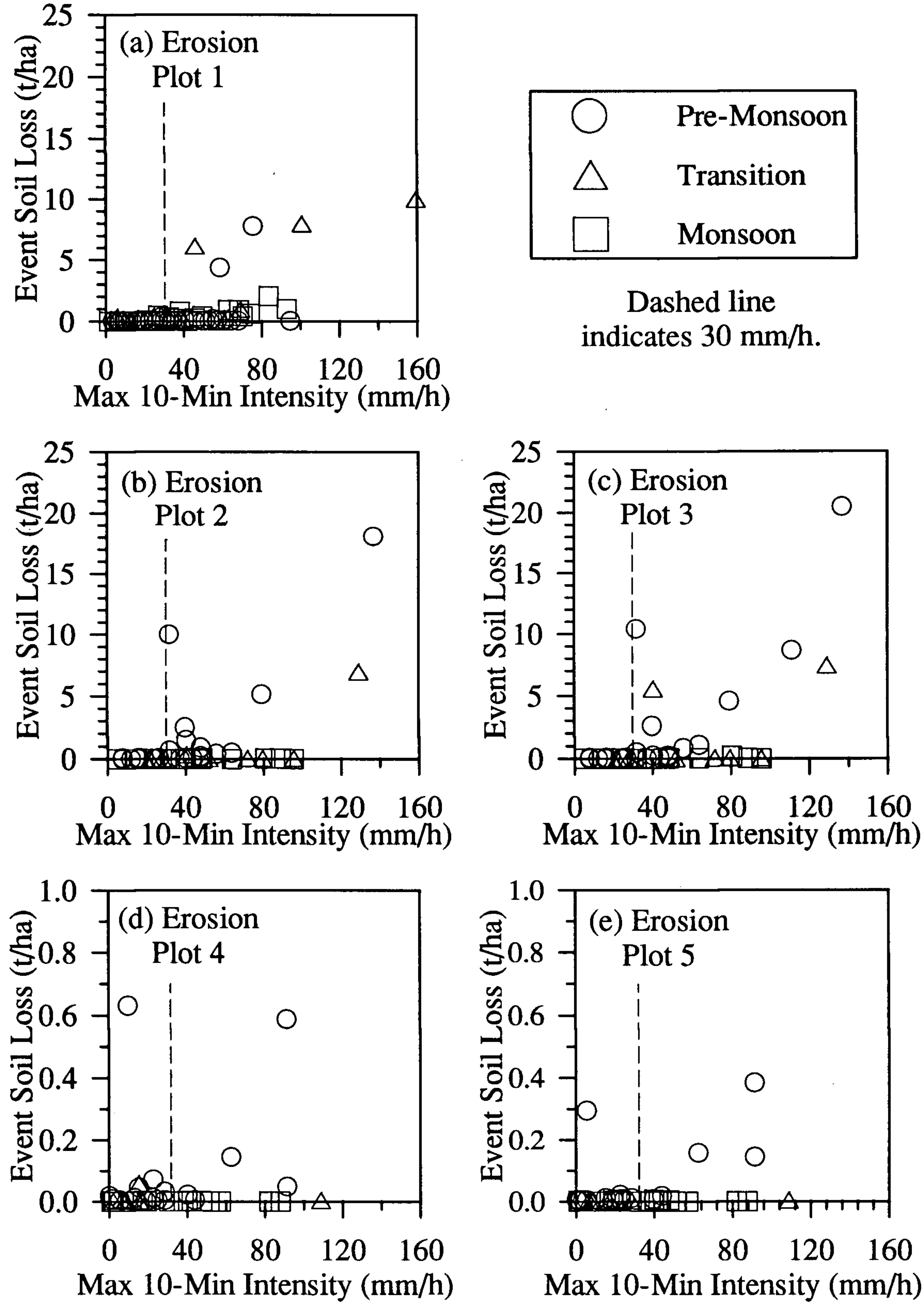
Note: Dates (day/month) represent when the two events occurred.

5.3.4 Erosion plots: event regimes

In Chapter 4, it was shown that rainfall characteristics of storms in the pre-monsoon season differ - but not greatly - from those of the monsoon and transition seasons. In section 5.3.2, it was suggested that soil texture strongly influences the likelihood of runoff to occur (and hence surface erosion) in any season. It was determined that under conditions when storm runoff occurs, it is vegetative cover that is the dominant seasonal control on surface erosion, with other factors such as soil aggregate stability exercising a non-seasonal control. But to what extent do differences in storm-period variables, and particularly rainfall intensity, contribute to the observed seasonally-variable surface erosion at the plots?

Figure 5.3 shows the influence of peak 10-minute storm rainfall intensity on soil loss at the five erosion plots for each event of the three-year period. The seasonal differences observed in the last section are reinforced here and the effect of rainfall intensity is revealed. There appears to be a threshold of about 30 mm/hr below which storms are non-erosive at the plot scale. Above this value, significant surface erosion can occur in the pre-monsoon and transition seasons, increasing with peak rainfall intensity. A threshold of this order was described by Hudson (1981) based on African data.

Figure 5.3 The effect of maximum 10-minute rainfall intensity (I_{10}) on soil loss at all erosion plots, seasonally stratified for all events of 1992-1994.



High-intensity rainfall clearly occurs at all plots in all seasons yet it is rarely of concern at this scale during the monsoon season. This observation is consistent with the conclusion that vegetative cover is a dominant seasonal control on surface erosion at the plot scale. Above the threshold, a relation between I_{10} and soil loss is of limited use because of the lack of data with respect to the tremendous variability in soil loss resulting from the timing of heavy rainfall relative to the development of a vegetative cover. Consistent with the limited spatial scale of the erosion plots and the resulting minor extent of channelised flows within the plots, soil loss does not correlate with rainfall intensity over significantly longer periods than that of I_{10} (including R_{TOT}).

Figure 5.4 relates event runoff coefficient (C_R) to the corresponding I_{10}. C_R is defined as the percentage of incoming event rainfall which runs off the plot. It tends to be the highest during the pre-monsoon season (declining in value through the transition season) at all plots except Plot 1. With saturated soils often prevailing in the monsoon season, one might expect higher C_R during this period but the opposite is generally observed. This behaviour might be due to a change in dominant runoff mechanism with season for significant erosion events.

Figure 5.5 shows seasonal variation in the influence of C_R on the soil loss at the five erosion plots. The greater C_R, the more likely are overland flow and surface erosion to occur. There appears to be a threshold in C_R below which erosion does not occur, though it is inconsistent across the plots. Above some threshold of between 5 and 10% (depending on soil characteristics), erosion can be serious in the pre-monsoon and transition seasons. Permeability also influences the number of events that occur at each plot and is reflected in C_R. About half as many runoff events occur at Plots 4 and 5 as occur at Plot 1, with Plots 2 and 3 intermediate to these. This is a direct result of the coarse-fragment texture of the surface soils, influencing the propensity for erosion to be able to occur on a given high-elevation cultivated field.

Although within-plot observations during rain events are few in number, the presence or absence of rills combined with an examination of the pattern of rainfall for specific events suggests

Figure 5.4 The effect of maximum 10-minute rainfall intensity (I_{10}) on event runoff coefficient (C_R) at all erosion plots, seasonally stratified for all events of 1992-1994.

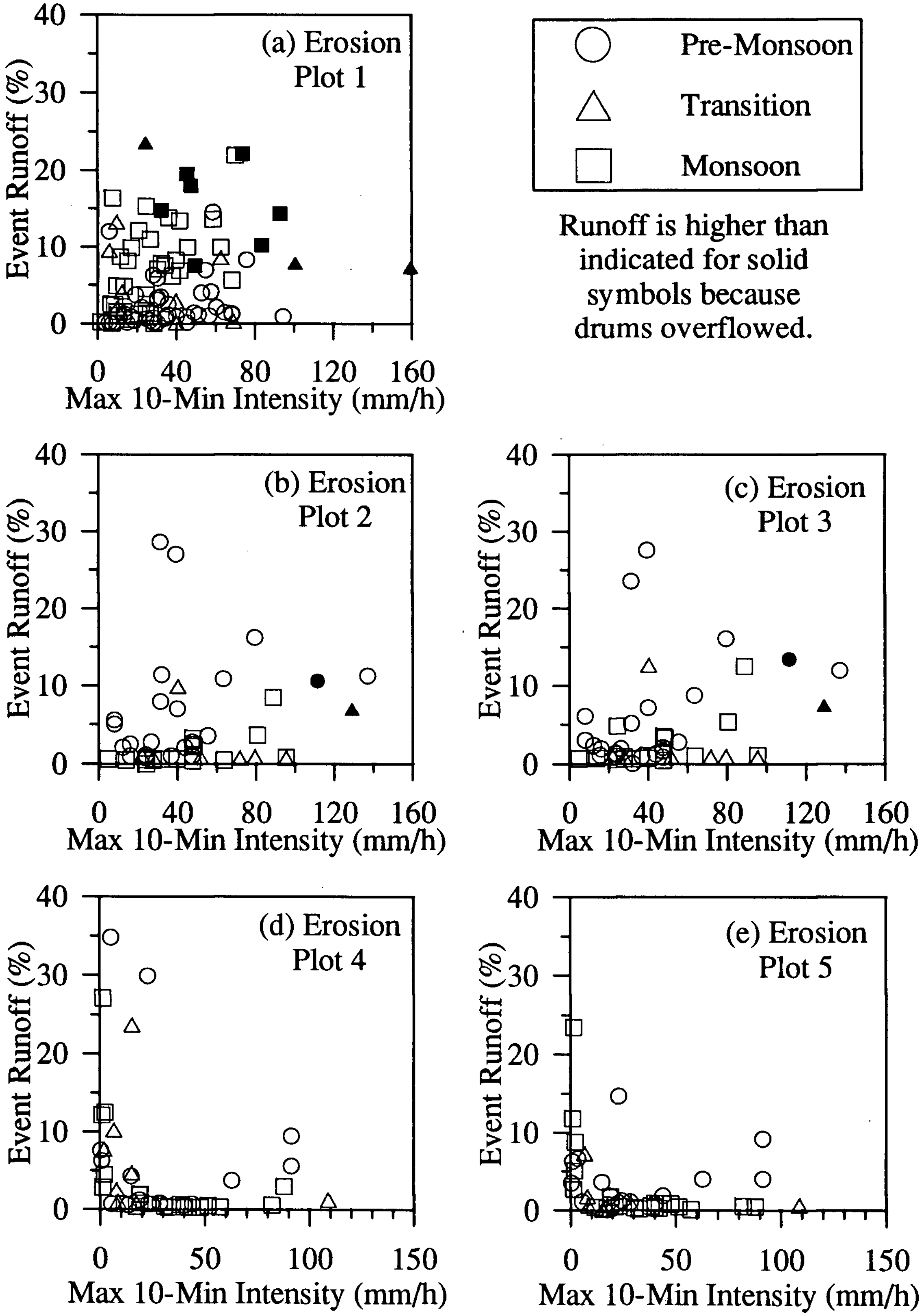
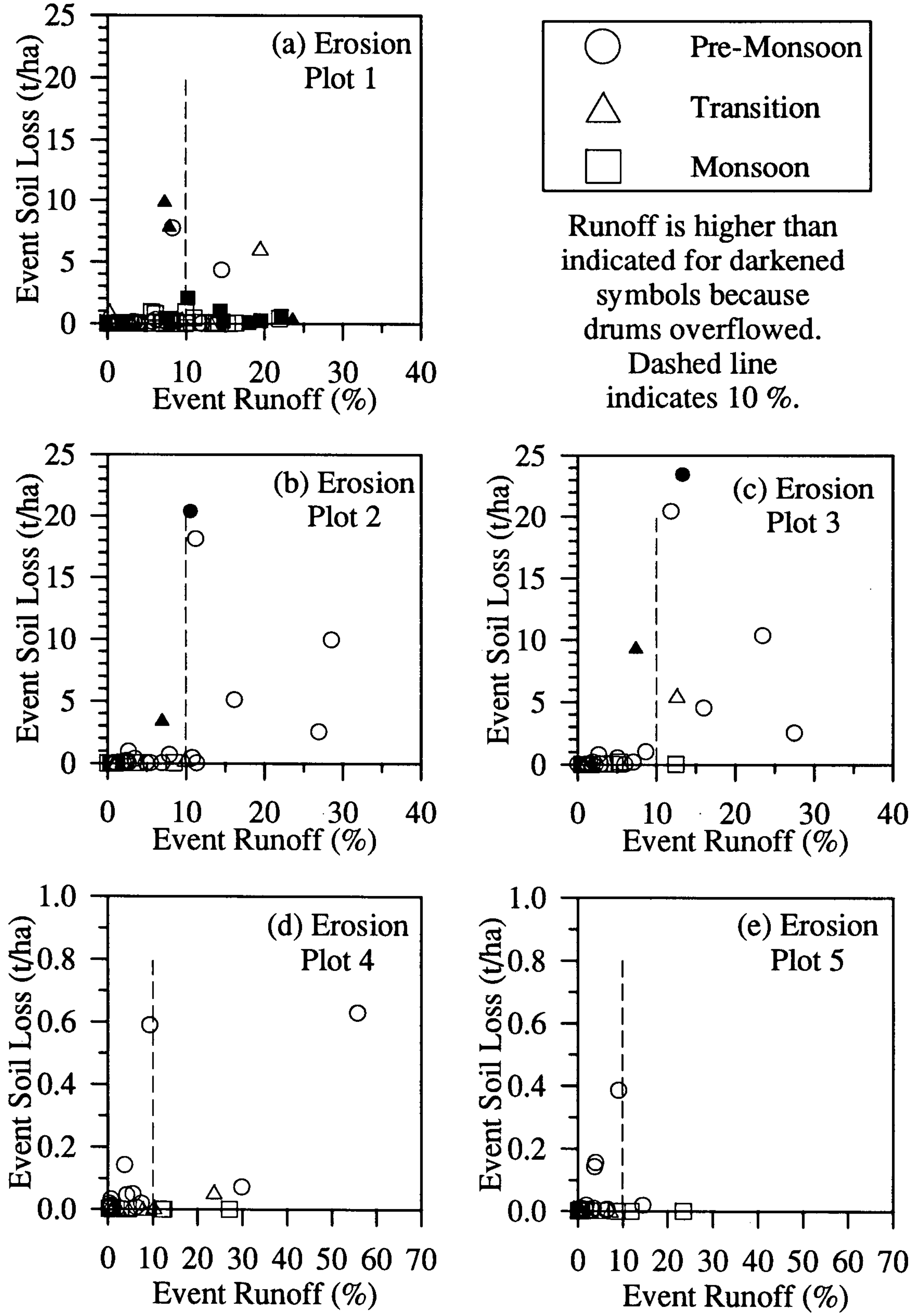


Figure 5.5 Relation between runoff coefficient (C_R) and event soil loss at all erosion plots, seasonally stratified for all events of 1992-1994.



runoff mechanisms for different storm types. Those storms which bring heavy rainfall on dry ground within the first few minutes (during the pre-monsoon season in particular - see Chapter 4) resulted in Hortonian overland flow. Storms bringing high total rainfall initiated saturation overland flow in those instances when a rate of erosion was measurable; brief periods of Hortonian overland flow when the rainfall intensity was sufficiently high may also have been possible during those storms. In Chapter 4, it was concluded that the most significant seasonal differences in rainfall regimes involved total storm rainfall, the period of time before a storm without rain, and the within-storm timing of storm rainfall: pre-monsoon storms are more likely to bring heavy rain on dry ground than are their monsoon counterparts. This is very important to surface erosion and may be a major factor contributing to the high values of C_R during the pre-monsoon season.

There are several possible explanations for the more-frequent runoff at Plot 1 as compared to the other plots. The farmer who monitors this plot tended to sample all the small (minor) events which were not sampled at Plots 2 and 3 because they are insignificant in the soil-loss budget. It is also possible that the soil in Plot 1 possesses a greater aggregate stability and can sustain greater overland flow before being entrained. This is consistent with farmers' comments on this soil using the indigenous classification; it is a clayey soil with high productivity and different behaviour as discussed further in Chapter 7. A final possibility is that the soil of Plot 1 may contain swelling clays which increase cohesion, discouraging entrainment. This is an area of potential research on these cultivated steeplands. If so, this could explain why Plot 1 shows its highest percentage runoff during the monsoon season (when the soil is frequently saturated) instead of during the pre-monsoon season as it occurs at the other four plots.

5.4 Stream sediment regimes

The findings of the last section are expanded by examining sediment regimes in the streams of the detailed study basins especially those nested around erosion plots 2 and 3. As the spatial dimension under consideration grows larger, so does the variety of sediment sources and mechanisms of erosion. The size of these basins varies between 1 and 100 km^2 - a range in spatial scale that has been examined rarely in the Middle Mountains.

Five hydrometric stations in the Jhikhu River basin have been monitored during most of the 1992-1994 study period and two additional stations during 1993-1994. Suspended-sediment sampling and stream-flow measurements were carried out at five of these sites during flood events at all times of the rainy season. The relation between suspended-sediment concentration and discharge forms the basis of the sediment-rating-curve technique. Discharge is determined from a relation with gauge height as explained in section 3.3.1. Observed patterns in suspended-sediment transport can be explained by linking these patterns to storm-period variables, inherent characteristics of the basins, and landuse activities.

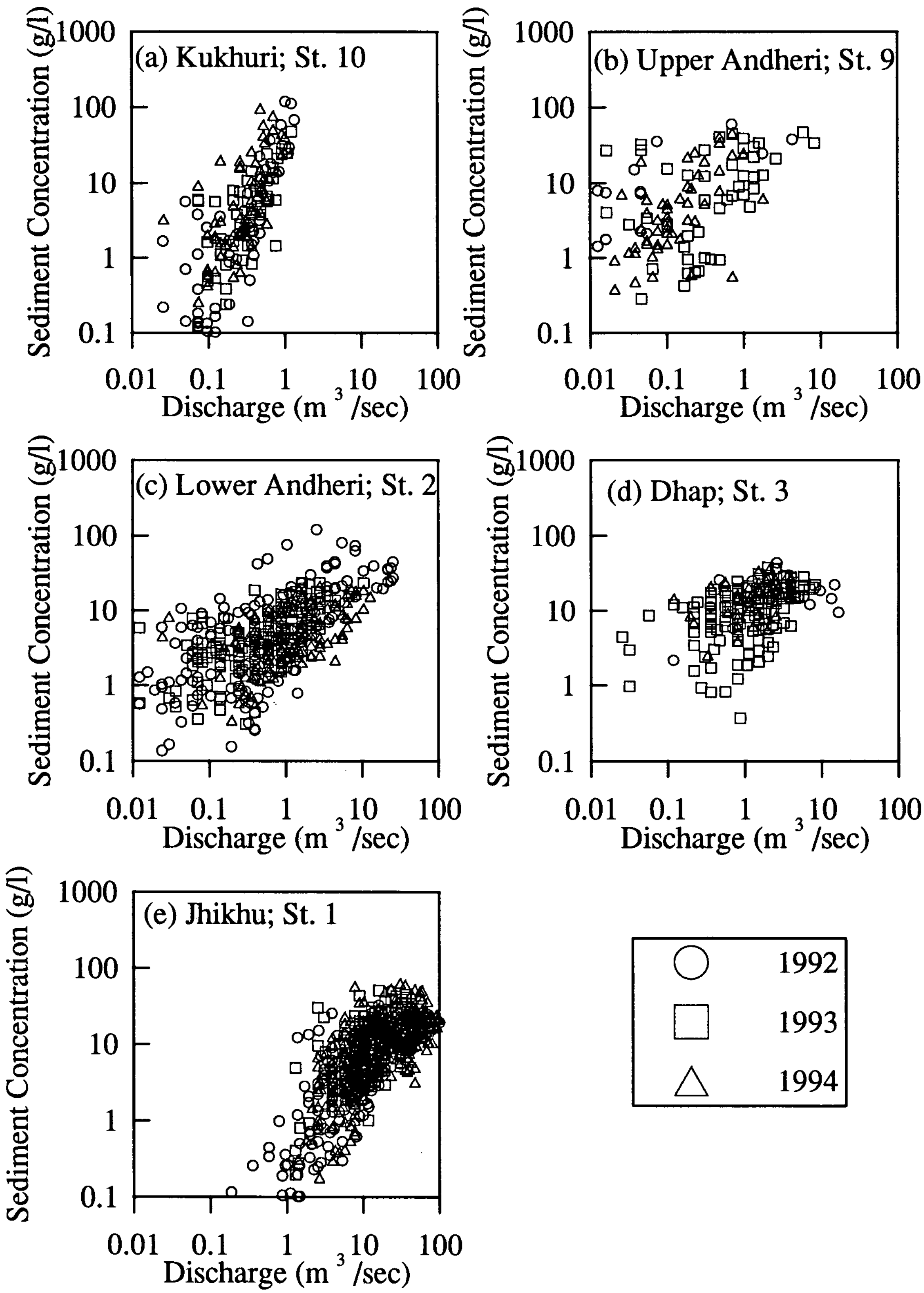
5.4.1 Controlling factors

A wide range of factors is responsible for shaping a basin's sediment-discharge relation. Rainfall characteristics of importance include peak intensity, spatial variability, and total storm rainfall. Soil-surface condition is important because it directly affects the entrainment process. Management activities can shape both the susceptibility of the surface to erosion and the rainfall-runoff process itself. Soil moisture, antecedent flood history, sediment storage, and sediment exhaustion can also be important factors as discussed in section 5.2.1. The next section characterises and contrasts the prevailing suspended-sediment regimes of all study basins.

5.4.2 Seasonal regimes

The entire suspended-sediment data set consists of 2287 high-flow samples and 820 low-flow samples taken during 1992-1994 at seven hydrometric stations. For each sample taken, the measured sediment concentration is coupled with the corresponding discharge and presented in its station's C-Q

Figure 5.6 Sediment rating curves for monitored hydrometric stations based on entire data set (1992-1994): (a) Kukhuri, (b) Upper Andheri, (c) Lower Andheri, (d) Dhap, and (e) Jhikhu.



graph. Figure 5.6 presents the C-Q distributions for the major hydrometric stations located within the Jhikhu basin stratified only by the year in which the samples were taken. In particular, Figures 5.6a and 5.6b present the results for the steep, headwater catchments (stations 10 and 9 respectively) within the Andheri basin. Figures 5.6c and 5.6d show the data for the Lower Andheri and Dhap catchments (stations 2 and 3 respectively), catchments of similar area but of strongly contrasting topography. Finally, the data for the entire Jhikhu basin (station 1) are found in Figure 5.6e. Stage-discharge relations are not available for the mid-reach Andheri basins (stations 11 and 12) so these distributions cannot be presented.

These unstratified C-Q graphs reveal the general nature of suspended sediment transport in these basins. The small size and steepness of Kukhuri basin is reflected in steep C-Q behaviour. As basin scale increases, the distributions shift toward higher discharge values and weaker relations with Q. The graphs in Figure 5.6 show that the data derive from a wide cross-section of the period of study (1992-1994) and hence can be expected to reflect a wide variety of controls present during that period.

A comparison of sediment transport in these basins is made possible by developing relations based on functional analysis (Kendall and Stewart 1979) for each station. Section 5.3 demonstrated a strong seasonal discontinuity in the rate of soil loss at the plot scale. This knowledge is used to improve the relations by applying an initial stratification by season before applying functional analysis.

Seasons important to erosion and sediment transport need definition. Elevated levels of suspended sediment were readily observed at the beginning of the pre-monsoon season with lower values resulting during the later part of the rainy season. Where is it appropriate to define the extent of each season? To determine the end of the pre-monsoon season, sediment data were added incrementally to those of the beginning of the rainy period (generally early June). High sediment concentrations were maintained until the end of June then started to decline indicating the beginning of a transition season. The same process was carried out from the end of the rainy period adding incrementally sediment data earlier in the monsoon. Levels remained low until those before July 20 were included and this pattern was present at all five hydrometric stations. As a result of these sensitivity analyses, the pre-monsoon season is defined to last until and including the last day of June, the monsoon season from July 20 to the end of the rainy season, and the transition season (showing intergrade behaviour) from July 1 to 19 inclusive.

The concept of a floating rating curve has also been considered to model the change in suspended sediment concentration through the rainy season. This approach would assume specific (daily) rates of decline in suspended sediment concentration through the entire rainy season. In this situation, the rate(s) would reflect changing supplies due to increased vegetative cover during the pre-monsoon season and perhaps an additional supply-exhaustion effect during the monsoon season. Though such a model may provide a valid simulation for these basins, synoptic-scale variation in suspended sediment concentration *within the data available* obscures the observation of a floating rating-curve pattern. For instance, samples taken during May at the Upper Andheri station reveal a heightened response during the early stage of the pre-monsoon season. Unfortunately, storms and floods are less frequent at this time than in June and too few samples are available at any station (including Upper Andheri) for adequate development of a floating rating curve model for the pre-monsoon season. In addition, a systematic decline in suspended sediment concentration *within* either the transition or monsoon seasons was not evident; only a September drop at Lower Andheri appeared defensible. This remains a useful area for further research

C-Q relations derived from these data are used both to compare the sensitivity of the basins with respect to the operating controls and to predict C values for given Q values. The comparison demands functional analysis whereas the prediction requires simple log-linear regression. Mark and Church (1977) have provided equations for the computation of the functional relation in terms of the marginal regression derived for prediction. Because both are required here (prediction - Chapter 8), their equations are used and both relations presented.

The results of simple log-linear regression are expressed in terms of $C=aQ^b$ and are given in Table 5.7 for each of stations 10, 9, 2, 3, and 1. The correlation coefficient (R^2) and the standard error (s_r) of the regression are provided in terms of the transformed ($\log_{10}$) values. These values are used in Chapter 8 for predictive purposes and a standard bias correction is applied in that application to better predict the influential high-flow estimates (Miller 1984).

Table 5.7 Sediment-rating-curve relations based on seasonally-stratified data using log-linear regression (1992-1994, assuming Q known without error) excluding data from the transition season.

Station	No.	Season	a_r	b_r	n	R^2	s_r
Kukhuri	10	P	36.13	1.431	45	0.397	0.413
		M	16.91	1.520	110	0.604	0.199
Upper Andheri	9	P	30.33	0.385	31	0.225	0.170
		M	8.27	0.583	75	0.390	0.218
Lower Andheri	2	P	12.20	0.586	150	0.592	0.0913
		M	3.15	0.740	243	0.678	0.0911
Dhap	3	P	11.53	0.284	62	0.402	0.0312
		M	8.24	0.429	128	0.218	0.122
Jhikhu	1	P	1.44	0.872	201	0.546	0.0937
		M	0.45	0.950	489	0.688	0.0819

Rating curves based on $C=aQ^b$ power law relation; n=number of samples;
R^2=correlation coefficient; s_r=standard error of the regression ($\log_{10}$ g/l);
P - pre-monsoon season; T - transition season; M - monsoon season

To determine the functional relations for each station, it is necessary to estimate the ratio of the error variances of C and Q ($\lambda = E_C^2/E_Q^2$) as explained by Mark and Church (1977). The calculation of E_Q^2 is straightforward using the standard error of the regression for the stage discharge relations presented in Appendix A5. A geometrical approach is followed to determine E_C^2. It is assumed that any additional departures in the C-Q relation between the measured and expected C values (beyond that attributed to Q) can be attributed to real variance in C. Hence by geometry,

$$E_C^2 = \Sigma\ [dC]^2 = \Sigma\ [(C_{meas} - C_{exp} - b_r(dQ)]^2$$

where C_{meas} is the actual measured suspended sediment concentration (g/l), C_{exp} is the expected value based on the marginal regression, b_r is from the marginal regression, and dQ is the error (m^3/s) associated with the measurement of discharge. Using this approach, all synoptic variability in suspended sediment concentration including hysteresis is attributed to the C variate. This is appropriate since adjustments for these synoptic effects are typically unavailable. Following Mark and Church (1977), this relation is used to calculate values of b_f for each station/season combination:

$$b_f = \{(b_r^2/R^2-\lambda)+\sqrt{[(b_r^2/R^2-\lambda)^2+4\lambda b_r^2]}\}/2b_r$$

where R^2 is from the marginal regression (Table 5.7). Church and Mark (1980, p. 385 and erratum) provide confidence limits for b_f in terms of the one-tailed Student's t for n-2 degrees of freedom:

$$\lambda^{1/2}\tan\{\tan^{-1}(b_f\lambda^{-1/2})\pm {1/2}\sin^{-1}\{(2t\lambda(1-R^2))/((n-2)(b_r^2/R^2+\lambda^2R^2b_r^2-2\lambda+4\lambda R^2))\}^{1/2}.$$

All calculations are carried out here using $\log_{10}$ transformed units.

Figure 5.7 illustrates the results of these calculations (for the expected relations) and the equations of the resulting lines appear in Table 5.8. This table indicates that the error variance associated with the measurement of C is between 2 and 19 times greater than that of Q. A small set of replicate samples (21 pairs) taken at Upper and Lower Andheri, Dhap, and Jhikhu stations under conditions representative of high flow has a small associated error variance in comparison to the values calculated to yield Table 5.8 (0.0019 versus a range of 0.087-0.45). This contrast suggests that the unstructured variance in C is due largely to the effect of synoptic controls on suspended sediment operating within seasonal scales with a minimal contribution derived from random fluctuations during sampling.

The estimated error associated with Q is at times larger than the one suggested by the standard error of the regression for the stage discharge relations. At Dhap station (3), the stage discharge relation is not developed over the highest flows putting a larger error expectation on the high-flow values calculated through extrapolation. In addition, bed control difficulties at Upper Andheri station (9) and some uncertainty in reading the gauge at the highest flows at Jhikhu (1) and

Figure 5.7 Seasonally-stratified sediment rating curves based on all entire data set: (a) Kukhuri, (b) Upper Andheri, (c) Lower Andheri, (d) Dhap, and (e) Jhikhu.

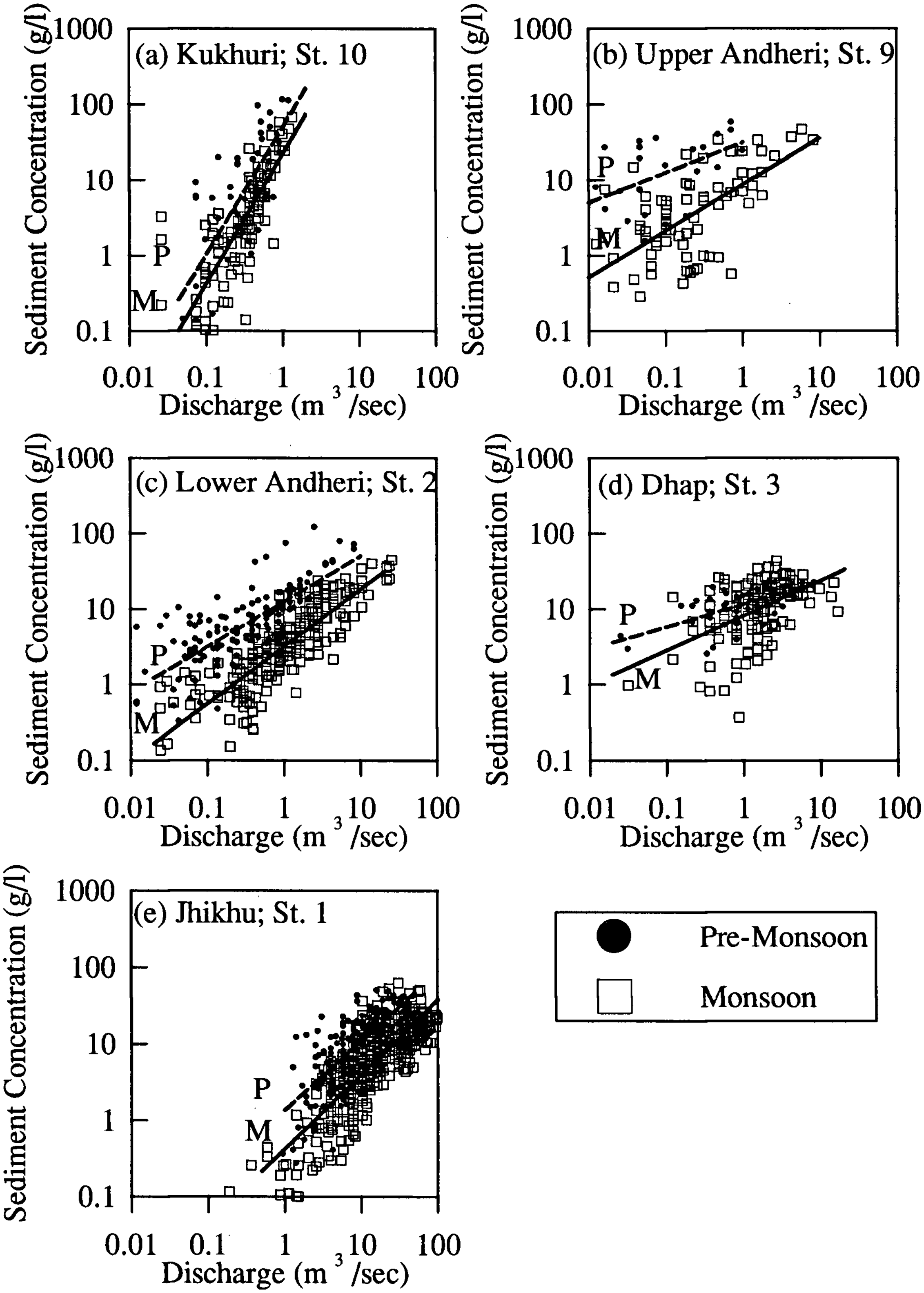


Table 5.8 Sediment rating-curve relations derived using functional analysis.

Station Name	No.	Season	λ	b_f expected	b_f range	a_f expected	a_f range
Kukhuri	10	P	18.47	1.68	1.28-2.11	49.5	29.9-84.5
		M	10.44	1.72	1.55-1.90	21.9	17.6-27.5
Upper Andheri	9	P	12.18	0.402	0.221-0.585	31.6	20.7-48.2
		M	9.68	0.616	0.500-0.733	8.70	7.27-10.4
Lower Andheri	2	P	11.59	0.598	0.545-0.650	12.4	11.7-13.1
		M	12.51	0.755	0.712-0.798	3.154	3.14-3.15
Dhap	3	P	2.29	0.299	0.239-0.361	11.5	11.5-11.5
		M	8.99	0.462	0.362-0.563	8.13	7.80-8.47
Jhikhu	1	P	15.53	0.907	0.832-0.983	1.34	1.13-1.58
		M	14.60	0.976	0.938-1.01	0.42	0.38-0.46

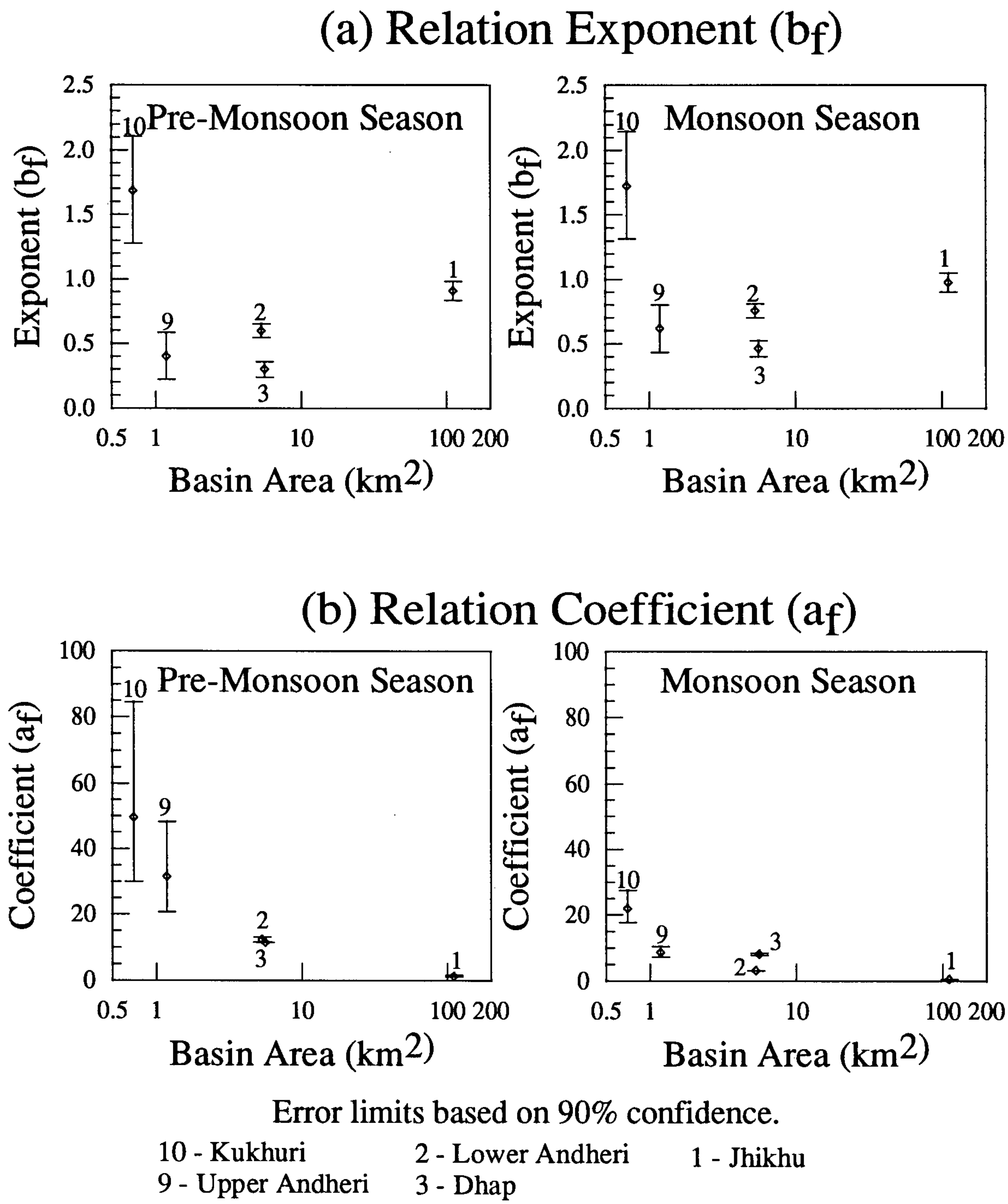
Each a_f calculated by applying its respective b_f to the means of C and Q from each data set ($a_f=C_{mean}-b_fQ_{mean}$). Ranges are based on 90% confidence. λ is the ratio of the error variances (E_C^2/E_Q^2). P = pre-monsoon season; M = monsoon season.

Lower Andheri (2) increases the expected error of the Q values for these situations. However, due to their limited nature, these are not incorporated further in the present analysis.

The pre-monsoon sediment response is greater by up to an order of magnitude in comparison with its associated monsoon response and shows a tendency to merge with the monsoon-season result at the highest flows (Figure 5.7). This pattern is evident within all basins including that of the largest Jhikhu basin. The similarities suggest that the same controls are operating over all scales (1-100 km^2), with their relative influence changing with season and scale. The influence of basin character on these sediment regimes can be examined further by contrasting the parameters of these ten equations (a_f and b_f).

Figure 5.8 compares the expected values and ranges (here at 90% confidence) in b_f and a_f between all five basins. This comparison reveals the relative vulnerability of these basins to floods, vis-a-vis suspended sediment. The exponent of the relation (b_f) expresses the extent of coupling

Figure 5.8 Seasonal variation in a_f and b_f with basin area ($C={}_aQ^b$).



between Q and C. Relief has a strong but not exclusive effect on this coupling. The higher b_f is, the greater is the possible transport limitation. The coefficient (a_f) provides an indication of the magnitude of the relation between Q and C. Higher values of a_f (for equivalent b_f) indicate a greater sediment availability. Considered together, especially in light of basin characteristics (including area), the comparison can shed light on the relative behaviour of these basins. It is important to realise that these two parameters are not independent because they are coupled through the bivariate mean in the linear regression (and functional analysis) and hence they are related to one another through R^2. For example, a higher a_f and lower b_f of one relation in comparison to another may suggest higher sediment concentration at low flow and lower concentration at high flow.

Figure 5.8a shows the seasonal sensitivity of each basin to changes in discharge. The pattern - consistent within each season - suggests a decline in sensitivity with scale within the major tributary basins then an increase to the largest scale (100 km^2). In particular, Kukhuri demonstrates a highly coupled C-Q behaviour with slopes (range of 1.18 to 2.11) higher than those generally quoted elsewhere (section 5.2.1). In this steep basin where cultivation is found on over 63% of the land area (see Table 2.5), discharge has a dominant influence on sediment regime. At low flows, sediment contribution is negligible (Figure 5.7) while at medium and high flows, sediment concentrations climb rapidly, yielding the highest value recorded in the study, 123.7 g/l. The low values of b_f for the Upper Andheri basin are anomalous: this basin is proportionately as steep as the Kukhuri basin yet yields a range of b_f similar to the two 5-km^2 study basins. Its larger area (2.5 times the area of Kukhuri basin) may contribute to an attenuation of this strong headward coupling. The effect may also be due to the presence of pockets of degraded land in the vicinity of the hydrometric station (easily eroded at low flow), exaggerated by measurement difficulties that were faced only at this station. Additionally, sampling during May when it is suspected that concentrations of suspended sediment are considerably higher (in comparison to those of June) was successful at this station and certainly provided an unusual number of high-C/low-Q pre-monsoon samples to raise the low-Q end of this relation. The relations for the entire Lower Andheri basin (2) show steeper slopes than that of the Upper Andheri basin (9), though having three times the area. Management factors which are not as influential on the sediment regime within the Upper Andheri and Kukhuri basins come into play in the lower reaches of the overall basin. Two of these factors, surface degradation and sediment storage within the irrigation system, are discussed respectively in detail in sections 5.5.2 and 5.5.3.

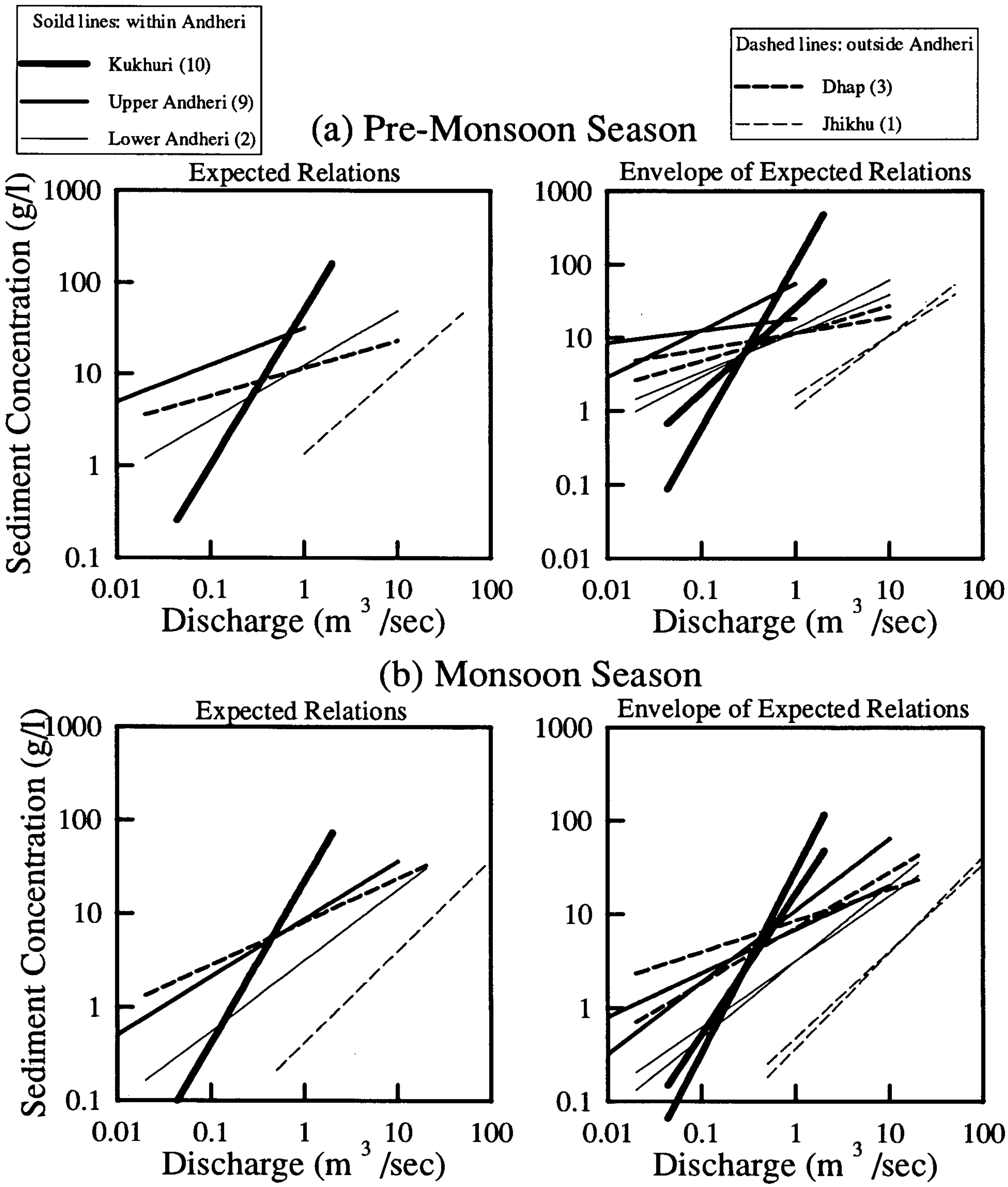
Dhap, though of the same size as Lower Andheri has a significantly lower sensitivity to Q. Dhap is dominated by modest relief containing little steep land like that characterising the upland of Lower Andheri (Table 2.5). The sensitivity of Jhikhu basin increases over that of the major tributaries suggesting a change in dominant processes between the 10- and 100-km^2 scales. The most likely explanation appears to be a loss of sediment to storage within the large valley meanders between the Dhap and Andheri Rivers' confluences with the Jhikhu River.

It is only for the major tributary basins (Dhap and Lower Andheri) where the sensitivity to discharge changes significantly between seasons. Both Jhikhu and Upper Andheri show a trend of increasing sensitivity under the monsoon regime in comparison with the pre-monsoon regime, however, the differences are not statistically significant. Kukhuri basin shows no change in sensitivity with season, a fact consistent with its small area and steep topography.

Not unexpectedly, a_f shows a consistent decline with basin scale as a direct result of increased storage opportunities. The only exception to this is the Dhap basin during the monsoon season - its high coefficient (given the *relatively* consistent behaviour of b_f in Figure 5.8a) suggests a high rate of sediment output during the monsoon season. This situation is related to this basin's degraded condition and is examined in detail in section 5.5.1. During the pre-monsoon season, the coefficient rises to very high values for small basin areas indicating - especially in light of the strong C-Q coupling observed in Figure 5.8a - a high degree of sediment mobilisation and an important area of concern for soil-erosion management.

In Figure 5.9, the regression results for all five stations are overlaid for the pre-monsoon and

Figure 5.9 Seasonal sediment rating curves overlain for all study basins showing both the expected functional relations and envelopes representing confidence limits to these relations (at 90%): a) pre-monsoon regime b) monsoon regime.

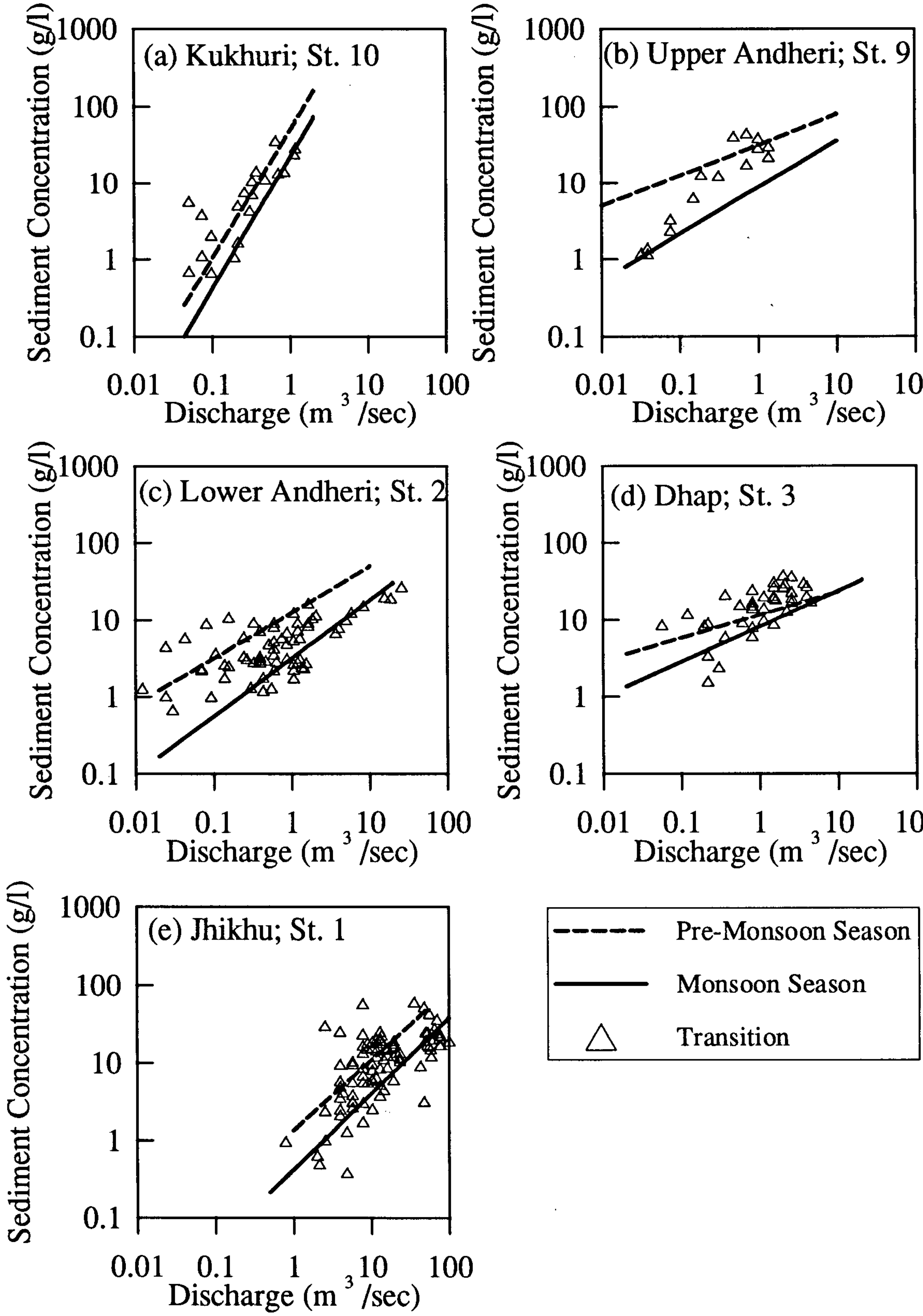


monsoon seasons. These overlays present an "integrated" comparison of a_f and b_f between basins. It appears from this figure that within the 1 to 10 km^2 range of scale, differences between the relations are due to rotation of the curve as a result of the rapid reduction in specific relief over these small scales. Between 10 and 100 km^2, the change is dominantly one of translation - basin sensitivity to discharge remains similar but specific suspended sediment transport declines, perhaps due to alluvial storage. This pattern is stronger during the monsoon season because the plentiful sediment supply of the pre-monsoon season raises suspended sediment concentrations at all scales and relatively more at low Q, reducing the dominance of Q during this season. This may provide a conceptual framework within which to examine further the sediment regimes in this agricultural system.

The sediment rating curves presented in this section corroborate the findings of section 5.3 in which pre-monsoon surface erosion was seen to be over an order of magnitude higher than the level in the monsoon season. However during the monsoon season and over all studied scales, the rate of sediment production from these upland cultivated fields is not sufficient to equal the amount of sediment which is transported in the streams. It must be concluded that there are other sediment sources present particularly during the monsoon season over scales larger than that of the individual field. These sources are streambed and streambank erosion and terrace damage and are of particular importance during "major" storm events (see section 4.6.1) and at high flow rates. The distribution of floods of the monsoon season tends to have higher peak flows than their pre-monsoon counterparts: this corresponds well to a seasonal increase in erosion due to mass wasting and is backed up by observation (discussed in Chapter 8).

Another important source of suspended sediment is revealed by considering the regimes of the transition season. Figures 5.10a through 5.10e show the suspended-sediment data of the transition season for stations 10, 9, 2, 3, and 1 respectively and the seasonal regression lines for reference. In each case, the transition-season data show intergrade behaviour between the other two seasons. The vegetative cover - discussed in section 5.3 - does not develop instantaneously at all locations within

Figure 5.10 Suspended sediment data of the transition season and the seasonal regression regimes based on the entire data set: (a) Kukhuri, (b) Upper Andheri, (c) Lower Andheri, (d) Dhap, and (e) Jhikhu.



the basin and during this period, heavy erosive rains may or may not occur at any particular location within a basin. This mechanism is operating throughout the transition season to a variable degree. At the onset of the monsoon season, the vegetative cover is ostensibly complete and this production opportunity gone. On-site observation during this period supported by the seasonal contrasts provide the evidence for these statements. In addition, the sand component of the suspended sediment load may show a declining availability through the transition season as this fraction (mobilised during the pre-monsoon season) is flushed through the basins (see Chapter 6).

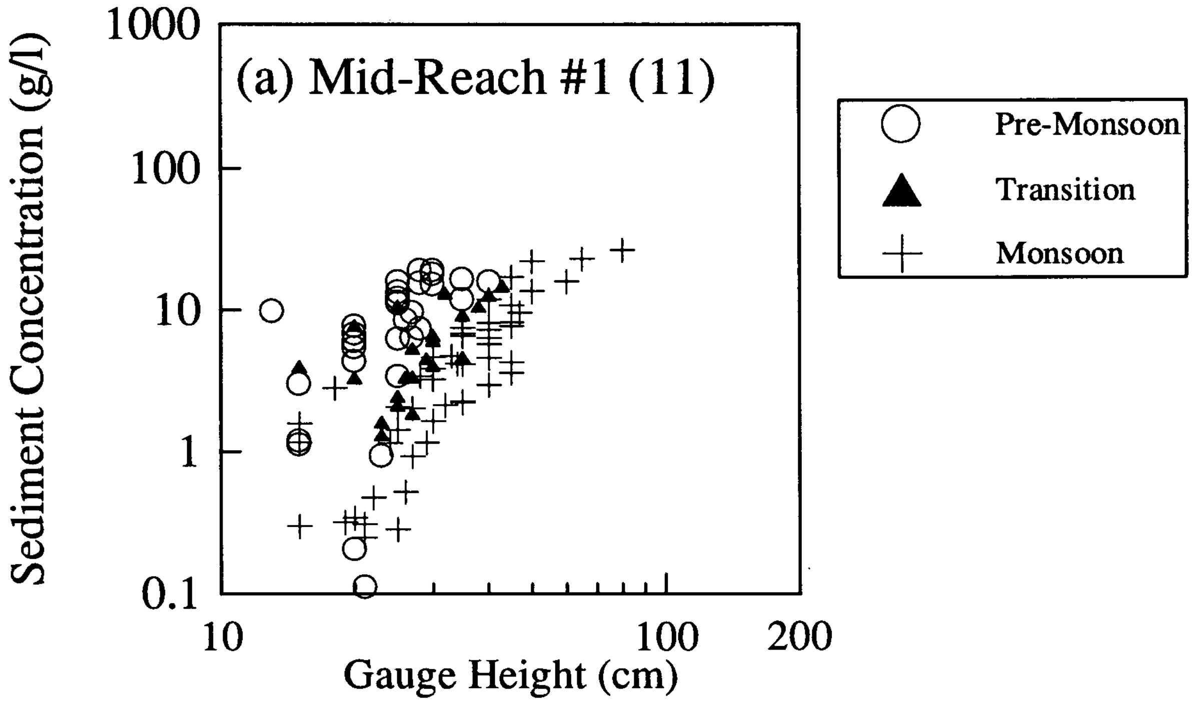
The data from the mid-reach Andheri stations (11 and 12) provide further evidence of the trends observed in this section. Seasonally-stratified suspended-sediment data from these stations are given in Figure 5.10 for stations 12 and 11 respectively. In both cases, higher regimes occur during the pre-monsoon season. Also, the transition season displays intergrade behaviour between that of the pre-monsoon and monsoon seasons. Due to the lack of stage-discharge relations at these stations, it is not possible to comment on the relative influence of discharge compared to the other basin scales.

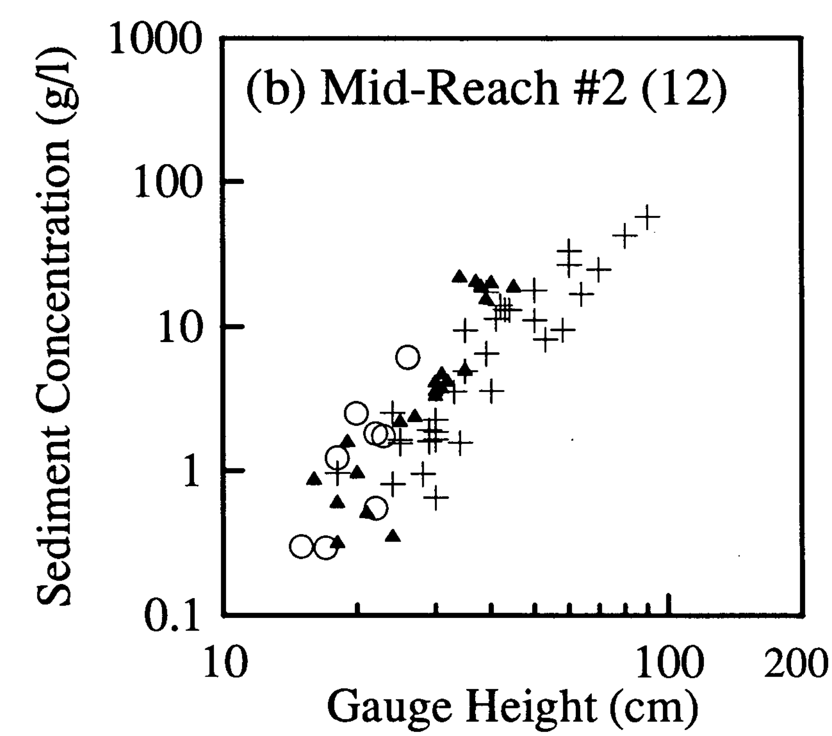
In conclusion, the suspended-sediment data from the streams reinforce and extend the results of section 5.3. The effect of surface cover in the pre-monsoon is evident clearly and it takes almost three weeks for a complete surface cover to develop in order to virtually eliminate this sediment production mechanism. The presence of significant suspended sediment during the monsoon season points to additional sediment sources beyond surface erosion from individual cultivated fields. Controls on suspended-sediment delivery change with scale; sensitivity to discharge declines with basin scale whereas management controls become increasingly complex with basin scale as explored in the following section.

5.5 Landuse signatures

Human manipulation through the indigenous agricultural system is pervasive in the study basins, affecting nearly every aspect of erosion and sediment transport. Terracing, cropping practices,

Figure 5.11 Seasonally-stratified suspended-sediment data for the mid-reach Andheri River station based on 1993-1994 data: (a) mid-reach #1 (11), and (b) mid-reach #2 (12).





water diversion, and many other soil and water management techniques control the movement of soil and sediment from its source location to its eventual discharge from a basin.

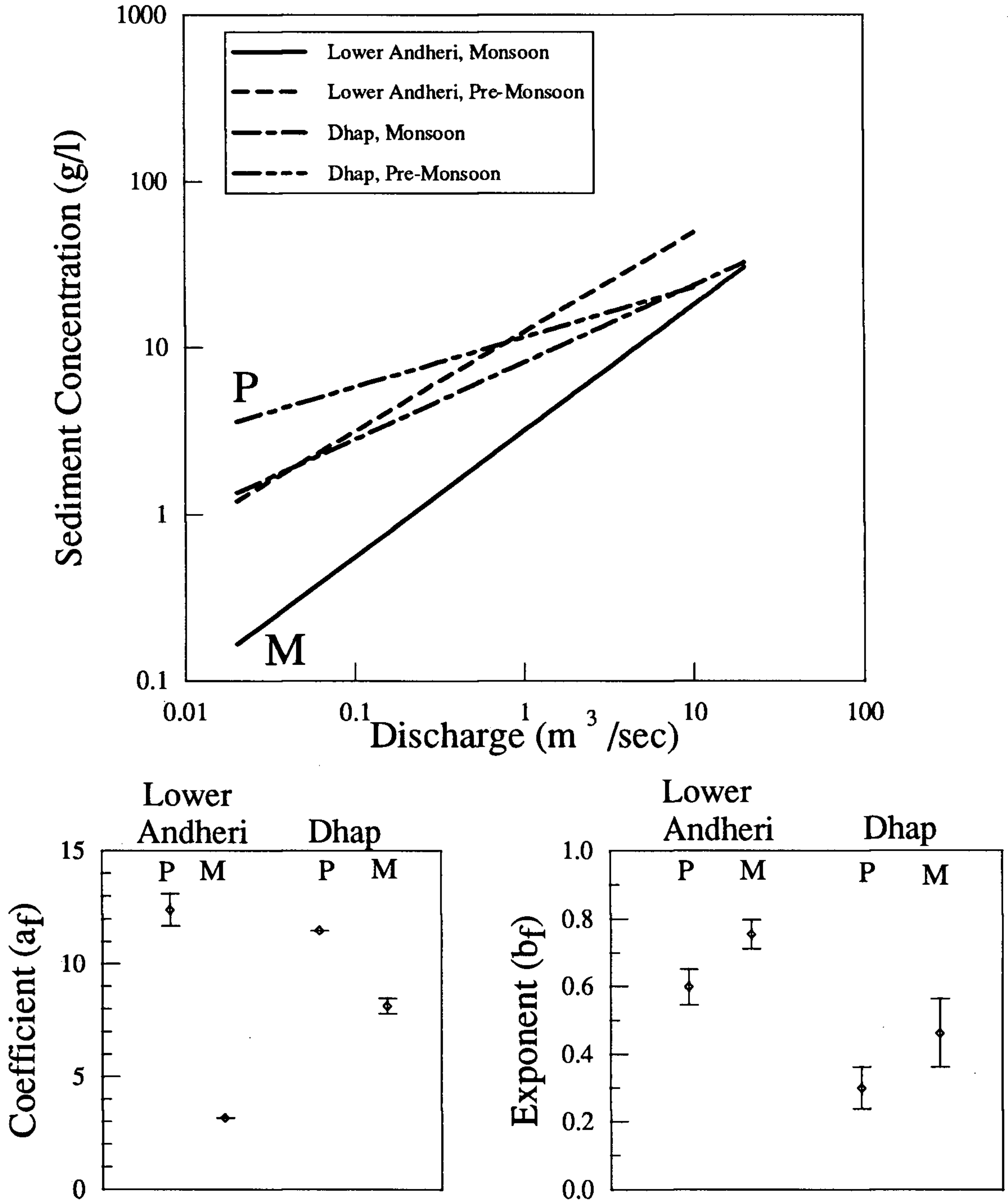
Three analyses are presented here. In the first, two basins are compared - Dhap (3) and Lower Andheri (2). These basins are similar in area but have contrasting character and management regimes. This comparison studies the effect of degradation on annual and seasonal sediment regimes. In the second analysis, the effect of degradation is studied within the Lower Andheri basin. This basin contains contrasting landuse between its upper- and lower-elevation areas. The effects of this spatial distribution in surface condition is examined particularly in light of the spatial variability in rainfall delivery which was quantified in Chapter 4. The final analysis looks at water diversion to estimate the extent to which this management activity recaptures previously eroded soil, redistributing soil from the upland rather than losing it from the larger basin.

5.5.1 Surface degradation: comparison of two basins

There are frequent pockets of degraded land in the Middle Mountains, especially below 1400 m where red soils occur. Though these soils can be highly productive, they can also be difficult to manage and require high inputs of fertilizer and compost. Once these lands degrade, it can be difficult to bring them back into production. To what extent do these degraded areas contribute to the basin sediment budget? How important are they in modifying the patterns which have been discovered in the previous two sections? To help answer these questions, two basins of equal size and of differing character (especially with respect to their level of degradation) are compared in this section.

Figure 5.12 contrasts the seasonal sediment rating curves for the Dhap basin with those of the Lower Andheri basin. These two basins are of equal size but the Dhap basin has a more gently-sloping topography and is in a lower elevation range. Despite these characteristics which should reduce this basin's tendency to erode, the sediment rating curve for the Dhap basin is higher than that of Lower Andheri during each season except at high-flow during the pre-monsoon season.

Figure 5.12 Seasonal sediment rating curves for Lower Andheri and Dhap basins overlaid for comparison.



The monsoon-season regression curves of these two basins are further separated than are their pre-monsoon counterparts. This enlarged separation develops because the sediment-yield response in Lower Andheri basin drops in the monsoon whereas that of the Dhap basin does not. Recall the anomalous pattern of a_f shown in Figure 5.8 with b_f consistently lower in Dhap basin relative to Lower Andheri (due to Dhap's modest relief). These contrasting seasonal changes can be explained by surface cover and soil degradation. The Lower Andheri basin contains large amounts of well-managed cultivated steeplands. These soils experience a seasonal change in surface cover as examined in sections 5.3 and 5.4. The Dhap basin contains a greater proportion of seriously degraded land - gullied soil with little or no vegetation. In the Dhap basin, 24% of the land is seriously degraded whereas in the Lower Andheri basin, there is only 15% in this state. This apparently small difference must have a large effect on sediment production within the basin especially given the limited relief of Dhap in comparison to Lower Andheri. Because these degraded lands do not experience a change in surface cover with the onset of the monsoon season, these small areas - if present - play a big role in the basin sediment budget.

This finding underlines the importance of preventing land from becoming degraded. In the Andheri basin, 25% of the area is in a moderately degraded condition (minor gullies or limited crown cover) whereas only 18% of the Dhap basin is moderately degraded. If the moderately-degraded land in the Andheri basin is allowed to slip further out of production, the suspended sediment regime of the Andheri basin could become similar to that of the Dhap basin or even higher due to its steeper topography.

Re-examination of Figure 5.7d indicates that the seasonal difference in the regression results for the Dhap basin is a result of low sediment data derived from monsoon-season samples. The high-sediment data show no seasonal dependence at any discharge suggesting that the soil surface responds similarly to heavy rainfall in both seasons. The seasonal difference in low-sediment data may be the result of local (<5 km^2) convective showers over the less degraded parts of Dhap basin.

It is important to also consider flood frequency to understand the overall significance of the seasonal suspended-sediment behaviour. The sediment loads during the pre-monsoon season, though generally quite high throughout the Middle Mountains, are short-lived because this season is brief and rainfall infrequent. The monsoon season, in contrast, lasts longer and experiences a greater number of flood events. The increased flood frequency in the monsoon season underlines the importance of the lower surface erosion during the monsoon season. In a basin with degraded surface conditions like the Dhap basin, elevated pre-monsoon sediment levels are maintained during almost twice as many floods through the monsoon season. Local management which encourages the rapid return of a complete vegetative cover is therefore the key to reducing net sediment output. To determine the overall and relative importance of these processes, annual budgets need to be calculated and this is done in Chapter 8.

5.5.2 Surface degradation: within Lower Andheri basin

The effect of surface degradation on stream suspended sediments can also be examined *within* the Andheri basin because the basin contains large areas of contrasting landuse. The lowlands are dominated by bare red soils, often gullied, while the majority of the headwaters is under intensively-managed, steepland agriculture on non-red soils. In Chapter 4, it was learned that flood-producing rainfall over this basin is local in nature (<5 km^2) for about half the storms. By linking the rainfall database to the flood database, suspended sediments in floods resulting from storms over each of the two landuse classes noted above can be isolated.

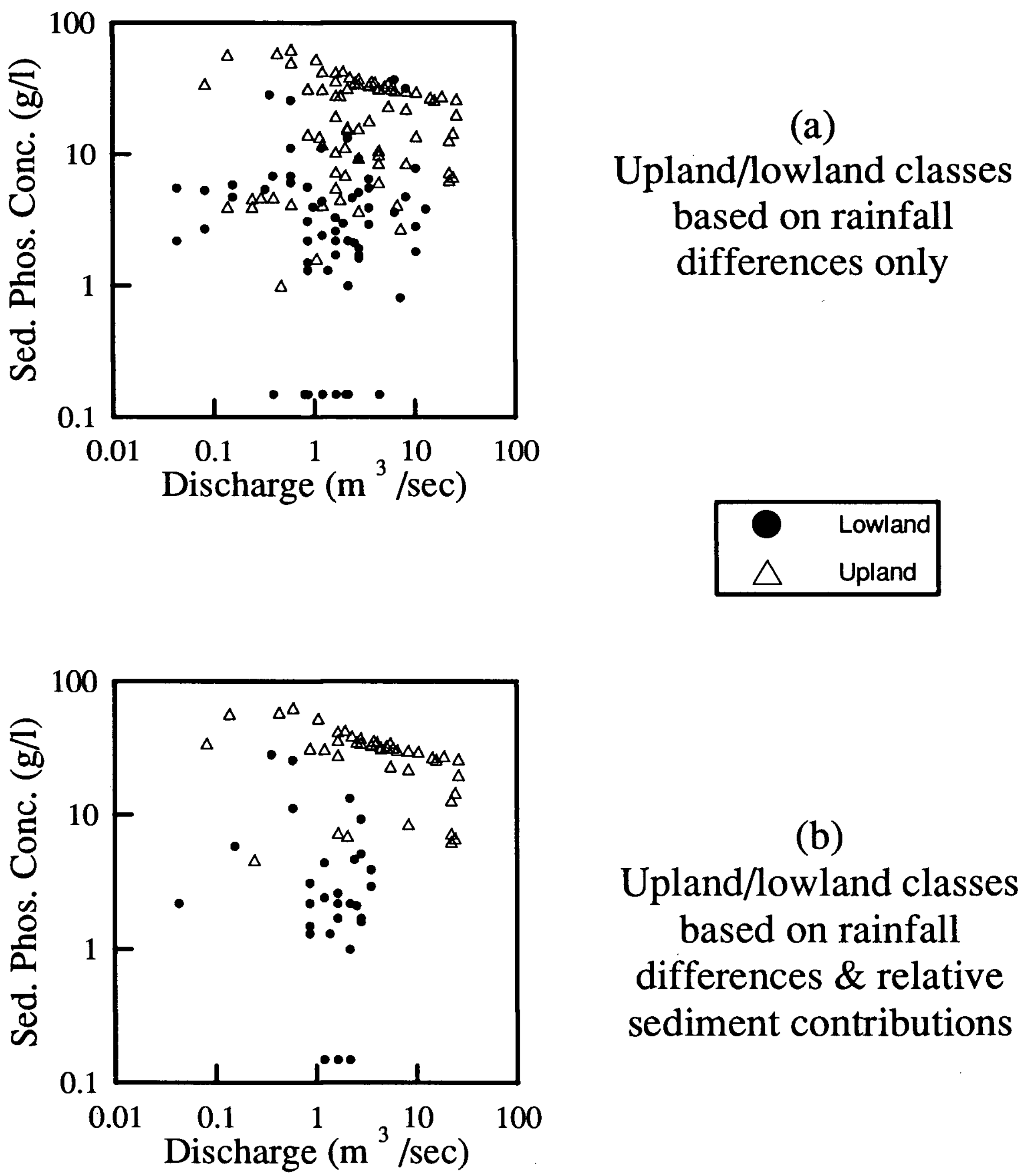
Section 5.3 demonstrated that high levels of surface erosion occur on steep cultivated fields (like those in the headwaters of the Andheri basin) during the pre-monsoon season. In the previous section, basin sediment rating curves were used to conclude that the gullied badlands yield high sediment levels though no plot measurements were provided to substantiate those statements. In several gullies of the Andheri lowlands, gully pins were maintained in place to monitor the change in gully dimensions during 1992-1994. Gully growth is highly variable: one gully showed little or no growth in size while the other two changed greatly in dimensions, reflecting the instability of their vertical headwalls. These results confirm that this gullied area is an important sediment source and also suggest that gully management may be focused on the individual gullies which show particularly active behaviour.

To carry out the comparison of suspended sediments arising from storm events over these two areas, it must first be clarified what constitutes upland-dominated versus lowland-dominated floods as it concerns suspended sediments. The approach taken here extends the classification described in Chapter 4 in which basin, lowland, and upland events were defined based on the average rainfall for 12 gauges within each of the lowland and upland clusters. If the average of the two clusters was not significantly different, then the event was considered a basin event. If the difference was significant, it was a lowland or an upland event depending on which area received more rainfall.

Of the events which are erosive and cause floods, it is necessary to stratify them removing those events which yield suspended sediment from a mixture of upland and lowland source areas. Then the amount of suspended sediment can be related to the source area directly. To accomplish this, the phosphorus content of the sediment is used as a fingerprint to calibrate a threshold which identifies relative source area contributions. The red soils of the degraded lowland are low in phosphorus whereas the non-red soils of the upland are high in phosphorus. This contrast is exploited to identify suspended sediment originating from these two source areas (see section 6.5 for more details).

For each flood within Andheri basin, the ratio of the average rainfall in the upland versus that of the lowland was calculated. Beginning with all the suspended sediments for upland and lowland rain events on one C-Q plot, the requirement for a minimum ratio of rainfall in one area to the rainfall in the other area was made incrementally more stringent and the resulting phosphorus content of the sediments at the hydrometric station examined. At a threshold of 1.7 (one area delivering 1.7

Figure 5.13 Sediment-phosphorus rating curves stratified by rainfall location and colour for Lower Andheri basin (2) based on (a) rainfall differences only, and (b) both rainfall differences and their relative upland-lowland sediment contributions.



times the rainfall of the other area), the phosphorus content of the sediments separated as seen in Figure 5.13. Below this threshold, sediments sampled at Lower Andheri from upland rainfall events contain a significant number of red, low-phosphorus samples and those from lowland rainfall events contain brown, high-phosphorus samples. The threshold value represents the point at which the contribution from one area dominates overwhelmingly that of the other area. The sediments derived from "mixed" events are removed from the C-Q graph altogether. For example, if a lowland event brings 40 mm average rainfall to the lowland, it is retained as a lowland event in this analysis only if it also brings no more than 23.5 mm of average rainfall to the upland cluster. Those area events which do not satisfy this added constraint are termed basin events.

In Figure 5.14, the locations of the rain gauges within and near the Andheri basin are overlaid on the red soil map. The areas of red soil in the Andheri basin lowland correspond to the bare and degraded land. This figure shows that if a storm event is a lowland one, it is dominantly over the degraded areas (on red soils) whereas if it is an upland event, it is dominantly over the intensively-managed cultivated (non-red) soils.

C-Q data from the Lower Andheri (2) station introduced earlier in this chapter (Figure 5.7c) are stratified according to lowland and upland events and the result is presented in Figure 5.15 (data from basin-wide events are not shown). The upland displays a greater sensitivity to Q (as reflected in b_f) than the lowland and the difference is significant (90%) during the *monsoon* season. In addition, a_f for the upland is double that of the lowland during the *pre-monsoon* season and this difference is significant. The higher response during the pre-monsoon reflects the vulnerability of the steep upland during this season especially given the potential sediment production capability of the degraded lowland given the findings of the previous section.

These functional relations are based on only 22 independent flood events. In addition, due to the more frequent occurrence of lowland events, 17 (P - 9; M - 8) of these are lowland events and only 5 (P - 3; M - 2) are from the upland. As a result, the upland data used to develop the relations

Figure 5.14 Locations of the rain gauges within and near the Andheri basin overlain on the red soil map.

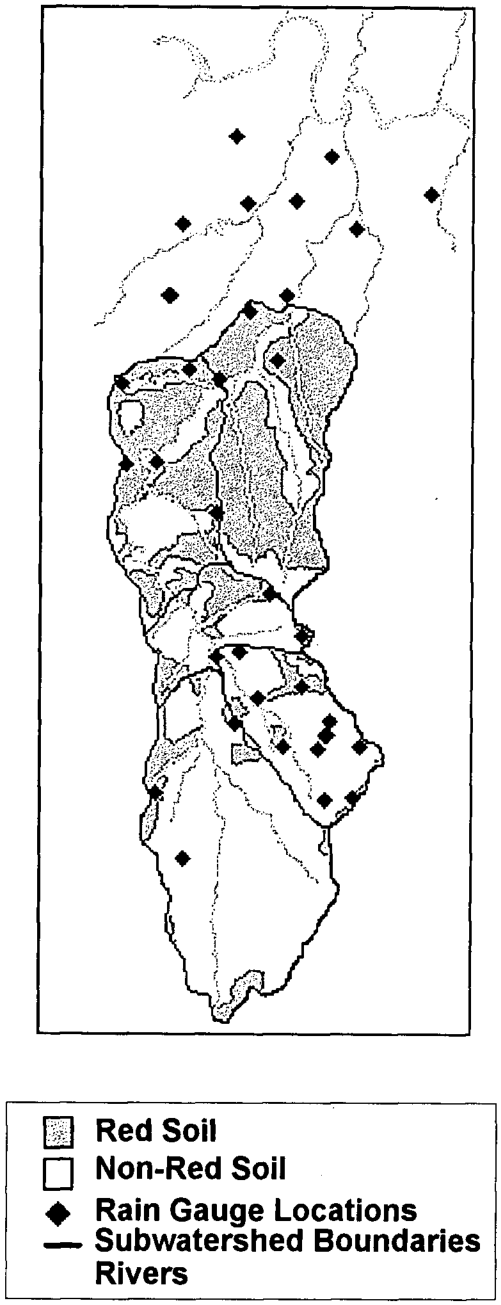
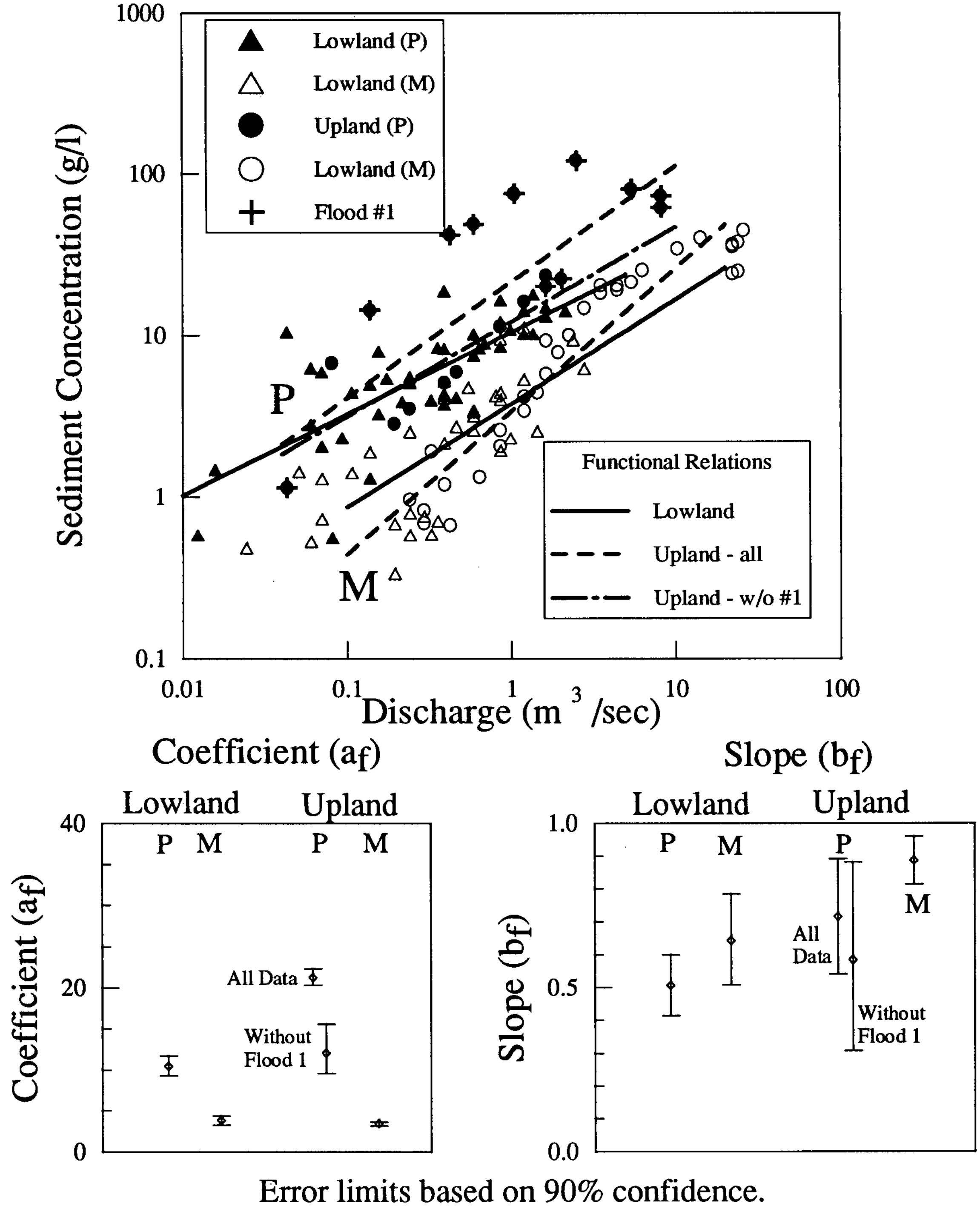


Figure 5.15 Sediment rating curves for Lower Andheri station (2) including sediments from only lowland and upland events (1992-1994).



presented in Figure 5.15a are dominated by a well-sampled *major* event (see section 4.6.1 for definition of storm classes) of June 9, 1992 (Flood #1) identified on the figure. The effect of this event is investigated by recalculating the functional relation excluding these data. This relation is shown in Figure 5.15a and in the confidence ranges shown in Figure 5.15b and 5.15c. These recalculations show that without this one event, there is no difference during the pre-monsoon season between the upland and lowland flood events. Clearly, an analysis cannot rely on one independent event to reach a conclusion of statistical significance. This finding suggests caution in situations where the number of independent *events* is small.

Table 5.9 Annual and seasonal sediment-rating-curve relations for Lower Andheri station based on lowland/upland data using log-linear regression.

Area	Marginal Regression						λ	b_f		a_f	
	Season	a	b	N	R^2	s_r		expected	range	expected	range
lowland	P	10.30	0.494	44	0.547	0.0589	8.03	0.506	0.414-0.600	10.45	9.35-11.71
upland	P	21.23	0.704	19	0.637	0.124	19.59	0.715	0.541-0.891	21.30	20.32-22.34
lowland	M	3.694	0.624	33	0.551	0.0806	10.15	0.644	0.509-0.783	3.77	3.29-4.33
upland	M	3.398	0.875	32	0.892	0.0400	6.87	0.886	0.813-0.960	3.36	3.61-3.13
upland (w/o #1)	P*	11.864	0.561	8	0.598	0.0472	4.80	0.585	0.308-0.881	12.10	9.58-15.52

* Upland/pre-monsoon recalculated without the single large pre-monsoon event of June 9, 1992.

A comparison of seasonal sediment yield between the upland and the lowland must also consider the relative frequency of upland versus lowland events. The functional relations suggest that upland events deliver a higher sediment concentration but in section 4.5.2, it was found that almost 43% more lowland events (≥10 mm; 1992-1994) were monitored in comparison to upland events. Together, these results suggest that the degraded lowland may leak sediment throughout more of the rainy season whereas the upland's losses are episodic, particularly during the pre-monsoon season.

What does this analysis tell us about the effect of landuse on suspended sediment concentration within this 5-km^2 basin? It suggests that event sediment yield is higher for events in the pre-monsoon season originating in the steep, well-managed upland. This increase is due to high-Q samples. This difference is not present during the monsoon season because high-C samples are limited to high-Q conditions. Although the degraded lowland did not generate C values as high as those from the upland, this area yielded higher C values for conditions of low and intermediate flows, especially during the monsoon season. This is consistent with the previous section where it was found that the Dhap basin retained an elevated rate of sediment output during the monsoon season. This analysis is useful because it confirms that we can also see this behaviour *within* a 5-km^2 basin.

According to Burt (1989), the mixing of runoff from widely differing source areas (*e.g.*, in terms of precipitation inputs and surface response) obscures the process-response relations that can generally be identified in smaller basins. Burt pointed out the importance of basin scale in mediating the degree of obscurity: it is in the intermediate-sized basins where variability in surface response (surface cover and condition) and rainfall input is greatest. In the study area, this area appears to correspond to about 5 km^2. Above and below this scale, process-response relations are identifiable. The analysis presented in this section reveals that surface response and variability in rainfall input contribute formatively to sediment regimes at these limited spatial scales (roughly 5 km^2). This conclusion has major implications for monitoring in similar mountainous environments.

5.5.3 Sediment storage by water diversion for irrigation

The irrigation system serves as a sediment trap in diverting flow and halting the movement of eroded material out of watersheds. But how effective is this process? To what extent are the farmers able to recapture soil and nutrients lost from their upland agricultural fields and entrained in the fluvial system? To answer this question, two analyses are presented. The first focuses on the diversion of water while the second looks specifically at the extent of sediment accumulation in the irrigated fields.

Water diversion

As it progresses downstream, runoff is concentrated and thus streams generally grow in size. If rainfall is uniform over the basin and if there are not significant losses to the subsurface nor dramatic changes in the surface characteristics downstream, one would expect the stream to grow in volume in proportion to the ratio of the basin areas which contribute to their outflows. This principle is used here to evaluate the extent of diversion of floodwaters by diversion dams.

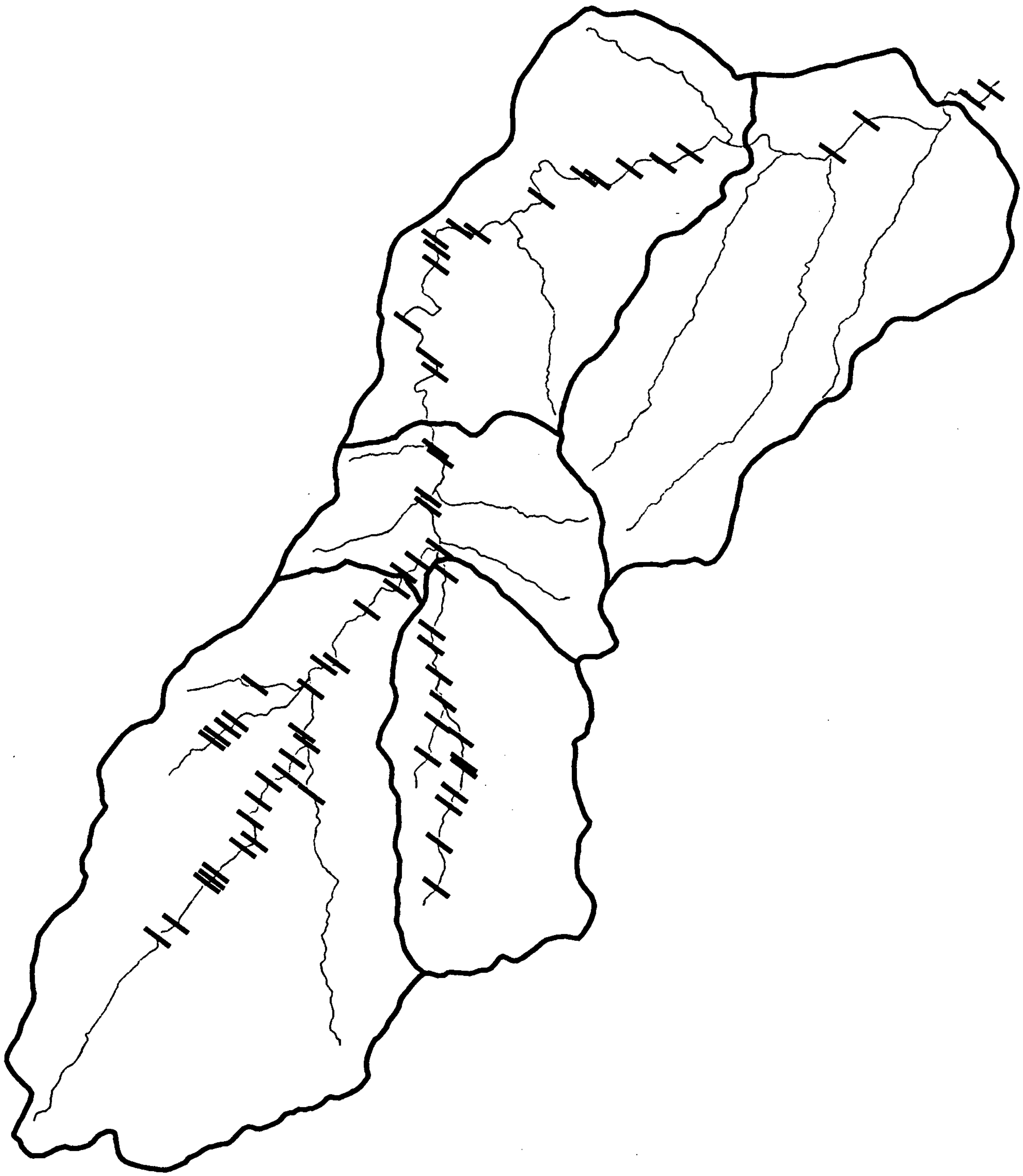
Figure 5.16 shows the Andheri and Kukhuri Rivers and the locations of the 62 diversion dams which are built along this drainage. This figure also shows the locations of two automated hydrometric stations within this basin. Table 5.10 summarises the pertinent information about each of these hydrometric stations. Though there is irrigated land above the Kukhuri River station (10), it is in the basin headwaters where water is scarce and unreliable. Hence, the flow passing through the Kukhuri station is probably not much different than it would be in the absence of the structures of the irrigation system. The ratio of the contributing areas of the two stations is 7.4, as shown in Table 5.10.

Table 5.10 Contributing areas and number of irrigation dams for Kukhuri and Lower Andheri hydrometric stations (stations 10 and 2 respectively).

	Kukhuri Basin (station 10)	Lower Andheri Basin (station 2)	Ratio
Total Contributing Area (ha)	72	532	7.4
Irrigated area (ha)	7	37	5.3
Number of dams	14	62	4.4

Between these two stations, there are 21 large diversion dams. Without these in place, and assuming losses to the subsurface and groundwater are negligible, then we would expect to see about 7.4 times more flow at the Andheri station from rainfall events which provide even coverage over the entire basin. During the period of monitoring, 16 basin rainfall events (see section 4.5.2) were

Figure 5.16 Map of Andheri basin showing all irrigation diversion dams on the Kukhuri and Andheri rivers.



monitored simultaneously at both stations by the automated equipment and are available for comparison. For each of these flood events, the total flow through the two stations has been calculated. The results are presented seasonally and in terms of the ratio of the lowland to upland stations. These results are summarised in Table 5.11.

Table 5.11 Flow-ratio comparison of 16 individual floods for Kukhuri (station 10) and Lower Andheri (station 2) hydrometric stations.

Outflow Ratio Class (Andheri/Kukhuri)	Pre-Monsoon and Transition Seasons	Monsoon Season	Total Number	Percentage of Total
0 - 1.0	2	3	5	31
1.0 - 3.7	3	5	8	50
3.7 - 7.4	1	0	1	6
> 7.4	1	1	2	13
Total	7	9	16	100

In all but two cases, the ratios are far less than would be expected under unmanipulated hydrological conditions. In fact, 31% experience *less* flow at the lowland than the upland station. Further, the seasonal separation suggests that the tendency for a reduction in basin output may be greater during the pre-monsoon and transition seasons than it is during the monsoon season. However, because of the small number of events available, this seasonal consideration will have to be revisited when there are more events monitored in this comprehensive way.

The extent of irrigation in the upland compared with the lowland and the surface soil characteristics both serve to make stronger the conclusion of this analysis. The upland has proportionately greater irrigated area than the lowland. If the dams are effective at diverting floodwaters in the steep upland, then this greater area should cause the flow ratio (lowland-flow/upland-flow) to be higher, not lower. Further, the water-holding capacity of the surface soils in the lowland is less than in the upland; this should further cause the ratio to be higher than if this factor was equal. Despite these differences, the low flow ratios persist.

The flow-ratio analysis suggests that the diversion dams are very effective at directing floodwaters out of the stream and into the irrigation system. In fact, it appears that a majority of the floodwaters is redirected into the irrigation system. Quantitative water budgets including measurement of runoff diverted into *khet* on a flood basis is a useful area of further research. In addition, we know from the hydrometric data that large amounts of suspended sediments are carried with the floodwaters. If the hypothesis is correct, then there should also be evidence of soil accumulation within the irrigation system. We know that the farmers annually maintain the canals removing considerable deposition (see Chapter 7) but what of the fields themselves?

Sediment accumulation pins

To examine this, pins were placed in a wide selection of *khet* fields before the onset of each flood season during the study period. The pins were collected after harvest and the soil level noted and compared to the level before the pre-monsoon season began. These results, summarised in Table 5.12, suggest that considerable deposition occurs within the *khet* fields themselves. For instance, of the 25 fields sampled in 1992, 76% showed accumulation and 40% showed more than 0.5 cm. Further, these enriched deposits enhance soil-nutrient condition: lab analyses show that all the base cations are higher in the deposited sediment than in the underlying field soil (see Figure 7.1).

These two analyses suggest that management can recapture large amounts of previously-eroded fertile soil from upland cultivated fields. Due to its fertility, this redistribution of soil represents a redistribution of wealth from the upland farmers to those in the lowland. To what extent is soil redistributed and not lost from these headwater basins? This question and others will be addressed in Chapter 8 after a more detailed analysis of sediment dynamics is explored in Chapter 6.

Each of the above three sections, considered individually, gives an indication of landuse effects on sediment regimes. Collectively, they provide a stronger indication of the effect on sediment regimes of landuse practices.

Table 5.12 Sediment accumulation in irrigated fields measured using pegs.

Year	Accumulation (mm)			Accumulation Distribution (mm)				
	n	x	s	≤0	>0, ≤5	>5, ≤15	>15, ≤25	>25
1992	25	10.5	21.2	6	9	5	3	2
				24%	36%	20%	12%	8%
1993	33	7.8	6.1	2	11	16	4	0
				6%	33%	49%	12%	0%
1994	47	1.4	1.3	12	34	1	0	0
				26%	72%	2%	0%	0%

Note: overall average accumulation = 6.6 mm/yr

5.6 Conclusions

Soil losses are observed to be strongly seasonal with rates of surface erosion from upland *bari* being one to two orders of magnitude higher in the pre-monsoon season than in the monsoon season. High annual rates of erosion (up to 40 t/ha) are due primarily to a lack of surface cover during the pre-monsoon when high-intensity rains may fall on newly-cultivated sloping fields due to unfortunate timing. The high nutrient content of soils during this season means that the seasonal change in nutrient loss is proportionally higher than the change in soil loss.

Soil characteristics influence erosion at the plot scale through two mechanisms. For a given storm, they determine the rate of runoff which directly affects the soil's rate of erosion. If the surface is exposed, they determine the soil's erodibility in relation to rainfall intensity. Thresholds of I_{10} =30 mm/h and C_R = 5 to 10% were observed below which surface erosion rarely occurs. Above this I_{10} threshold, soil loss increases with I_{10}.

There is little evidence of seasonal changes in rainfall characteristics sufficient to cause observed seasonal changes in erosion and sediment regimes. In particular, high-intensity rainfall occurs during all seasons within the study period. Higher volume rainfall occurred more often during the monsoon season. The likelihood of heavy rainfall falling on dry ground is measurably higher in the pre-monsoon season and this may contribute to the higher erosion regime of the pre-monsoon season. When coupled with spatial variability in surface condition, rainfall spatial variability can result in significantly different sediment regimes over spatial scales smaller than 500 ha.

Degraded land with a year-round lack of surface cover (and often gullied) experiences an elevated rate of erosion due to rain in every season. Because these soil losses have little nutrient value, these losses are of greatest concern for downstream sedimentation rather than the farming system.

Indigenous management techniques are their most effective at low and intermediate flows. The indigenous irrigation system captures a significant portion of storm runoff during the pre-monsoon season, thereby capturing a large amount of soil eroded from upland fields. However, they are also vulnerable as the pre-monsoon losses indicate. The limited surface erosion from *bari* during the monsoon season when rainfall is equally intense illustrates the potential effectiveness of indigenous management in these environments.

Spatial and temporal variabilities place constraints on monitoring for erosion and sediment transport studies. Temporally and spatially, surface erodibility and rainfall erosivity operate simultaneously and show interactions. Within basins of 10 000 ha in size, monitoring resolution can be important over spatial scales from 100-1000 ha, to 0.01 ha. Within an annual period, monitoring resolution can be important over time periods of the season and the single event.

These conclusions relate to the normal-regime behaviour of these basins. During the three-year period of study, heavy rainfall with significant erosivity occurred - including one event which may have been a 10-year storm event over 5 km^2 - but absent were events sufficient in magnitude to destabilise these sediment regimes (*e.g.*, deep-seated landsliding). Regardless, the conclusions suggest specific management recommendations germane to the normal-regime behaviour. Recommendations for management are discussed in Chapter 9 following the presentation of sediment budgets.

6. Signatures of Erosional Sources and Sediment-Transport Behaviour in the Physical and Chemical Character and the Patterns of Movement of Suspended Sediments

6.1 Introduction

In this chapter, suspended-sediment behaviour is examined in the context of both its behaviour during floods and of the physical and chemical character of the sediment itself. The examination of suspended sediment as a simple, single quantity masks important differences in how its concentration and composition are shaped by the range of controls. Sediment properties serve as sensitive indicators able to reveal a wider range of controls. Controls are generalised in relation to supply and transport limitations. Strengths and weaknesses of the sediment rating curve technique for prediction are identified.

Three analyses are presented. An analysis of hysteresis provides further evidence of source and transport controls. Rating curves for individual particle-size classes are developed, illustrating the contrasting behaviours of separate size fractions. Sediment colour and phosphorus content are used as fingerprints to trace the origin of suspended sediment and relate this information to the conclusions reached regarding hysteresis and particle-size behaviour.

6.2 Research Background

In all basins, sediment supply and the competence of transport mechanisms interact through time and space to yield a sediment regime. Chapter 5 showed how bulk behaviour changes as a function of specific controls. The exponent (b) and coefficient (a) of the power-law relation ($C=aQ^b$; C - suspended sediment concentration; Q - discharge) were used to discuss the effect of transport and supply limitations respectively.

Patterns of hysteresis also reflect supply and transport limitations but their sensitivity is far greater than that of composite rating curves. And these patterns can be examined over various spatial and temporal scales to investigate embedded regime controls. Particle-size controls on sediment yield are important yet poorly studied. Clay, silt, and sand behave in contrasting ways and reveal patterns which can also be linked to supply and transport concerns and related to hysteresis. And, finally, sediment properties can be used as tracers to further identify dominant controls, especially where interactions are occurring.

This section reviews existing research findings relevant to these three areas - hysteresis, particle size, and tracers.

6.2.1 Hysteresis

Hysteresis in suspended-sediment transport is used to indicate departures from a direct relation between discharge and sediment concentration. Hysteresis can impair predictive ability because the assumption of simple C-Q relations may lead to variously biased predictions. Fortunately, when multiple controls are operating in complex ways on suspended sediment, the presence of hysteresis can actually help to enhance understanding of sediment sources and dynamics. The term hysteresis is normally applied to the event or synoptic scale. Seasonal and annual changes are generally termed rating "shifts". The remainder of this discussion refers to the event and synoptic timescales.

Many authors have observed hysteresis (Johnson 1942; Heidel 1956; Walling and Teed 1971; Walling 1974; Wood 1977; Paustian and Beschta 1979; Bogen 1980; van Sickle and Beschta 1983; Sidle and Campbell 1985) and generally attribute the phenomenon to the following primary factors:

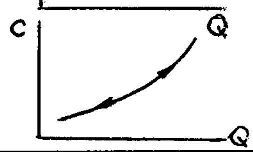
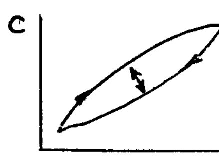
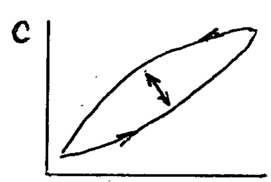
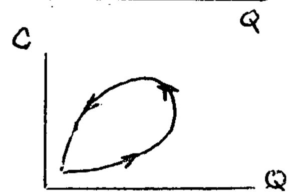
- supply exhaustion
- supply thresholds
- kinematic effects (*e.g.*: lag time, source variability)

These controls dominate differentially through time and space and, in some instances, their effects are scale embedded. Since most basins are supply limited (Einstein 1943), supply-related controls are most often cited.

Conceptual models of hysteretic behaviour have been presented by several authors in terms of

C-Q graphs (Olive and Rieger 1985; Williams 1989; Nistor 1996) and all include both primary and secondary behaviours. Table 6.1 presents a summary of primary hysteretic behaviour and its dominant controls. A wide variety of more complex behaviour is found in basins due to the superposition and sequencing of these primary behaviours (Williams 1989; Nistor 1996).

Table 6.1 Theoretical models of primary hysteretic behaviour.

Regime Behaviour	Graphical Representation	Explanation of Controls
Single Line		**Unlimited supply**
Straight		Transport is the only significant control.
Curved		Curved line suggests the presence of thresholds for new supplies or for the transport of specific particle-size classes.
Clockwise Loop		**Supply exhaustion important** *Width of loop indicates extent of supply exhaustion.*
Synchronous peaks (variable loop width)		Transport is the major control. Wide loop indicates high short-term sediment availability on rising limb.
Nonsynchronous peaks (wide loop)		Relative importance of transport as a control declines due to severe sediment exhaustion.
Counterclockwise Loop		**Supply threshold and/or spatial variability**
Synchronous peaks (variable loop width)		Transport is a strong control; some supply exhaustion present. *Width of loop represents extent of source creation (e.g., discharge-induced supply)*
Nonsynchronous peaks (wide loop)		Relative importance of transport declines due to delayed sediment pulse: travel time of sediment wave, or rainfall-runoff variability causing late sediment production.

Single C-Q lines generally reflect unlimited sediment supply, suggesting that transport capability is the dominant control on suspended sediment concentration. If the line is straight, then the effect of discharge is equal throughout the event and supplies are likely indeed unlimited. If the line is curved (Williams 1989), then supplies may be sensitive to discharge, perhaps reflecting the presence of a supply threshold. For example, above a threshold discharge, coarser sediment may be accessed in the channel margins resulting in an increase in the slope of the C-Q relation.

Supply exhaustion causes sediment production to drop in advance of the decline in transport capacity resulting in "clockwise-loop hysteresis". Exhaustion can occur within event and sub-event timescales (Wood 1977; Olive and Rieger 1985) through sub-seasonal (Walling and Teed 1971; Walling and Webb 1982; Beschta 1978), seasonal (Paustian and Beschta 1979; Bogen 1980; Tropeano 1991) and annual (Brown and Krygier 1971; Anderson and Potts 1987) timescales.

Supply exhaustion relative to transport capacity can occur for several reasons. In general, as Williams (1989) points out, a limited supply flushed during the onset of a flood event, or a much larger supply subject to a prolonged event (Wood 1977) can both suffer relative exhaustion. Material deposited on a streambed at the end of one event, can form a sediment supply flushed during the rising stage of the subsequent event, contributing to this effect. In gravel-bed rivers, bed armour can be disturbed during the rising stage creating a short-term (exhaustible) supply of fine sediment with re-armouring occurring at or near the discharge peak (Paustian and Beschta 1979).

The sediment peak does not need to occur in advance of the peak in discharge for clockwise hysteresis to occur. The sole criterion for clockwise loops to occur is that for every Q, C/Q must be higher on the rising limb (Williams 1989). However, if the peaks are temporally separate, this is a good indication that transport is greatly diminished in relative importance compared with the supply control. As Table 6.1 shows, the same principal applies whether or not the sediment peak leads or lags the discharge peak.

Counterclockwise loops may result from kinematic effects involving differential travel time or rainfall/runoff heterogeneity but can also result from a discharge-induced sediment supply. If sediment and discharge peaks are simultaneous and the relation forms a counterclockwise loop, transport remains a strong control with new sediment sources likely induced by the high flow or prolonged rainfall. For instance, Kung and Chiang (1977) studied 5- to 40-km long streams in the rolling loess area of China's Yellow River and found sediment concentration to peak after discharge due to prolonged soil erosion and to taper off slowly following peak discharge (in Williams 1989). Prolonged rainfall on unstable slopes can heighten pore-water pressures and cause widespread slope failures at or beyond the time of maximum discharge in a basin flood event. In some systems, sediment supplies at channel margins may be accessible only during high flow (Nistor 1996).

If the peaks are not simultaneous and counterclockwise behaviour occurs, then transport is diminished in relative importance in controlling the sediment regime. Source control related to spatial effects may become the dominant cause of hysteretic behaviour. A difference in travel time of the water and sediment waves for events in which rainfall is isolated over a distant part of the basin causes there to be a lag time in the arrival of peak sediment concentration. Heidel (1956) termed this "time-of-lead". In basins with spatially-diverse sediment sources subject to localised rainfall, desynchronised tributary inflow can result in high sediment concentrations arriving in the main stem during falling stage. For instance, Tropeano (1991) calculated that 30 to 50% of total input into the main stem of a 9.51-km^2 basin in Northwestern Italy derived from a 0.75-km^2 basin dominated by bare surfaces, representing only 8% of the larger basin's area. The effect is greatest in mid-sized basins: the effect is less likely as basin size becomes small and as basin size becomes large, the effect is lost.

The basic behaviours and causes outlined in Table 6.1 and discussed above can be combined to yield other, more complex models. "Figure-eight" behaviour (Arnborg *et al.* 1967; Williams 1989; Nistor 1996) results from sediment exhaustion during the rising stage of an event followed by sediment replenishment. Olive and Rieger (1985) found that in events with multiple peaks, the sediment peaks decreased successively to the point that the final peaks sometimes showed no sediment response. These combined behaviours can become so intractable that sediment response appears random: Olive and Rieger (1985) examined 39 storm hydrographs in Australia and found "an apparently random" response with "no identifiable pattern observed" to be by far the most common sediment response, occurring in almost half (16) of the events studied.

The stratification of sediment rating curves on the basis of stage (rising-limb versus falling-limb) is a useful approach for identifying hysteretic behaviour if it operates consistently throughout a specific period (Walling 1978; Tropeano 1991). Supply limitations generally result in a difference between the two relations. Unfortunately, the lack of a difference between rising-stage and falling-stage behaviour does not confirm a lack of hysteresis. As implied in the above discussion, the direction of hysteretic behaviour can quickly reverse (even within a single event) due to changing supply and transport limitations with discharge causing a "null result" in the overall stage-stratified rating curve. Such contrasting hysteretic behaviour increases the variance of the sediment-discharge relation.

6.2.2 Particle-size behaviour

The patterns of sediment yield studied in Chapter 5 were the net result of several systems operating simultaneously. These systems are governed by different particle-size classes which show distinctly different source and transport behaviour. More can be learned about the system under study if the size fractions are considered individually.

Geomorphologists and hydrologists have traditionally emphasised measurements of total suspended sediment, ignoring both its physical and chemical characteristics. Sediment properties have a strong influence on entrainment and transport and are of environmental importance. In particular, chemical characteristics of suspended sediment are strongly influenced by particle-size distribution which in turn is determined by source and transport controls.

In contrast to geomorphological approaches, agricultural approaches to studying particle-size effects in basin sediment yield have generally been concerned with clarifying nutrient loss. Geomorphologists have shown a greater interest in sediment quantity while agriculturalists have emphasised sediment quality. Further, the geomorphological research has emphasised stream suspended sediment and the agriculturalists' measurements have been based on individual fields or plots. Sutherland and Bryan (1989) pointed out that little work has been done linking the findings from the hillslope to those of the stream. Results from the two approaches offer useful, complementary information about the importance of particle-size and are combined in the following discussion.

Particle-size characteristics exercise a strong control on initial entrainment and continued suspension of river sediment. In gravel-bed rivers, flux concentration of the largest fractions is strongly affected by transport constraints (flow velocity) whereas transport of the finest sediment (clay) is completely unaffected. Every fraction is influenced by the size characteristics of the sediment supply. It is within the fine-fraction size distribution (less than 2 mm) where the greatest change occurs in how sediment responds to the supply and transport limitations discussed in the previous section (Hjulstrom 1935).

Sundborg (1967) presents a modification of Hjulstrom's curve (Hjulstrom 1935) showing the relation between flow velocity (one metre from the stream bed), grain size and its state of movement for uniform material (specific gravity = 2.65). From this diagram, four classes of fine-sediment transport can be defined according to particle size:

Clay (<0.002 mm)

- minor velocities entrain particles unless highly cohesive
- particles remain in suspension regardless of flow velocity

Silt (0.002 to 0.063mm)

- minor velocities entrain particles; begin to see evidence of threshold velocity for entrainment

- once entrained, particles generally remain suspended though coarser silts (0.010 to 0.063mm) show a very weak tendency to deposit at low velocities

Fine Sand (0.063 to 0.180mm)

- transition between washload-dominated and traction-dominated transport
- threshold velocity required for initial entrainment
- the tendency to deposit increases rapidly with particle size

Coarse Sand (0.180 to 2.000mm)

- particles are entrained and remain in suspension with only significant flow velocities (0.3 to 0.5 m/s); may move in traction

With heterogeneous particles, lithology, and bed configurations, thresholds vary but the basic distinction between washload-dominated movement of the clay and silt and the energy-dominated motion of the fine and coarse sands remains. The 0.180-mm breakpoint between fine and coarse sand is consistent with the lower limit to traction-phase movement in rivers (Church, personal communication).

Under energy-dominated motion, transport constraints dominate in shaping suspended-sediment concentrations. In non-episodic events, Hamlett *et al.* (1987) observed a coarsening of suspended sediment with flow in five nested agricultural basins (5 to 5055 ha) in east-central Iowa. This coarsening was partly attributed to the increased transport competence of the stream; as flow increases, thresholds are crossed for the movement of sand-sized particles thereby altering the overall sediment regime markedly. Nordin (1963) studied sand-bed rivers with extreme concentrations of suspended sediment (greater than 300 g/l), 1/3 to 2/3 of which was sand. Once hydraulic conditions were conducive to the suspension of sand particles, sand quickly came to dominate in the overall sediment distribution to the point that fluid properties changed so predictive relations were unavailable. Most work on the mobility of different size fractions has been in gravels due to the weaker discrimination in the fine fraction (Church, personal communication).

In contrast, the suspended concentration of clay and silt is largely unaffected by flow competence. Once entrained these particle sizes remain suspended even at low flow velocities. Peart and Walling (1982) found the particle size of suspended sediment to be insensitive to discharge in the River Dart - this may be due to the dominance of silt and clay in the material available for transport within the range of events considered. Griffiths (1981) found the lower range of sediment rating curves (of rivers in New Zealand) to be insensitive to discharge; in this flow range, transport capacity did not meet threshold requirements for sand transport hence washload was controlled by source characteristics alone. It remains useful to discriminate between clay and silt because clay shows no influence of discharge whereas behaviour within the silt range may vary greatly between the fine and coarse silts.

The above discussion illustrates that source constraints affect the suspended concentration of *all* particle-size classes. If it is not available for transport, it won't be transported regardless of flow competence (Stone and Saunderson 1992). Climate, geology, soils, and landuse which Walling and Moorehead (1987) list as controlling factors on the particle size of suspended sediment are all source effects because they determine sediment availability. Smith and Olyphant (1994) found that rainfall intensities (>60 mm/h) caused the imbricated bed to be disturbed, releasing coarse sediment, resulting in this material dominating the sediment regime for episodic events in contrast to normal-regime events. The change in sediment supply resulting from the change in flow competence indicates the difficulty in disentangling source and transport effects, especially in supply-limited basins. Apparently contradictory trends can result: Walling and Moorehead (1989) found sand content to decrease and clay content to increase at the highest flows in the River Dart. Fleming and Poodle (1970) presented sediment results from Scottish rivers and recommended that sediment-yield models incorporate consideration for sediment supply-rate and particle-size distribution alongside the standard use of discharge.

Walling and Moorehead (1989) stress the importance of particle aggregation to suspended-sediment analyses. If particles are aggregated, they may behave differently than the "ultimate" particle-size distribution would suggest. Higher clay and organic-matter contents both tend to increase the effective particle size (Walling and Moorehead 1989). In looking at the transport of separate size fractions in ephemeral gullies, Duncan *et al.* (1987) left intact the naturally-occurring aggregates since they behave like single particles in terms of settling in the streams. The ultimate particle size draws attention to the source whereas the effective particle size places emphasis on transport constraints. This has influenced research because geomorphologists (*e.g.*, Bogen 1992 and Fenn and Gomez 1989) have tended to focus on ultimate particle size while agriculturalists (*e.g.*, Foster *et al.* 1985, Foster *et al.* 1992, and Hamlett *et al.* 1987) have looked at **both** effective and ultimate particle sizes (Sutherland and Bryan 1989). Foster *et al.* (1985) found that only 25% of suspended clay was delivered as clay with the remainder transported as part of larger aggregates. They state that the type of clay also influences the amount of silt-sized aggregates. Specifically, the quantity of silt-sized aggregates is greater with swelling clays than non-swelling clays. However, Foster *et al.* (1992) carried out a detailed evaluation of ultimate and effective particle sizes of aggregates in streamwater and dispersant and found no significant differences between them. Walling and Moorehead (1989) point out that aggregate stability of eroded soil in the field should also affect the level of aggregation present in the suspended sediment (unless the salinity is low).

Source and transport constraints on the individual particle-size classes vary through time and space yielding complex net sediment regimes. Foster *et al.* (1985) found little selectivity in detachment from steep (20%) plots, concluding that preferential output sorting comes off-field as a result of transport and deposition processes. In fact, Lal (1976, in Walling and Moorehead 1989) found that enrichment of silt and clay at the field scale depends on the slope of the field; enrichment is always non-negative and reaches zero above a certain plot steepness and is also influenced by the landuse within the field. Young and Onstad (1978) examined the relative contribution from rill and inter-rill areas in small plots (1.5 m x 4.5 m). They found inter-rill erosion to be dominated by splash erosion which generates bigger aggregates (higher sand content) and better represents the field soil texture. In contrast, the rill material is more selective and consequently "enriched" with clay and silt. Predictably, as the plot slope was increased, the relative contribution from the inter-rill area also increased (Lal 1976). Luk *et al.* (1993) reached a similar conclusion from a larger plot (18 x 35 m) on a gentle piedmont slope near Tombstone, Arizona. Rhoton *et al.* (1979) found preferential transport of clay from the soil surface of Alfisols in basins (0.3-3.2 ha) in Ohio. As spatial scale increases, source and transport constraints change.

Various researchers have observed temporal changes in the particle size of suspended sediment. Fenn and Gomez (1989) examined the Glacier de Tsidjoire Nouve in Switzerland and found that the proglacial zone acts as a source during the rising limb and a sink during the falling limb. Ongley *et al.* (1981) found systematic seasonal changes in rivers in Ontario as sand disappears after the spring runoff, with clay-sized sediment occupying more than 80% of summer and fall samples. Bogen (1992) observed seasonal shifts and cautions that sampling frequency must be adequate to address short-term variability.

Geochemical analyses of suspended sediments and their particle-size distributions leads to conclusions which might be different from those based on total concentration alone. For instance, in developing predictive equations for nutrient output from agricultural basins, Foster *et al.* (1985) combined typical surface area estimates for sand (0.05 m^2/g), silt (4 m^2/g), clay (20-800 m^2/g) and organic matter (1000 m^2/g) to their particle-size predictions showing the disproportionate contribution to basin nutrient yield by small events. This relation also means that conservation activities which reduce basin sediment yield do not necessarily modify basin nutrient yield in a comparable manner (Young *et al.* 1986). Walling and Moorehead (1989) point out that mineralogy of suspended material can also change with particle size.

Individual particle-size classes can also be expected to show hysteretic behaviour. The discussion of source and transport controls on hysteresis presented in the last section applies equally well to separate particle sizes. Bogen (1992) stated that hysteresis was observed in his measurements of Norwegian Rivers. Very little is present on this in the literature. If the nutrient content of suspended sediment demonstrates hysteretic behaviour, it is likely that hysteresis in particle-size output is the main cause.

Nutrient output - perhaps the most important consideration in agricultural basins - is greatly influenced by particle-size controls. The clay and fine-silt fractions of the suspended-sediment load carry most economically-important nutrients from a basin. Any processes which concentrate these finer fractions beyond what is found in surface soils is important to agricultural nutrient budgets. Peart and Walling (1982) used the expressions preferential erosion and preferential deposition and suggested that these factors bring about a finer sediment than the source material. Young *et al.* (1986) termed this "enrichment" and applied this concept to each of the macronutrients. Ongley *et al.* (1981) who looked at the geochemistry of suspended sediment from a geomorphological perspective found little difference in nutrient content of sediment between nearby stations in Southern Ontario, but found substantial seasonal shifts.

The array of controls on supply and transport of suspended sediment and the complex interactions which can result, have led to the use of tracers to track the origin and movement of captured sediment. If the particle size of available sediment sources shows distinctive differences then particle size can, for example, be used to help trace the origin of suspended sediment (Walling and Kane 1984). A wide variety of techniques and sediment characteristics has been used as tracers and this is the subject of the next section.

6.2.3 Fingerprinting

Sediment fingerprinting and tracing techniques are useful diagnostic tools in supply-limited basins. They are an effective complement to the sediment-rating-curve method which is successful strictly under only transport-limited conditions. Techniques vary from the introduction and tracing of artificial particles to the tracking of naturally-occurring particles with distinguishing characteristics or "fingerprints" (Walling and Kane 1984). Other approaches involve the modification of particles already occurring within the basin, essentially creating a fingerprint for those particles. The usefulness of these techniques and the choice for a given application depend on the calibre of the sediment under study and on the specific opportunities present in the basin. The tracing of introduced particles (using radioactivity, glass, surface adsorption, and fluorescence) encounters many difficulties as explained by Coakley and Long (1990) and will not be discussed further in this section. Fingerprinting techniques can be readily distinguished according to the particle size under study and their description forms the remainder of this discussion.

Radioactivity, magnetism, elemental composition, mineralogy and lithology, fluorescence and colour, and miscellaneous chemical and physical characteristics have all been exploited as natural sediment signatures. Because effects are often confounded, it is useful to monitor multiple fingerprints to exclude competing hypotheses (Walling and Kane 1984; Peart and Walling 1986). Typically only a small selection of possibilities is present within a given basin.

The movement of coarse particles (pebbles, cobbles and boulders) has been determined by deliberately marking a volume of natural sediment to facilitate its recapture. Techniques include radioactivity, magnetism, and various visual clues. Magnetism offers, perhaps, the greatest potential for tracing the movement of coarse sediment. Hassan *et al.* (1984) placed ceramic magnets inside pebbles and cobbles in the channel of Nahal Hebron and had a 93% recovery rate after two events. They also reviewed a collection of related approaches: iron oxide coatings, metal strips attached to the particles, and enhancing natural magnetism through high-level heating of naturally-iron-rich fluvial particles. Radioactivity is prohibitive to exploit with large sediment due to security and safety difficulties. Visual markers such as paint, fluorescence, and exotic lithology (Katsumasa *et al.* 1969; Brown and Brubaker 1979) all suffer from retrieval difficulties since the particles must physically be seen.

Mineralogy is a common characteristic used as a sediment fingerprint (Packham 1960; Lund *et al.* 1972; Klages and Hsieh 1975; Wall and Wilding 1976; Walling *et al.* 1979; Ongley 1982). Moore (1961) analysed the mineralogy of bottom sediments from Lake Michigan to determine their source material and post-glacial history. Klages and Hsieh (1975) examine the mineralogy of suspended sediment in a mountain river and its tributaries in southwestern Montana to assess the ability of this fingerprinting technique to discriminate between potential sediment sources using variable and distinctive geology present within sub-basins. They were able to relate distinctive sediment mineralogy to the contrasting lithology of the studied sub-basins. The technique was more successful in smaller basins where the number of sediment sources was small and there was only a short distance between sampling points. Wall and Wilding (1976) contrast the mineralogy of suspended sediments of Maumee River in Ohio with that of the two dominant sediment sources - surface soils and unweathered parent material. Differential weathering of these sources has resulted in a contrasting mineralogy which was used to conclude that the annual suspended sediment yield of the Maumee River and its tributaries is dominantly surficial in origin. Unfortunately, the dominant sediment sources do not always possess contrasting and distinctive mineralogy. For instance, Lund *et al.* (1972) found no difference in the mineralogy of the clay fraction of suspended sediment in rivers within 13 basins in Indiana regardless of the point of sampling suggesting that clay mineralogy would be unsuccessful in isolating source contributions.

Chemical properties have also been successfully used to identify the source of suspended sediment. For example, elemental composition has provided some researchers with a useful sediment fingerprint (Ongley 1982; Walling and Kane 1984; Peart and Walling 1986). The field of geochemical prospecting exploits the chemical composition of stream sediments in seeking mineral deposits. Ongley (1982) found little variation in mineralogy over a complete year but, in contrast, found that concentrations of major elements were closely related to sediment source. The use of elemental composition as a fingerprint can facilitate the determination of specific nutrient budgets - the ultimate concern in many agricultural basins. Ongley (1982) reported that the proportion of sediment-associated phosphorus to total-phosphorus varies from 78 to 95% in a variety of fluvial settings revealing the usefulness of such elemental suspended-sediment budgets. Temporal variation in sediment geochemistry (Walling and Kane 1982) can be extreme causing difficulties in implementing this approach.

Walling and Kane (1984) suggested that Cesium-137, originating as fallout from atmospheric testing of nuclear weapons, would be a successful fingerprint if used in conjunction with particle size of source and suspended material. Loughran *et al.* (1986) used this technique to quantify sediment-source contributions within a small Australian basin. Cation-exchange capacity, percent organic matter (Wall and Wilding 1976), and bee pollen (Brown 1985) have also been used as fingerprints.

Physical properties used in fingerprinting include particle size, magnetism, and colour. Several researchers have noted that where sources possess contrasting particle-size distributions, texture can be used effectively as a fingerprint (Ongley 1982; Walling and Kane 1984; East 1985; Fenn and Gomez 1989; Stone and Saunderson 1992). Walling *et al.* (1979) used magnetic properties resulting from the natural transformation of iron compounds to differentiate sediment sources.

Grimshaw and Lewin (1980) observed distinct zoning of colours on the sediment rating curves and during individual events. They explained that sediment colour corresponds with source type: brown sediments correspond to surface soils whereas grey sediments represent contributions from material directly eroded by the river; mixtures were also present in their samples. They also pointed out that colour alone is only a coarse filter and that further mineralogical analysis may be necessary to distinguish between surface-soil and regolith contributions.

It is clear that there exists considerable potential for the fingerprinting technique to identify sediment sources and be a useful addition to basin sediment-budget efforts. However, its reliability drops when diverse sediment sources are present, especially in large basins under widespread, prolonged rainfall. For example, Coakley and Long (1990) concluded that fingerprinting techniques are inappropriate to study the movement of glacially-derived sediment along the Great Lakes shoreline because of the lack of distinction of these sediment sources. Peart and Walling (1986) pointed to some related unresolved concerns: enrichment in fines and organic material relative to source material; transformation of properties within the fluvial system; and storage and remobilisation within a conveyance system. Symader and Strunk (1992) used multivariate analysis to compensate for the loss of discriminating power of suspended particle characteristics when many sources are involved. They stressed the use of multiple clues to eliminate competing hypotheses: hydrograph dynamics, contrasting source availability during different high-flow events, and chemical characteristics of suspended material. They pointed out that if reference source material is used to test the conclusion, the sampled material must truly represent the condition of the source material when it was originally eroded. Despite these concerns and limitations, Walling and Kane (1984) stress the importance of integrating sediment properties and the fingerprinting technique into geomorphological research since only a small proportion of the wide range of possibilities has as yet been tried.

6.3 Hysteresis

In the present study, a wide range in hysteretic behaviours is possible because of the widely contrasting spatial and temporal scales under study. Since hysteresis has been defined as a synoptic phenomenon, this section begins with an examination of the types of hysteresis that occur during single flood events. Patterns observed are related to the relevant landuse and spatial and temporal scales of the basins under consideration. The second section asks whether evidence of hysteresis persists within seasonal ratings.

6.3.1 Single events

For the single-event analysis, a standard method is needed to classify sediment behaviour of C-Q graphs. The only flood events considered are those for which: at least three sediment samples are available, the peak flow is non-trivial and there is at least one sample available on each limb. In total, this includes 141 events.

To identify the presence of hysteresis two steps have been followed:

1) Designate hysteresis type

Initially it is assumed that the sample points in the C-Q graph are all known without error. Each C-Q graph is designated as one of four types - single-value (SV), clockwise (CW), counterclockwise (CCW), or complex (CO). Hysteresis is not present in a single-value (SV) C-Q graph: the C values are equivalent on both limbs. Relative to the SV graph, two types of class limits are observed in the C-Q graphs available. In the first, the sample points form a coherent loop with little or no overlap. If the maximum width of the loop is narrower than 50% of the C value at that point, then the C-Q graph is SV; otherwise, it is CW or CCW depending on the direction of the loop. Other C-Q graphs show apparently random fluctuations around a single-value line ("eyeball fit"). Departures are acceptable, but if there are three of them of at least 100% of C (the expected value) then the C-Q graph is termed complex (CO). If a C-Q graph contains SV behaviour as well as either CW (or CCW), then the C-Q graph is considered to be CW (or CCW).

2) Identify reliability of designation

Distinguish between Class A and Class B C-Q graphs. If one sample is removed from a C-Q graph and the result is unknown or changes, then it is a Class B graph (*i.e.*, designation depends on only one sample). Class B examples do not provide as reliable an indication of hysteresis patterns as Class A C-Q graphs which, by implication, contain at least two samples on each limb. In addition, if the removal of one sample point renders the C-Q graph SV, then it is considered SV.

Using these criteria, the total of 141 C-Q graphs have been analysed for hysteresis according to scale and season yielding 91 Class A and 50 Class B examples as summarised in Table 6.2. Selected graphs corresponding to the three spatial scales in Table 6.3 are presented here for detailed discussion.

Table 6.2 Classes of sediment behaviour observed in C-Q graphs.

St		Class	Σ	SV				CW				CCW				CO
Name	No			Σ	P	T	M	Σ	P	T	M	Σ	P	T	M	
Kukhuri	10	A	5	3	0	0	3	0	0	0	0	0	0	0	0	2
		B	11	8	1	1	6	1	0	1	0	2	2	0	0	0
Upper Andheri	9	A	2	0	0	0	0	2	0	1	1	0	0	0	0	0
		B	5	5	2	1	2	0	0	0	0	0	0	0	0	0
Dhap	3	A	21	11	1	4	6	3	1	0	2	7	3	0	4	0
		B	3	2	0	1	1	0	0	0	0	1	1	0	0	0
Lower Andheri	2	A	21	10	5	1	4	4	1	1	2	6	4	1	1	1
		B	12	2	1	0	1	6	2	1	3	4	3	0	1	0
Jhikhu	1	A	42	16	1	0	15	17	2	4	11	5	2	1	2	4
		B	19	10	7	0	3	3	0	1	2	6	2	0	4	0

CW=Clockwise; CCW=Counterclockwise; SV=Single-value; CO=Complex;
P=Pre-monsoon; T=Transition; M=Monsoon; See text for explanation of Classes A and B.

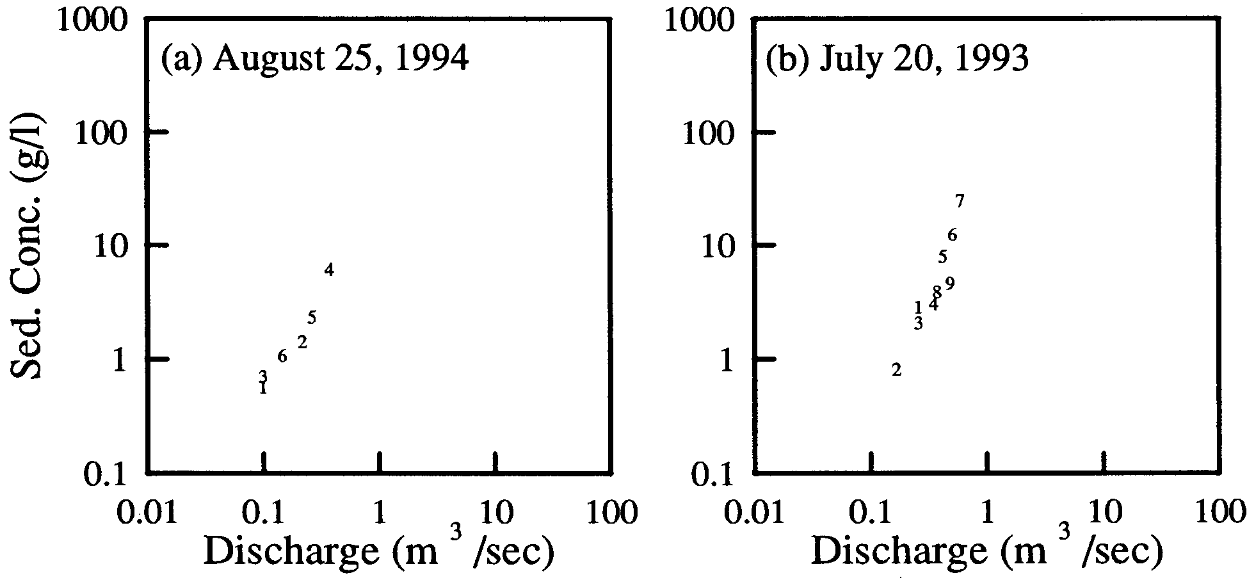
Headwater basins (1 km^2)

Events within the low-order basins (9, 10) consistently show a synchronised peak response of flow and sediment indicating a persistent dominance of transport as a control on sediment dynamics. Within these synchronous loops, SV (and in this case, straight-line) relations dominate the observations, particularly during the monsoon season suggesting an unlimited sediment supply (see Figure 6.1). This is consistent with the strong C-Q coupling at this scale identified in section 5.4.

Mid-sized basins (5 km^2)

The mid-sized basins display a wide range of C-Q behaviours. Hysteresis is frequently non-synchronous indicating a reduced dominance of transport as a control. It is at this scale in the pre-monsoon season where CCW loops are most frequently observed. CCW hysteresis can result from differential travel time of sediment and water and may be enhanced by diversion of floodwaters into

Figure 6.1 C-Q relations for events within Kukhuri basin (station 10) illustrating single-value behaviour.



the irrigation system. Figure 6.2 shows a selection of these loops. Loop (a) in the figure provides the best example of CCW hysteresis observed during the entire study and demonstrates the potential difference between the rising and falling limbs of a significant pre-monsoon event (one order of magnitude). Loop (b) occurred on July 17, 1993 during the transition season; this loop reflects the diminishing effect of travel-time as it is approaching a SV relation.

SV relations are common at this scale and can occur in any season. Most of the events included in this class resulted from rainfall which covered the entire basin. These events are indicative of sediment widely available throughout the basin and are most common during the monsoon season (see result in Table 6.2 for Dhap basin).

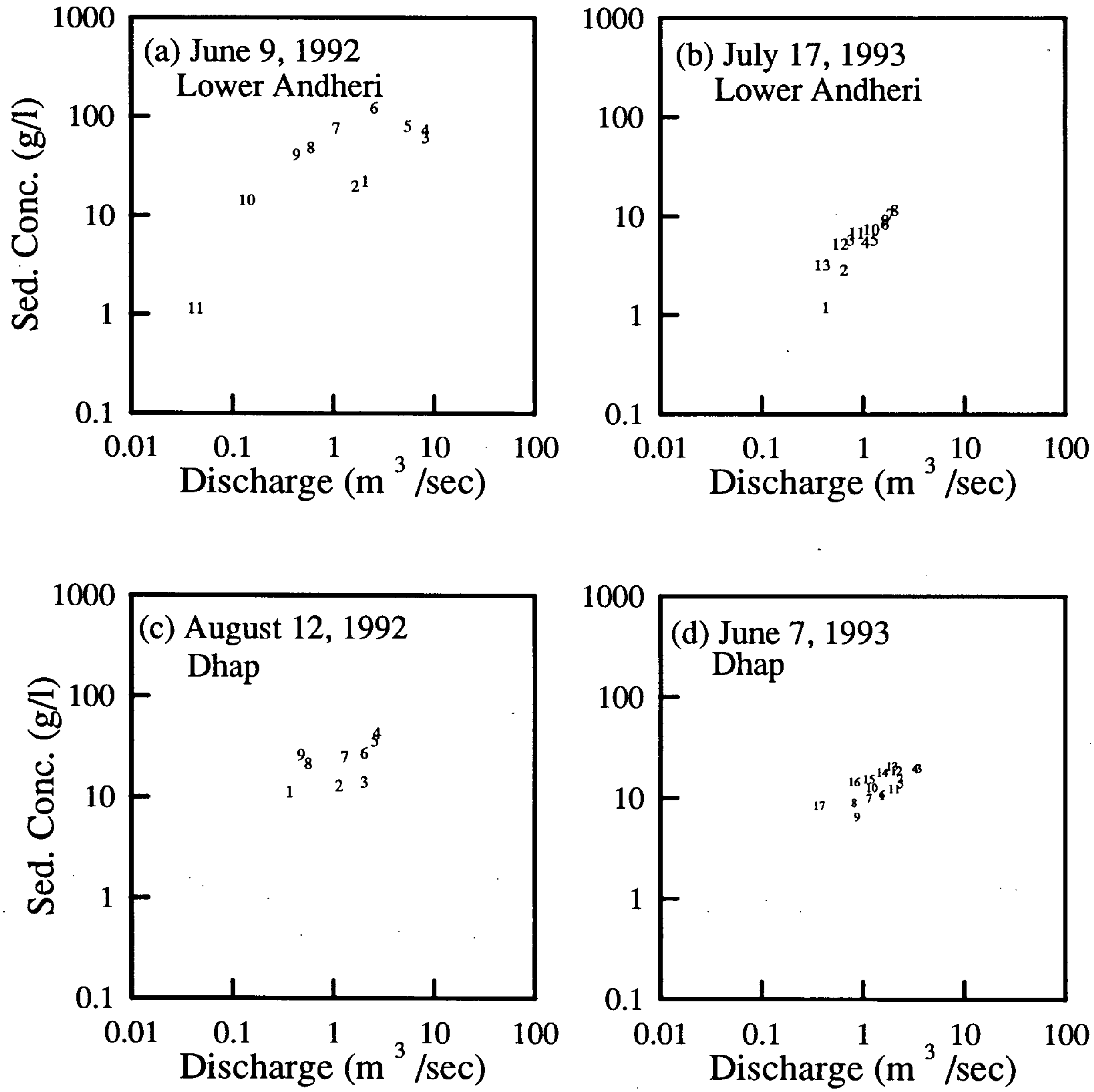
Jhikhu basin (100 km^2)

Events sampled at the Jhikhu station (1) are consistent with the findings from the mid-sized basins. In general, CW and SV relations occur during the monsoon season and CCW loops occur in any season. Because of its size, this station experiences more events annually than any of the others and the high-flow events are more easily sampled than at the other, flashier stations. Hence, a great number of C-Q relations is available for examination.

The five CCW C-Q relations occurred throughout the rainy season. The CCW loops consistently show non-synchronised sediment-water peaks suggesting a pronounced travel-time hysteretic effect. For example, the peaks in flow rate and sediment concentration are separated by over 17 minutes. The CCW hysteresis is consistent with the behaviour evident at Lower Andheri, and emphasises the diminished dominance of transport as compared to characteristics of the sediment supply.

SV relations are common at the Jhikhu station (1) as they are for the mid-sized basins. At this scale, sediment sources are widespread - from tributary basins and remobilisation from storage locations within the large meander bends of this main stem. Most of the SV relations occur during the monsoon season which reflects the fact that storms cover a wider area during the monsoon than they

Figure 6.2 C-Q Relations for events within Andheri Lower basin (2) and Dhap basin (3) illustrating CCW hysteretic behaviour.



generally do during the pre-monsoon season resulting in sediment availability during the full range of the hydrograph.

CW relations appear to be more common at this scale than at the mid-sized basins. Four examples from the Jhikhu basin (1) are shown in Figure 6.3. The 11 Class A events demonstrating CW behaviour are distributed throughout the rainy season though the majority occurs during the monsoon season. In general, CW relations are indicative of a degree of sediment exhaustion taking place during the event. At this large scale, the many controls - often easily isolated at other scales - interact to yield CW hysteresis during any season and for both synchronised and non-synchronised C-Q peaks. The two pre-monsoon CW-loop events are large events for their season indicating that these events were more widespread, thereby mimicking the behaviour of their monsoon counterparts. The great range in loops and wide distribution through the rainy season reminds us that this scale experiences a great deal of what happens locally within the entire basin.

Despite these explainable patterns in C-Q behaviour, there remain C-Q relations which fall outside the standard behaviour. Different types of CO C-Q graphs were observed including figure-eight and step behaviours. Figure 6.4 illustrates step behaviour observed at the Lower Andheri and Jhikhu stations and an additional CO graph from Kukhuri station. CO behaviour can result from differential tributary inflow, measurement limitations, and gully headwall failures alone or combined or from other effects. Notably, as the scale under consideration increases, so too does the opportunity increase for CO C-Q relations to occur.

The detailed C-Q single-event analysis presented in this section suggests that caution should be exercised when generalising supply- and transport-limited behaviour spatially and temporally. Though the results can be explained with sediment-transport theory, generalised statements based on limited data may have little predictive value *for individual events* at the studied spatial scales.

Figure 6.3 C-Q relations for events within Jhikhu basin (station 1) illustrating CW hysteresis behaviour.

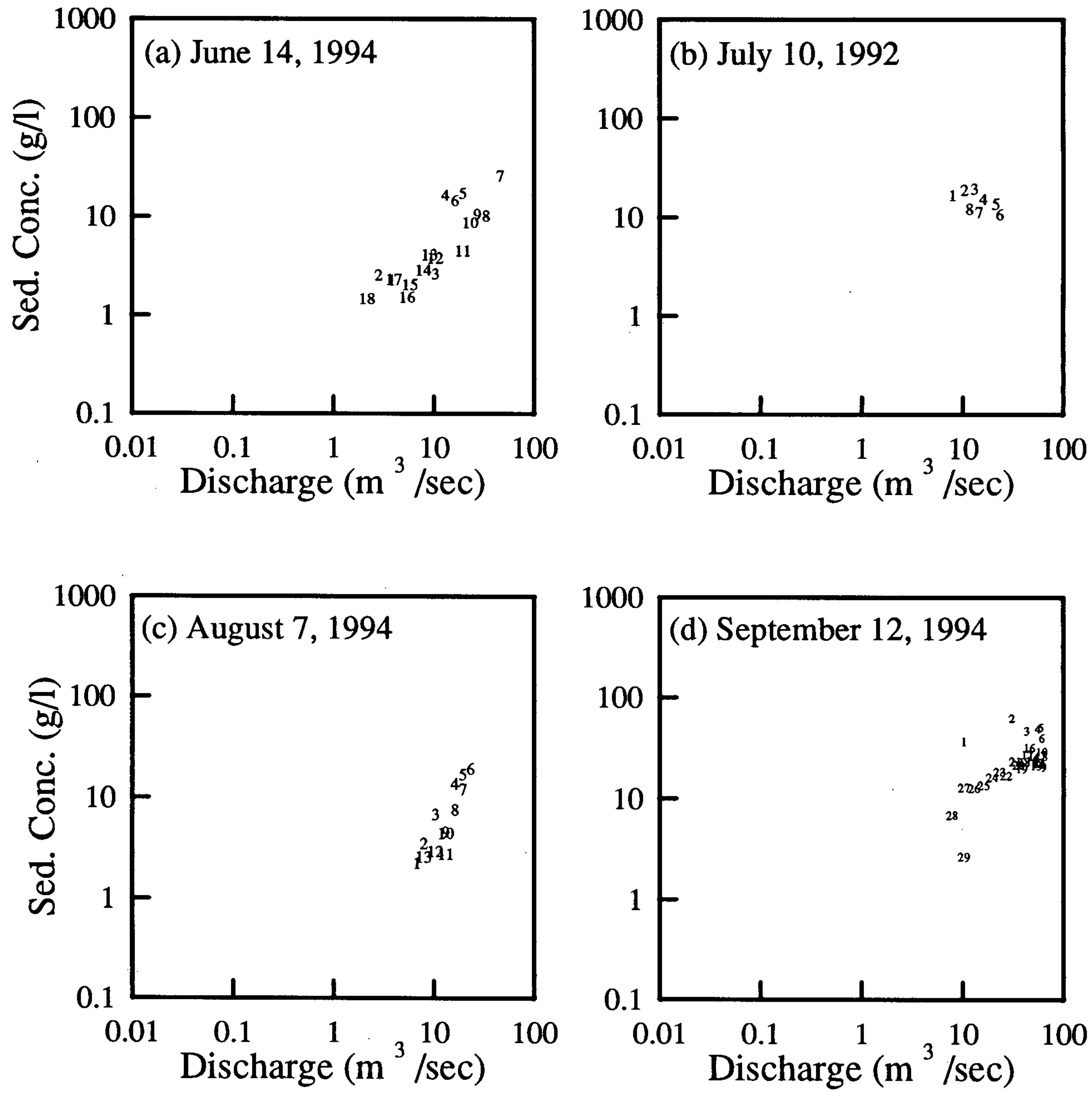


Figure 6.4 CO behaviours: (a)-(c) step CO C-Q behaviour at Jhikhu and Lower Andheri stations, and (d) CO behaviour at Kukhuri station.

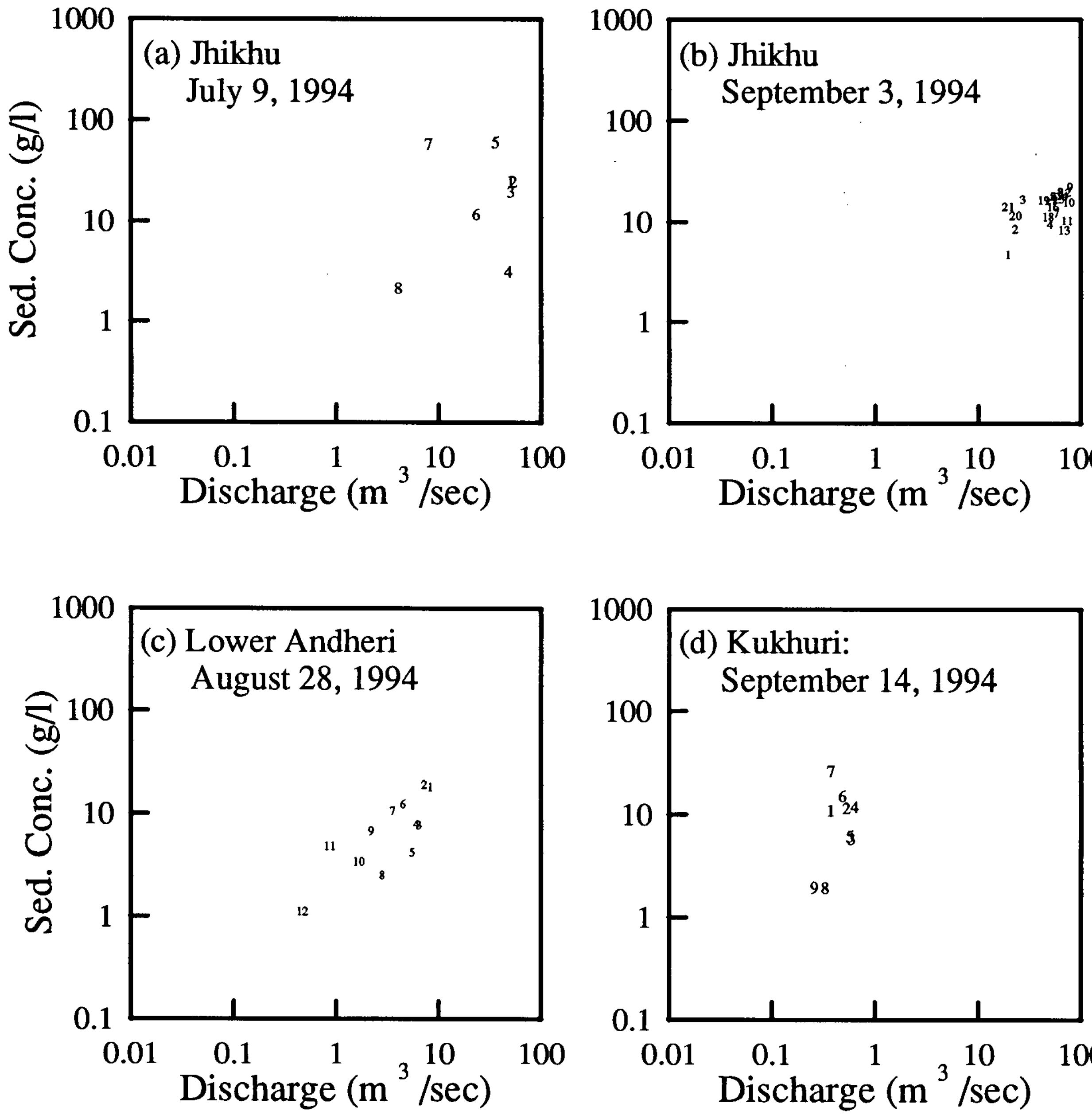


Table 6.3 Seasonal sediment-rating-curve relations derived using log-linear regression (1992-1994, Q known without error) for rising and falling hydrograph limbs.

Station	No.	Season	Stage	a_r	b_r	N	R^2	s_r
Kukhuri	10	P	R	36.2	1.02	8	0.426	0.216
		P	F	31.1	0.933	26	0.254	0.231
		M	R	35.2	1.95	33	0.864	0.0669
		M	F	10.6	1.11	67	0.405	0.232
Upper Andheri	9	P	R	58.3	0.561	6	0.906	0.0231
		P	F	19.0	0.234	18	0.066	0.208
		M	R	8.07	0.363	17	0.112	0.397
		M	F	7.46	0.599	46	0.486	0.139
Lower Andheri	2	P	R	9.92	0.484	42	0.509	0.129
		P	F	13.7	0.654	104	0.651	0.0664
		M	R	3.19	0.653	52	0.624	0.132
		M	F	3.14	0.790	187	0.694	0.0809
Dhap	3	P	R	8.85	0.396	21	0.586	0.0314
		P	F	13.0	0.259	36	0.388	0.0249
		M	R	7.54	0.510	54	0.276	0.127
		M	F	8.62	0.367	65	0.154	0.127
Jhikhu	1	P	R	1.40	0.910	55	0.607	0.0891
		P	F	2.11	0.717	133	0.433	0.0869
		M	R	0.632	0.885	120	0.641	0.0765
		M	F	0.458	0.927	344	0.639	0.0787

R - Rising limb; F - Falling limb; P - Pre-monsoon; M - Monsoon; Relation: $C=a_rQ^{b_r}$, log-transformed
N - sample size; R^2 - correlation coefficient; sr - standard error of the estimate ($\log_{10}$ g/l)

6.3.2 Multiple events

Does the hysteresis identified in the previous section persist in seasonal ratings? To address this question, individual relations are computed for the suspended sediment data for the rising and falling hydrograph limbs. Equations from simple log-linear regression (Table 6.3) are used to compute the functional relations (Table 6.4), following the approach in Chapter 5.

The rising and falling limb relations (defined by b_f and a_f from $C=aQ^b$) of each seasonal pair are contrasted in Figure 6.5 to identify hysteretic persistence. CW hysteresis is suggested if both a_f and b_f trend higher in the rising-limb relation than in the counterpart falling-limb relation with one of

Table 6.4 Seasonal sediment-rating-curve relations derived using functional analysis for rising and falling hydrograph limbs.

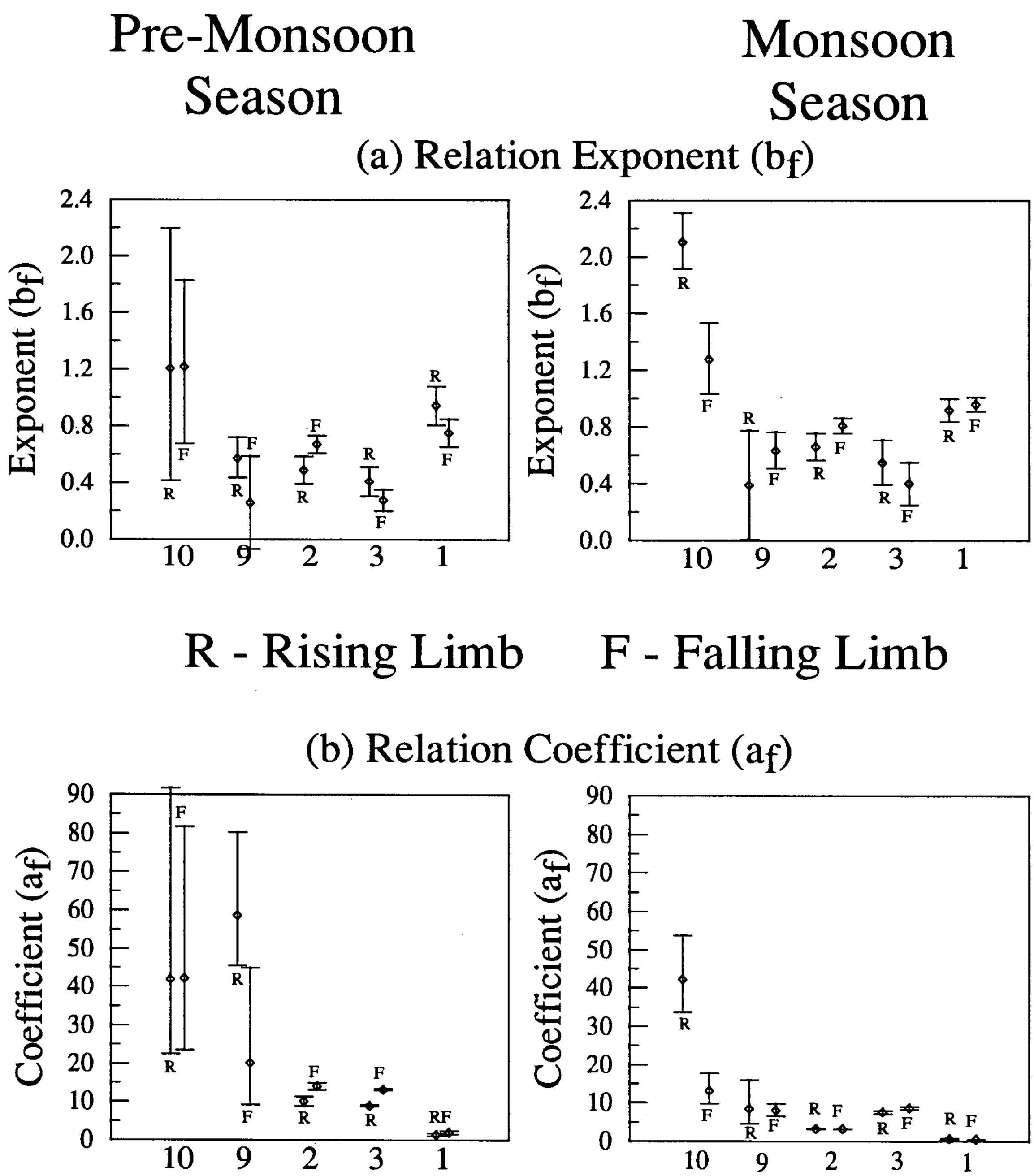
Station		Season	Stage	λ	b_f (slope)		a_f (coefficient)	
Name	No.				expected	range	expected	range
Kukhuri	10	P	R	7.82	1.20	0.415-2.208	41.9	22.5-91.7
		P	F	9.85	1.22	0.675-1.829	42.2	23.5-81.8
		M	R	4.27	2.10	1.92-2.31	42.2	33.7-52.8
		M	F	12.3	1.28	1.03-1.53	13.0	9.71-17.7
Upper Andheri	9	P	R	1.49	0.571	0.435-0.720	59.6	45.5-80.1
		P	F	8.48	0.257	-0.067-0.588	20.0	9.12-44.8
		M	R	15.6	0.389	0.010-0.775	8.43	4.51-15.9
		M	F	6.49	0.634	0.507-0.764	7.90	6.44-9.73
Lower Andheri	2	P	R	17.3	0.490	0.391-0.590	10.0	8.88-11.3
		P	F	8.45	0.671	0.609-0.734	13.9	13.1-14.9
		M	R	18.5	0.662	0.568-0.757	3.18	3.11-3.26
		M	F	11.2	0.809	0.758-0.860	3.15	3.14-3.15
Dhap	3	P	R	3.65	0.408	0.304-0.514	8.83	8.60-9.05
		P	F	1.77	0.275	0.198-0.353	13.1	12.8-13.3
		M	R	9.46	0.548	0.390-0.710	7.43	6.99-7.90
		M	F	9.14	0.399	0.247-0.553	8.54	8.17-8.91
Jhikhu	1	P	R	14.3	0.943	0.809-1.08	1.31	0.971-1.75
		P	F	14.7	0.750	0.654-0.847	1.95	1.56-2.43
		M	R	12.7	0.915	0.834-0.996	0.582	0.466-0.725
		M	F	14.7	0.957	0.907-1.01	0.421	0.367-0.484

R - Rising limb; F - Falling limb; P - pre-monsoon season; M - monsoon season.
Each a_f is calculated by applying its respective b_f to the means of C and Q from each data set ($a_f = C_{mean} - b_f Q_{mean}$). Ranges based on 90% confidence. λ is the ratio of the error variances (E_C^2/E_Q^2).

the rising-limb parameters being *significantly* higher than its falling-limb counterpart. The converse indicates CCW hysteresis. If one is significantly higher while the other trend is lower, the outcome is equivocal and a lack of consistent hysteresis is assumed as a result.

Table 6.5 summarises the net behaviour indicated by these seasonal relations. SV and CW occur in all but one of the station/season combinations. Lower Andheri experiences a travel-time hysteresis effect from pre-monsoon local upland storms which bring high sediment concentrations to floodwaters at Lower Andheri. At all other stations, this type of hysteresis is not persistent enough to

Figure 6.5 Functional relations for rising and falling limbs contrasted within the pre-monsoon and monsoon seasons.



Error limits based on 90% confidence.

10 - Kukhuri 2 - Lower Andheri 1 - Jhikhu
9 - Upper Andheri 3 - Dhap

Table 6.5 Dominant hysteresis indicated by net behaviour of suspended sediment of rising and falling hydrograph limbs.

Station		Dominant Behaviour	
Name	No	Pre-Monsoon	Monsoon
Kukhuri	10	SV	CW
Upper Andheri	9	(CW)	SV
Lower Andheri	2	CCW	SV
Dhap	3	SV	SV
Jhikhu	1	SV	CW

SV - single-value; CW - clockwise; CCW - counterclockwise

leave a seasonal signature. CW hysteresis persists during the monsoon season at Kukhuri and Jhikhu. This is consistent with a reduced sediment availability. In the headwater areas, there is reduced availability due to the development of a strong vegetative cover. A reduced availability at the Jhikhu station is possibly a result of alluvial storage near Baluwa. The CW result during the pre-monsoon season at Upper Andheri is anomalous and may be due to the problems encountered at that station. At all other station/season combinations, any departures from SV hysteresis are inadequate to persist in the seasonal relations.

6.3.3 Implications

One should be selective in applying the sediment rating technique when estimating suspended sediment concentration. Under certain conditions, hysteretic behaviour is sufficiently pronounced and consistent that it leaves a net seasonal signature in the sediment rating curve, decoupling the C-Q relation. Under other conditions, hysteretic behaviour is either consistently weak or sufficiently contrasting to leave no net seasonal signature. (Excessive variance in the C-Q regression may indicate contrasting behaviours.)

When calculating suspended sediment concentrations for individual events from seasonal ratings, one should verify whether SV behaviour is dominant during the period of interest. If not, then the application of a seasonal rating curve to individual hydrographs can yield erroneous results. If non-SV behaviour persists, but sediment and water peaks are consistently synchronised, then the error due to the sediment rating curve may be small due to the dominance of transport controls (discharge).

In situations in which significant decoupling of C and Q behaviours is present, two responses are available. If the style of hysteresis can be documented to be consistent for the season, a seasonal "hysteresis correction" to the sediment rating curve is possible. Alternatively, limited event sediment samples can be carried out and used to *calibrate* the seasonal sediment rating curve for the event.

6.4 Entrainment and transport behaviour by particle-size class

The particle-size distribution of available and entrained sediment greatly influences sediment-rating-curve relations because of differential response of constituent sizes to the governing controls. To investigate this effect, a total of 341 samples from the suspended-sediment data set considered in section 5.4 have been analysed for particle-size distribution as summarised in Table 6.6. Individual rating curves are developed for four separate particle-size classes.

6.4.1 Controlling factors

Suspended sediment consists of a range of particle sizes each of which can be affected differently by the many controls discussed in Chapter 5. Source sediment texture - in terms of the available supply of individual fractions and the transportability of these fractions - can be added to this list of influential factors.

Within the fine fraction of suspended sediment (below 2 mm), behaviour ranges from that which is uninfluenced by streampower (clays) to that which is dominated by hydraulic conditions (coarse sands) while the concentration of all particle classes is dependent on available supply.

Table 6.6 Number of samples analysed for particle-size distribution by station and season.

St. Name	St. No	# Independent Events	Total	Pre-monsoon	Transition	Monsoon
Jhikhu	1	46	89	30	16	43
Lower Andheri	2	29	76	29	10	37
Dhap	3	24	55	15	14	26
Upper Andheri	9	20	37	13	6	18
Kukhuri	10	19	46	16	7	23
Andheri Mid #1	11	9	21	13	3	5
Andheri Mid #2	12	3	17	0	6	11
Total		n/a	341	116	62	163

Consideration of the behaviour of separate classes helps in determining whether supply or transport limitations dominate and can also assist in deducing the origin of suspended material. Supply and transport limitations can be confounded under certain conditions and for specific particle-size classes. A careful analysis of separate classes of suspended sediment can overcome these difficulties and contribute to answering important questions regarding the behaviour of the entire spectrum of suspended material.

Four particle-size classes are considered in this analysis:

< 0.002 mm	clay
0.002 to 0.062 mm	silt
0.062 to 0.180 mm	fine sand
0.180 to 2.000 mm	coarse sand.

The common agricultural separation of clay and silt (0.002 mm) is used so that knowledge of surface soil texture can be directly linked to the texture of stream sediments. The Wentworth classification for silt-sand separation is used because of the growing importance at the sand boundary of transport controls and because the Wentworth classification is used widely in other research to facilitating comparison to other studies.

A distinction is made between fine and coarse sands for several reasons. Sand includes a wide range of material not all readily available or transported in this system. The measured distributions show a consistently large drop in sediment concentration above 0.150 mm. It is conceivable that fine sands contribute to the important export of agricultural nutrients however coarse sands definitely do not. Regardless, fine sands are at an advanced state of weathering and are more useful to future agricultural productivity than the coarse sands. It is also of interest whether or not the relatively-abundant fine sands move differently to the coarse sands. Church (1996, personal communication) found that a difference in the behaviour of sands - below and above 0.180 mm - exists in sediment carried by large rivers. For all of these reasons, 0.180 mm is used in the present analysis to distinguish between fine and coarse sand.

Ultimate versus aggregate particle size

The distributions presented here represent ultimate particle size (see section 6.2.2) because a dispersant was used before measurement. The organic-matter content of these samples is very low (typically 0.3 to 1.5%) and there is generally a wide range of particle sizes present in each sample. Hence, the level of aggregation in the stream is low so these results represent well the effective particle-size distributions. Because ultimate and aggregate particle sizes are roughly equal in this study, we are able to study both source and transport controls simultaneously.

Clay truncation

To what extent is clay lost during the filtering process due to the mesh size of the Whatman 40 filter paper (0.008 mm)? Fenn and Gomez (1989) used this same filter paper and found that filtered samples contained 5 to 10% less sediment than the unfiltered ones due to loss through the mesh. In the present study, clay content is higher than in their proglacial environment so we expect more clogging and less losses. Further, heavy clay samples were filtered routinely twice to capture lost sediment. Therefore, though there are losses in the clay fraction, the amount lost is less than 5% of the total clay fraction.

6.4.2 Seasonal regimes

Seasonal regimes in suspended sediment are examined by particle-size class using the approach taken in Chapter 5. Simple log-linear regression is used to determine the relations presented in Tables 6.7 and 6.8. Applying equations given by Mark and Church (1977), the regression relations are used to determine the associated functional relations which appear in Figures 6.6 through 6.10 for each of the five detailed study basins. The equations for these logarithmic lines are provided in Tables 6.9 and 6.10 along with ranges (Church and Mark 1980) based on 90% confidence. These ranges reflect the significance of the marginal regression: the smaller the R^2, the more likely the range in b_f will cross $b_f = 0$ and the larger the s_r the wider the confidence limits on the functional relation.

Differences between these seasonal relations are tested for significance by comparing the ranges of both b_f and a_f. The values of b_f are compared first since b_f is the primary parameter used to calculate the relations. If there is no overlap in b_f ranges, the relations are significantly different regardless of the ranges in a_f. If there is overlap between the two b_f distributions, then it is *possible* that they are not significantly different. Within the range of overlap of the two b_f ranges, the ranges of a_f are examined for overlap. If they too overlap, then the relations are considered to be not significantly different.

Each of the 40 pairs of relations was examined for difference as shown in Figures 6.11 and 6.12. In all but two cases, the seasonal regime pairs are significantly different hence seasonal differences persist at all scales in all size classes except sands at Kukhuri. (Within the overlap region in b_f for fine sand at Upper Andheri and silt at Jhikhu, the ranges in a_f do not overlap hence these

Table 6.7 Pre-monsoon sediment-rating-curve relations for coarse sand, fine sand, silt, and clay at stations 1, 2, 3, 9, and 10 using log-linear regression (1992-1994, Q known without error) excluding data from the transition season.

Station		a_r	b_r	N	R^2	s_r
				Coarse Sand		
Kukhuri	10	1.088	1.712	16	0.475	0.369
Upper Andheri	9	0.527	0.236	13	0.198	0.112
Lower Andheri	2	0.0803	1.767	23	0.795	0.144
Dhap	3	0.169	1.106	15	0.448	0.243
Jhikhu	1	0.00904	1.103	28	0.471	0.192
				Fine Sand		
Kukhuri	10	10.33	1.407	15	0.396	0.305
Upper Andheri	9	5.884	0.219	13	0.174	0.113
Lower Andheri	2	0.830	1.610	26	0.744	0.162
Dhap	3	0.604	1.082	14	0.501	0.143
Jhikhu	1	0.0466	1.372	30	0.608	0.209
				Silt		
Kukhuri	10	32.19	0.687	17	0.512	0.0498
Upper Andheri	9	19.04	0.00473	13	0.0004	0.0263
Lower Andheri	2	9.877	0.515	29	0.446	0.0910
Dhap	3	5.758	0.218	15	0.415	0.0108
Jhikhu	1	4.905	0.429	30	0.513	0.0302
				Clay		
Kukhuri	10	10.06	0.417	17	0.251	0.0573
Upper Andheri	9	5.833	-0.0900	13	0.128	0.0274
Lower Andheri	2	8.045	0.0860	29	0.045	0.0438
Dhap	3	6.465	-0.0514	15	0.008	0.0517
Jhikhu	1	4.497	0.0702	30	0.0143	0.0584

Relation: $C=a_rQ^{b_r}$, regression based on log-transformed values; N - sample size; R^2 - correlation coefficient; s_r - standard error of the estimate ($\log_{10}$ g/l)

relations, too, are significantly different following the explanation in the above paragraph.) At Kukhuri station (10), the coarse- and fine-sand relations are not significantly different and hence these relations are collapsed into one regime for the rainy season based on combined pre-monsoon,

Table 6.8 Monsoon sediment-rating-curve relations for coarse sand, fine sand, silt, and clay at stations 1, 2, 3, 9, and 10 using log-linear regression (1992-1994, Q known without error) excluding data from the transition season.

Station		a_r	b_r	N	R^2	s_r
				Coarse Sand		
Kukhuri	10	1.558	1.978	23	0.471	0.129
Upper Andheri	9	0.695	0.671	18	0.536	0.180
Lower Andheri	2	0.124	0.981	37	0.581	0.126
Dhap	3	0.173	0.316	25	0.108	0.185
Jhikhu	1	0.767	-0.224	42	0.0186	0.324
				Fine Sand		
Kukhuri	10	10.73	1.430	23	0.408	0.0867
Upper Andheri	9	5.609	0.569	18	0.477	0.164
Lower Andheri	2	1.338	0.624	37	0.558	0.0560
Dhap	3	0.819	0.464	26	0.192	0.203
Jhikhu	1	1.699	0.181	43	0.013	0.327
				Silt		
Kukhuri	10	16.87	1.206	23	0.667	0.0212
Upper Andheri	9	10.82	0.223	18	0.371	0.0389
Lower Andheri	2	4.638	0.293	37	0.364	0.0272
Dhap	3	7.647	0.0191	26	0.003	0.0276
Jhikhu	1	2.773	0.363	43	0.328	0.0350
				Clay		
Kukhuri	10	4.173	1.171	23	0.705	0.0167
Upper Andheri	9	2.388	0.111	18	0.119	0.0424
Lower Andheri	2	3.405	0.0413	37	0.0126	0.0242
Dhap	3	9.336	-0.0671	26	0.022	0.0449
Jhikhu	1	0.787	0.340	43	0.243	0.0467

Relation: $C=a_rQ^{b_r}$, regression based on log-transformed values; N - sample size;
R^2 - correlation coefficient; s_r - standard error of the estimate ($\log_{10}$ g/l)

transition, and monsoon season data (see Table 6.11).

Seasonal differences in the sand fractions are the greatest in the higher-order streams and conversely, differences in the clay and silt fractions are greatest in the low-order streams. This behaviour is the result of seasonal changes in sediment supply related to landuse. These and other

Figure 6.6 Comparison of pre-monsoon and monsoon sediment rating curves for four particle-size classes at Kukhuri station (10) based on functional analysis.

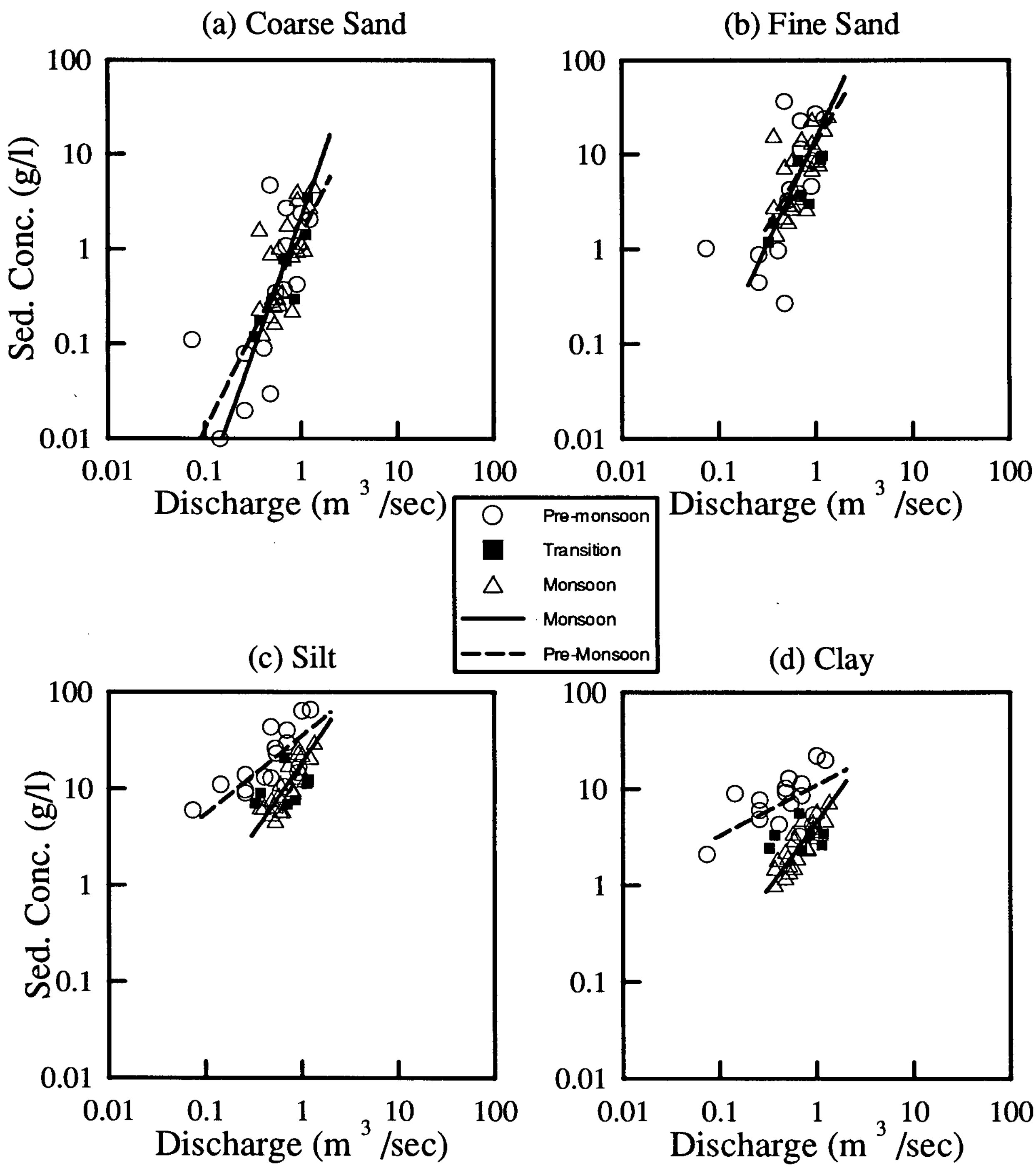


Figure 6.7 Comparison of pre-monsoon and monsoon sediment rating curves for four particle-size classes at Upper Andheri station (9) based on functional analysis.

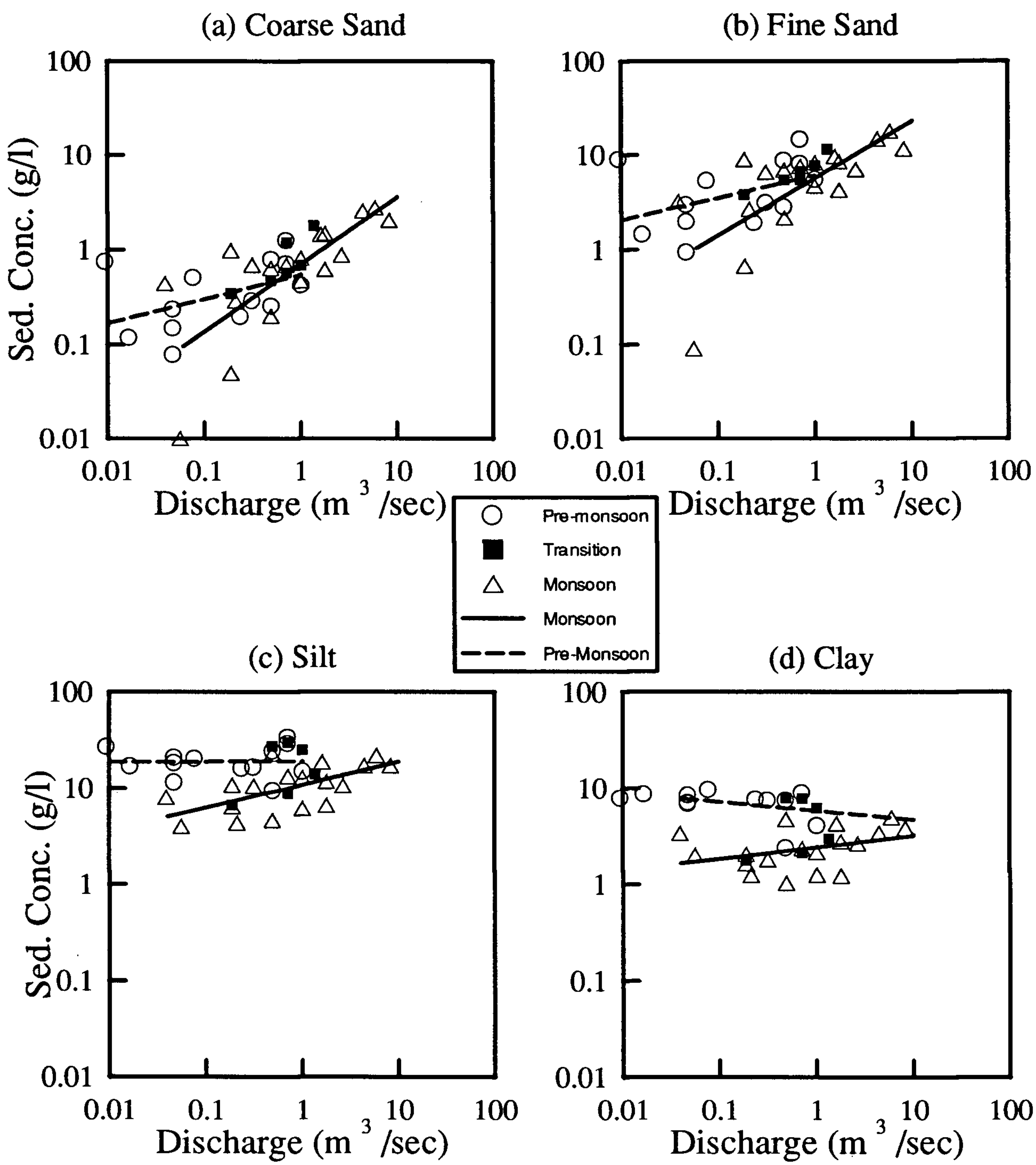


Figure 6.8 Comparison of pre-monsoon and monsoon sediment rating curves for four particle-size classes at Lower Andheri station (2) based on functional analysis.

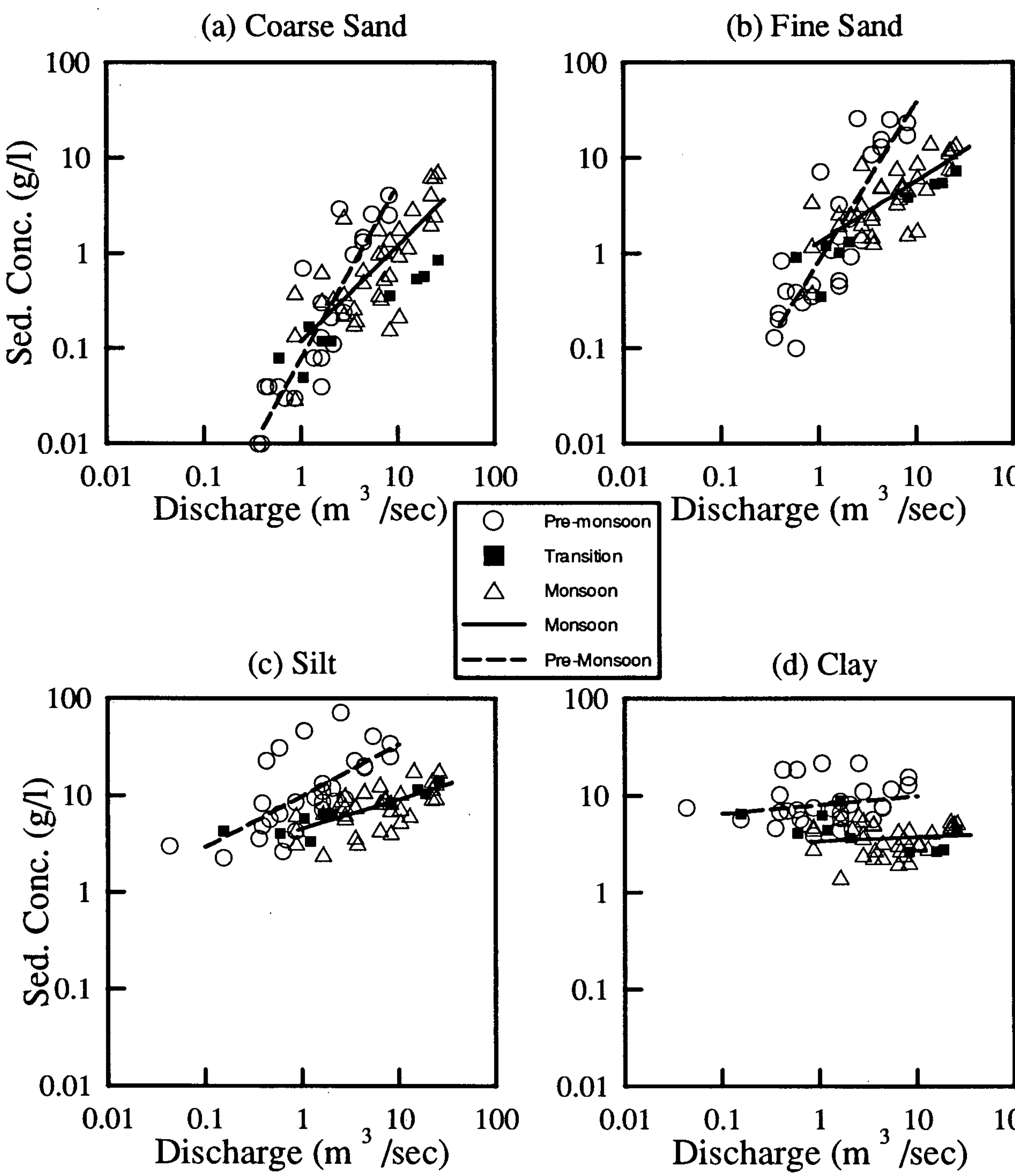


Figure 6.9 Comparison of pre-monsoon and monsoon sediment rating curves for four particle-size classes at Dhap station (3) based on functional analysis.

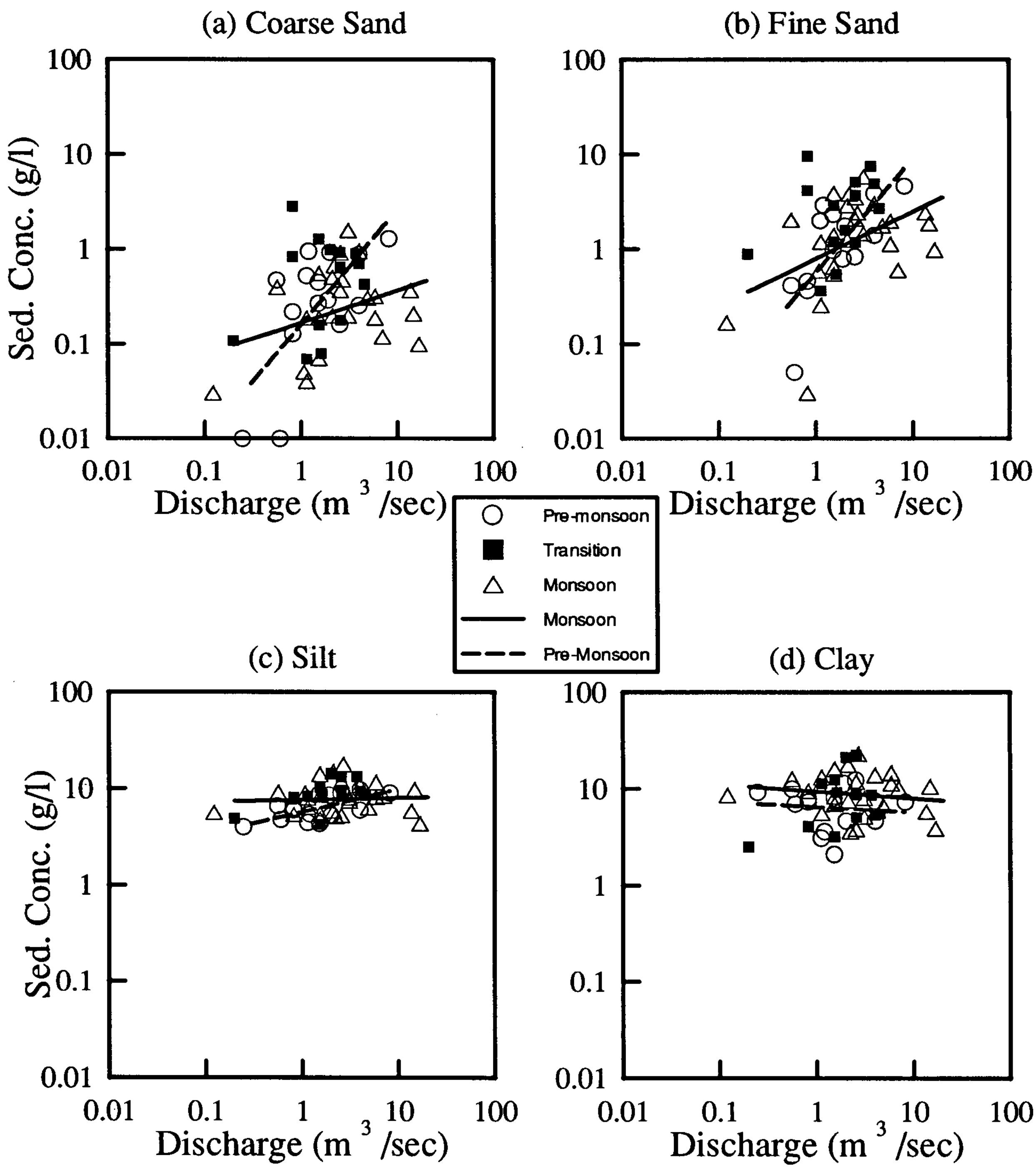


Figure 6.10 Comparison of pre-monsoon and monsoon sediment rating curves for four particle-size classes at Jhikhu station (1) based on functional analysis.

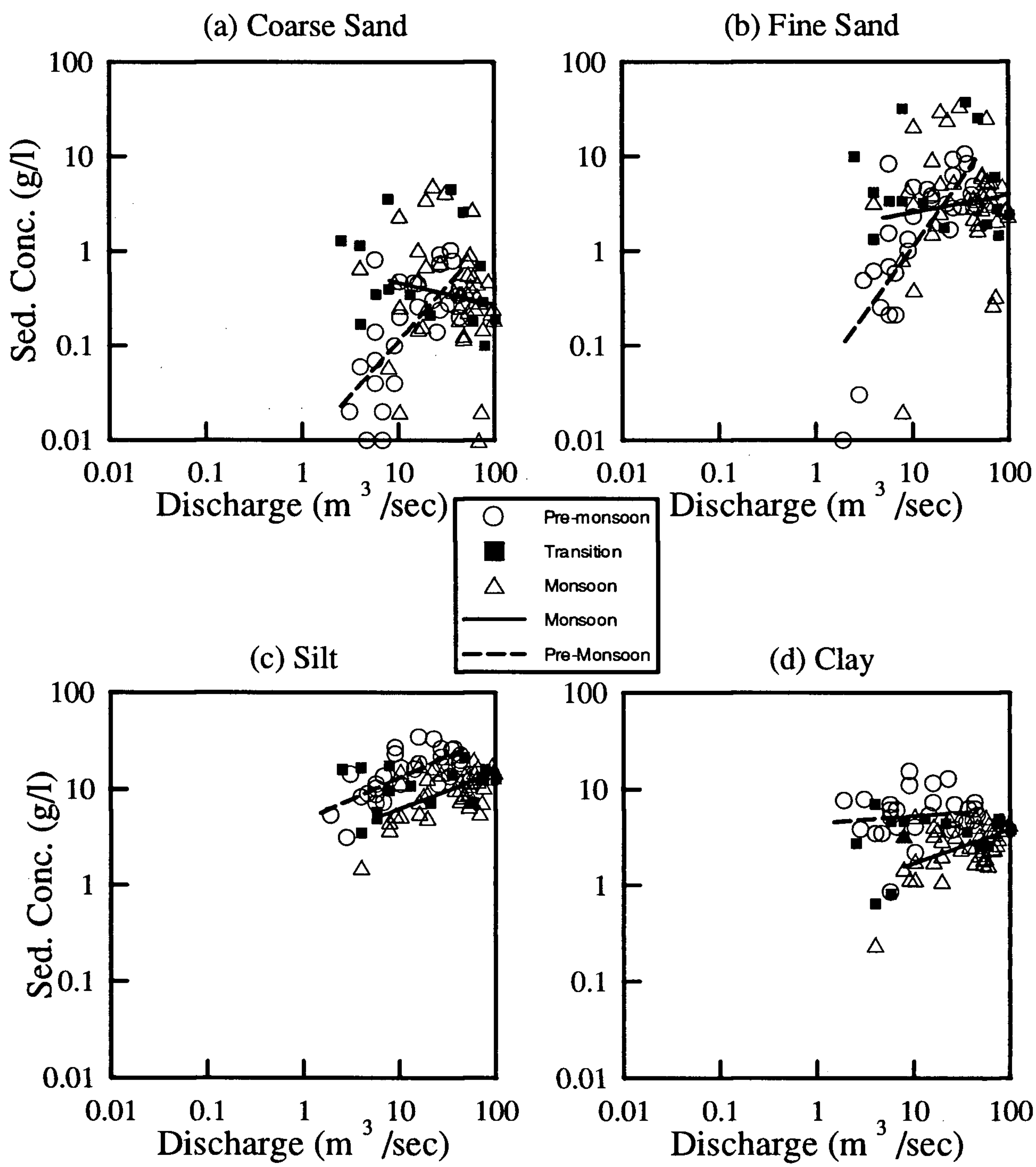


Table 6.9 Pre-monsoon sediment-rating-curve relations derived using functional analysis for coarse sand, fine sand, silt, and clay at stations 1, 2, 3, 9, and 10 excluding data from the transition season.

Station Name	No.	λ	b_f (exponent) expected	b_f (exponent) range	a_f (coefficient) expected	a_f (coefficient) range
Coarse Sand						
Kukhuri	10	16.4	2.05	1.31-2.91	1.39	0.807-2.64
Upper Andheri	9	3.16	0.254	0.033-0.483	0.546	0.355-0.852
Lower Andheri	2	20.4	1.83	1.57-2.10	0.0777	0.0679-0.0884
Dhap	3	16.6	1.21	0.716-1.73	0.163	0135-0.194
Jhikhu	1	30.9	1.15	0.840-1.47	0.00791	0.0181-0.00340
Fine Sand						
Kukhuri	10	13.0	1.75	0.982-2.67	13.0	7.80-24.0
Upper Andheri	9	3.18	0.236	0.013-0.466	6.09	3.94-9.52
Lower Andheri	2	22.0	1.67	1.41-1.94	0.812	0.734-0.895
Dhap	3	10.1	1.21	0.749-1.71	0.569	0.446-0.710
Jhikhu	1	34.1	1.42	1.14-1.71	0.0412	0.0200-0.0838
Silt						
Kukhuri	10	2.30	0.815	0.554-1.12	35.6	29.0-45.2
Upper Andheri	9	0.92	0.005	0.124 to -0.113	19.1	15.1-24.0
Lower Andheri	2	11.3	0.530	0.381-0.681	9.86	9.64-10.1
Dhap	3	0.73	0.238	0.134-0.349	5.72	5.49-5.93
Jhikhu	1	4.83	0.444	0.338-0.553	4.73	3.59-6.18
Clay						
Kukhuri	10	2.28	0.526	0.220-0.876	11.0	8.63-14.4
Upper Andheri	9	1.06	-0.095	-0.205-0.013	5.78	4.66-7.13
Lower Andheri	2	5.31	0.089	-0.015-0.192	8.04	7.92-8.16
Dhap	3	3.27	-0.057	-0.298-0.182	6.48	5.95-7.06
Jhikhu	1	9.05	0.073	-0.079-0.225	4.47	3.04-6.56

Relation: $C=aQ^b$. Each a_f calculated by applying its respective b_f to the means of C and Q from each data set ($a_f=C_{mean}-b_fQ_{mean}$). Ranges based on 90% confidence. λ is the ratio of the error variances (E_C^2/E_Q^2). P = pre-monsoon season; M = monsoon season.

factors are discussed below. The interaction of management and basin characteristics determines the relative dominance of supply and transport controls with basin scale.

Factors which control these relations are investigated with two comparisons. In the first, the effect of basin area is examined by contrasting the relations for each basin according to particle size

Table 6.10 Monsoon sediment-rating-curve relations derived using functional analysis for coarse sand, fine sand, silt, and clay at stations 1, 2, 3, 9, and 10 excluding data from the transition season.

Station		λ	b_f (exponent)		a_f (coefficient)	
Name	No.		expected	range	expected	range
Coarse Sand						
Kukhuri	10	8.80	2.84	2.07-3.89	2.18	1.61-3.27
Upper Andheri	9	7.18	0.707	0.490-0.933	0.704	0.654-0.759
Lower Andheri	2	22.7	1.01	0.822-1.20	0.118	0.0849-0.163
Dhap	3	12.5	0.338	0.071-0.609	0.170	0.132-0.217
Jhikhu	1	58.2	-0.234	-0.583-0.113	0.795	0.233-2.74
Fine Sand						
Kukhuri	10	5.34	2.20	1.53-3.15	14.4	11.1-20.9
Upper Andheri	9	6.46	0.601	0.394-0.817	5.67	5.29-6.10
Lower Andheri	2	10.1	0.643	0.517-0.770	1.30	1.04-1.61
Dhap	3	13.9	0.496	0.223-0.773	0.796	0.622-1.01
Jhikhu	1	58.5	0.189	-0.146-0.525	1.65	0.508-5.35
Silt						
Kukhuri	10	2.26	1.47	1.20-1.81	18.7	16.8-21.3
Upper Andheri	9	1.51	0.236	0.134-0.341	10.9	10.5-11.3
Lower Andheri	2	4.80	0.302	0.214-0.391	4.57	3.92-5.31
Dhap	3	1.86	0.020	-0.080-0.121	7.64	6.99-8.34
Jhikhu	1	6.35	0.379	0.269-0.490	2.62	1.78-3.85
Clay						
Kukhuri	10	2.01	1.39	1.15-1.68	4.54	4.14-5.08
Upper Andheri	9	1.60	0.118	0.011-0.226	2.39	2.31-2.48
Lower Andheri	2	4.21	0.042	-0.039-0.124	3.40	2.96-3.91
Dhap	3	3.03	-0.072	-0.201-0.057	9.38	8.37-10.5
Jhikhu	1	8.43	0.355	0.228-0.483	0.747	0.477-1.17

Relation: $C=aQ^b$. Each a_f calculated by applying its respective b_f to the means of C and Q from each data set ($a_f=C_{mean}-b_fQ_{mean}$). Ranges based on 90% confidence. λ is the ratio of the error variances (E_C^2/E_Q^2). P = pre-monsoon season; M = monsoon season.

class (and season). In the second, the relations for each particle-size class are contrasted for each basin (and season). When assessing relative *sensitivity* to Q, only the ranges in b_f are compared. When comparing *overall* relations, ranges in a_f are compared in light of differences in b_f.

Basin comparison by particle size class

The effect of basin area on coarse- and fine-sand behaviours is illustrated in Figures 6.13 and

Table 6.11 Annual coarse and fine-sand ratings for Kukhuri basin based on data from entire rainy season.

Fraction	a_r	b_r	N	R^2	s_r
Coarse sand	1.34	1.86	46	0.531	0.191
Fine Sand	9.89	1.40	45	0.429	0.143

Station		λ	b_f		a_f	
Name	No		expected	range	expected	range
Coarse sand		11.1	2.33	1.92-2.79	1.71	1.38-2.16
Fine sand		7.66	1.88	1.48-2.35	12.5	10.2-15.6

r - regression; f - functional analysis
See additional notes below Tables 6.7 and 6.9.

6.14 respectively. b_f declines with basin area reflecting the importance to sand transport of hydraulic controls (Upper Andheri anomalous for reasons discussed in section 5.4). The greater sensitivity of Lower Andheri (2) than Dhap (3) in coarse sand concentration is due to the steeper topography of Lower Andheri and is significant for the coarse sands during the monsoon season. The seasonal difference in the effect of basin area indicates that, in addition to being transport limited, these fractions are also affected by a discharge-induced supply. Sensitivity of sand content to discharge is greatest in the pre-monsoon season when supply is readily augmented during high-intensity (high-discharge) storm events because of a poorly-vegetated surface.

Measurement limitations place a constraint on the interpretation of sediment concentrations during the monsoon season when the highest flows occur. This concern is best represented in the results for station 1 (Figure 6.10a and 6.10b). The ability of the sample to fairly represent the suspended sediment sand content of the entire flow is greatly diminished due to a lack of mixing. The effect is acute for the coarse sand to the point that the functional relations are almost horizontal. In this large river, even the silt content appears to be affected by the limitation of the sampling technique. The effect also appears in Figure 6.9a and 6.9b for coarse and fine sands at Dhap station

Figure 6.11 Seasonal contrasts of functional relations (b_f and a_f) for suspended coarse- and fine-sand fractions.

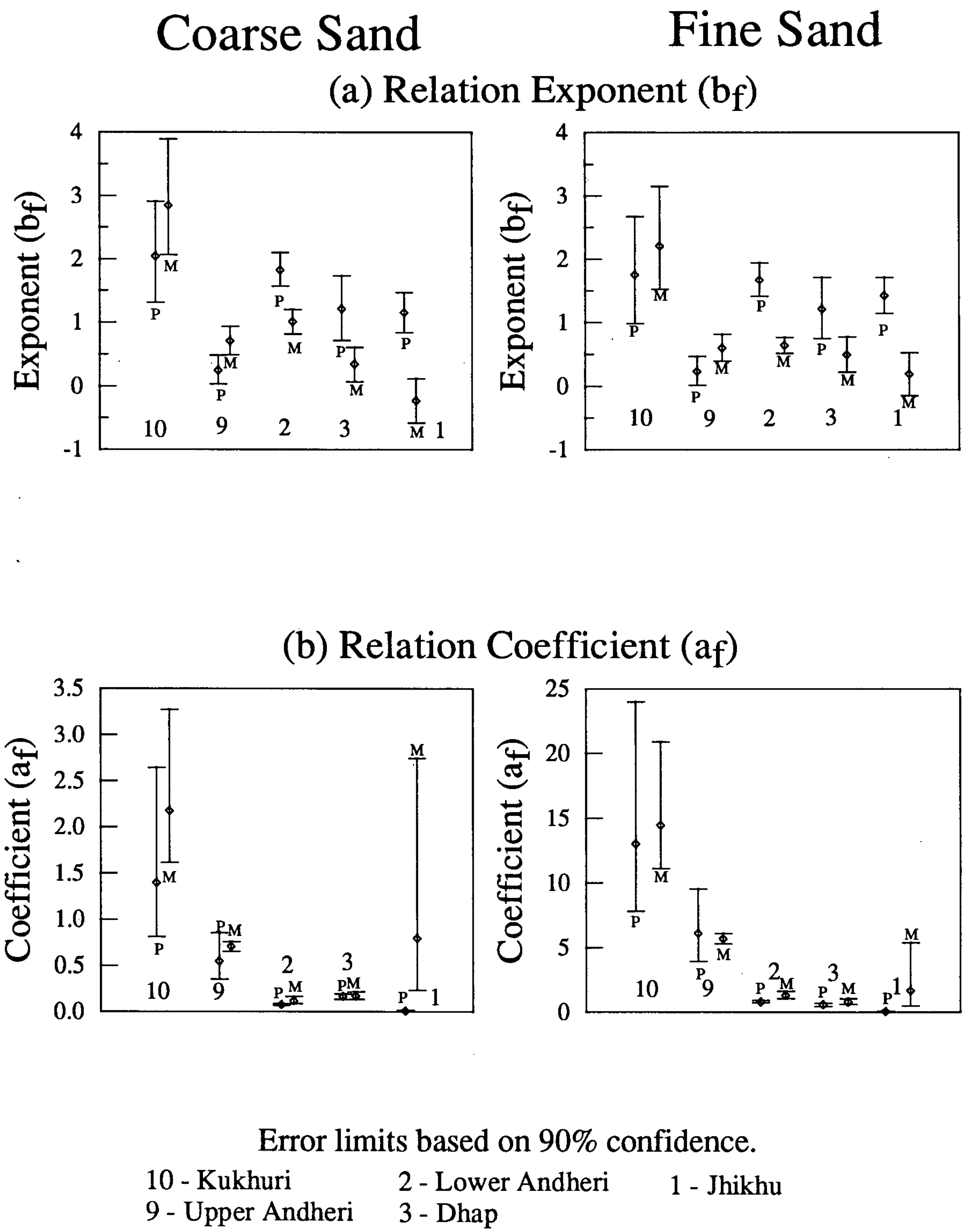


Figure 6.12 Seasonal contrasts of functional relations (b_f and a_f) for suspended silt and clay fractions.

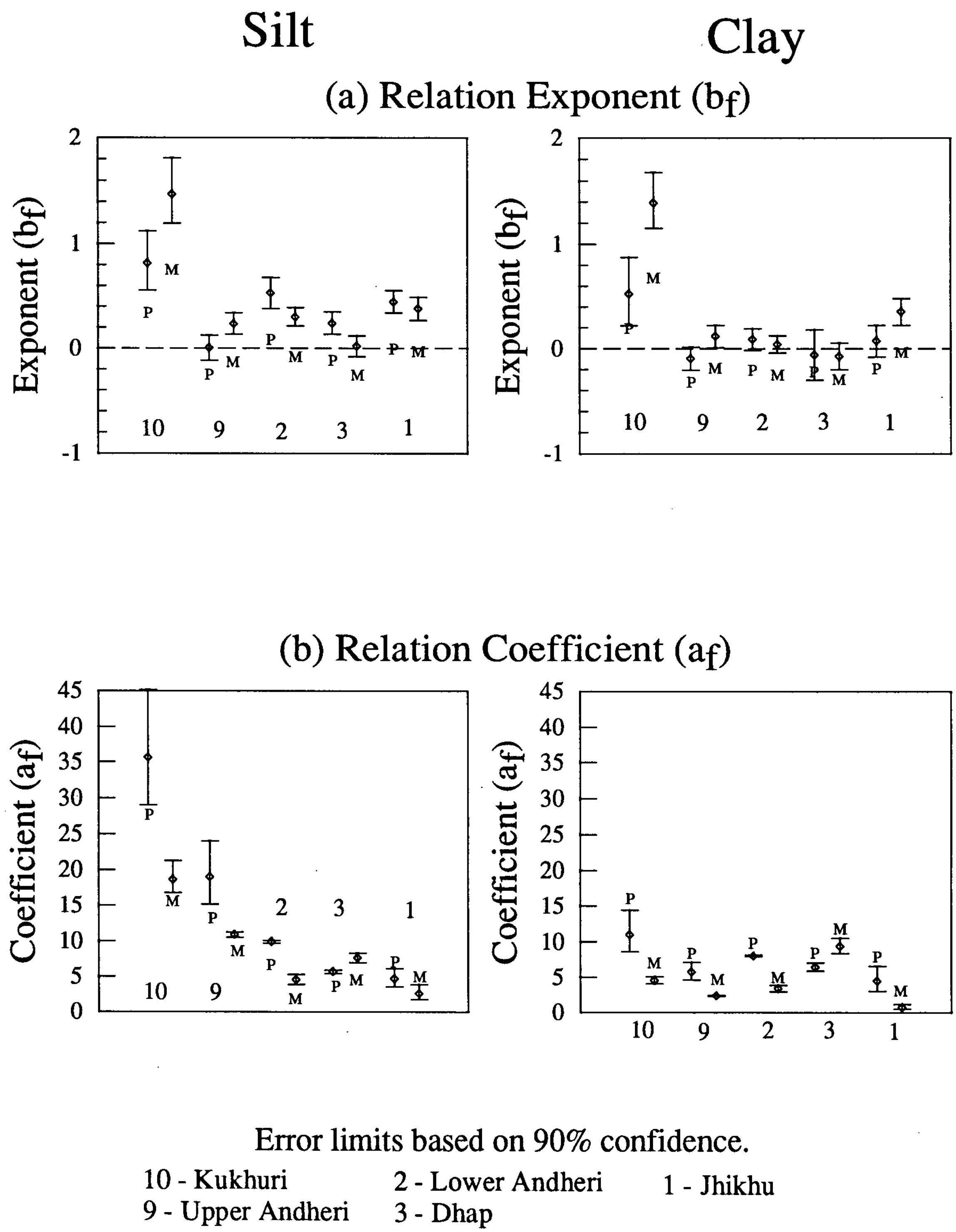


Figure 6.13 Seasonal functional relations for suspended coarse sand contrasted by basin area.

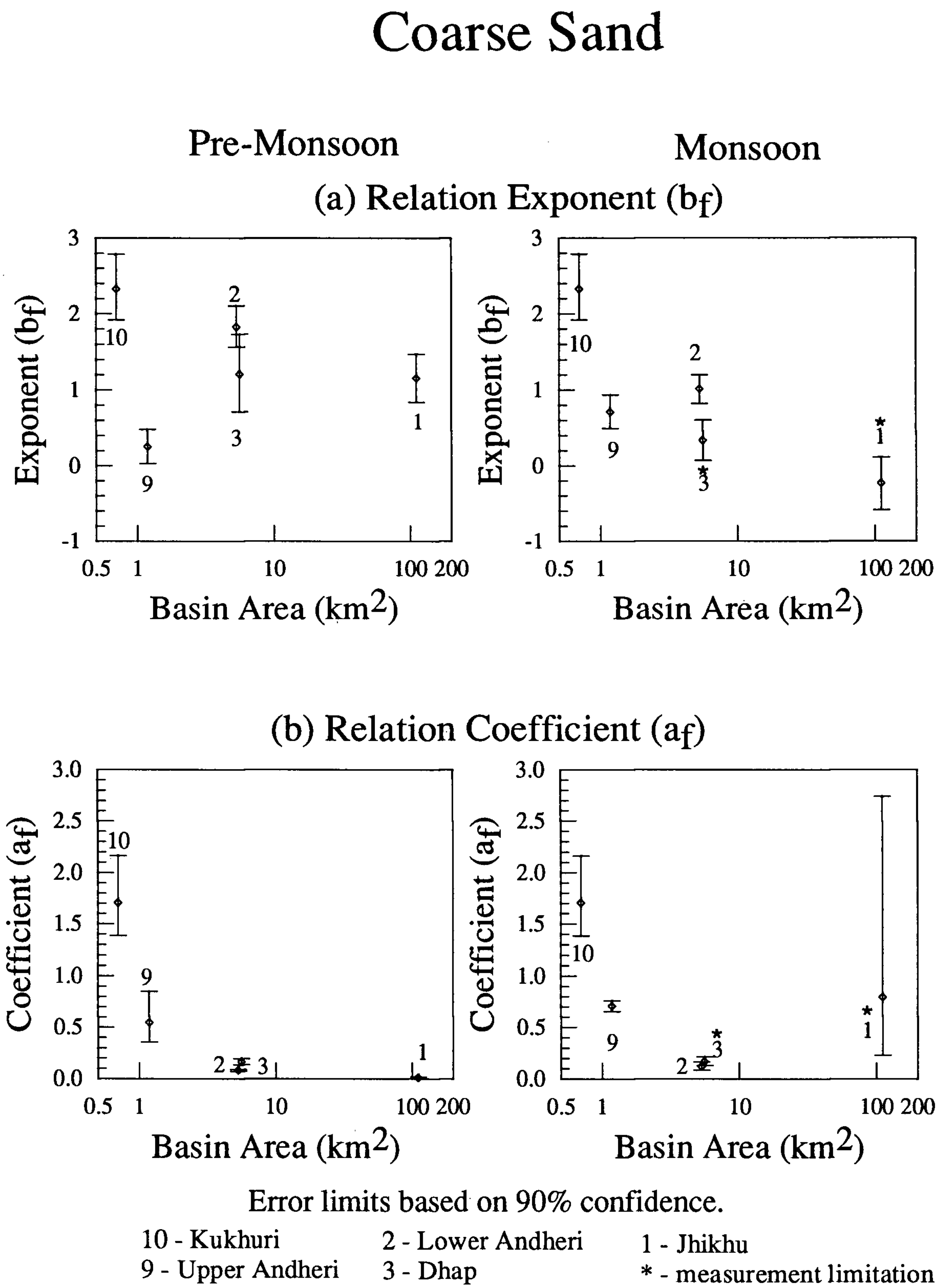
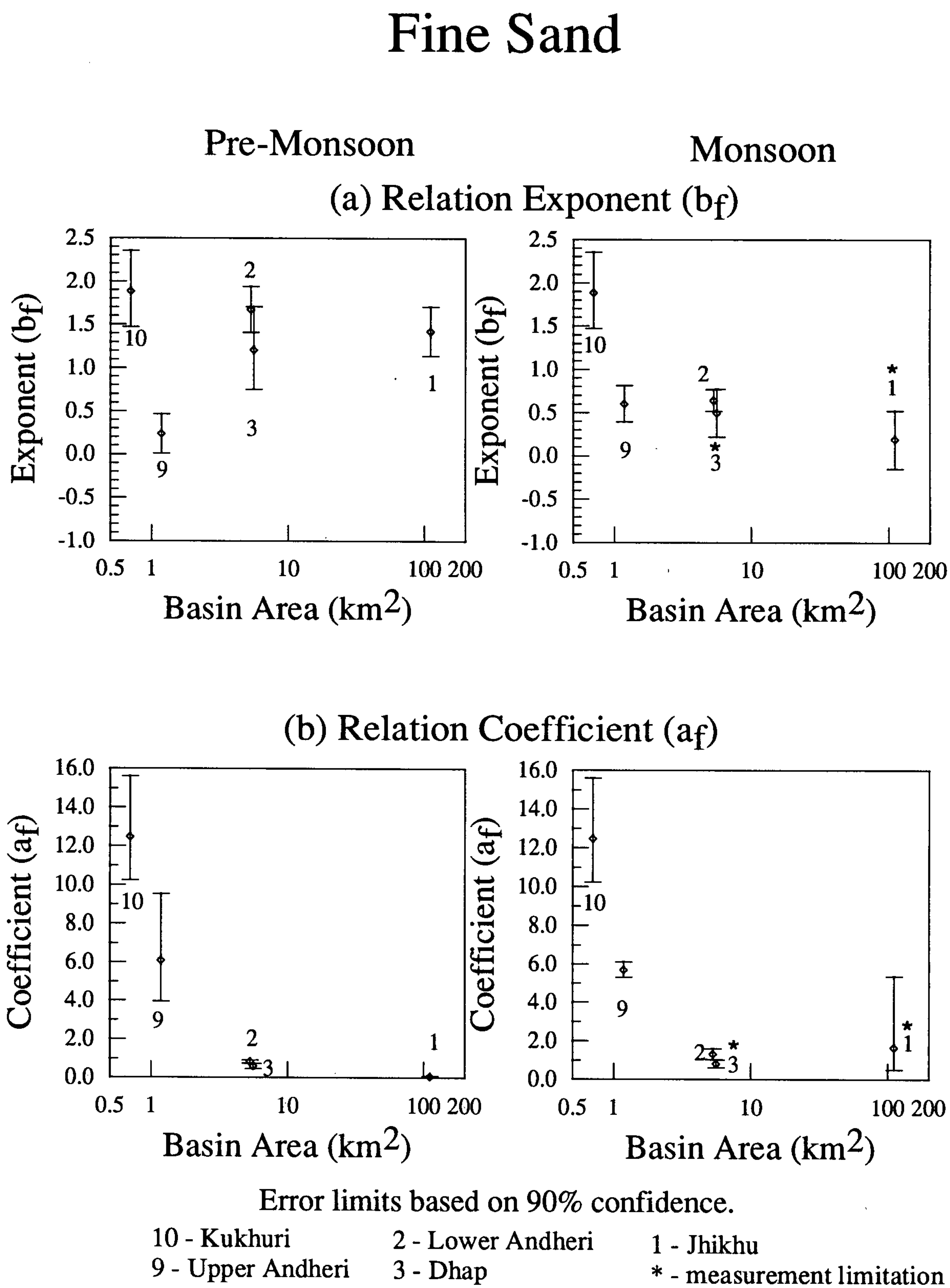


Figure 6.14 Seasonal functional relations for suspended fine sand contrasted by basin area.



(540 ha). Sampling at this location is in a smooth, straight reach where mixing is discouraged in contrast to the Lower Andheri station (532 ha) which does not show the effect. This result emphasises the need to select an appropriate measurement point if it is desired to characterise the sand fraction of the suspended load. The sand relations represented in Figures 6.13 and 6.14 are marked with an asterisk (*) to remind the reader of this serious limitation. At Lower Andheri, there is a systematic seasonal difference in the sand concentration at medium and high flows unrelated to sampling problems (see Figures 6.8a and 6.8b). The effect is due to a reduced availability of sand during the pre-monsoon season. Two reasons for this are suggested. The good vegetative cover of the monsoon season restricts availability of all size classes as discussed earlier. The indigenous irrigation system may be responsible for additional seasonal reduction in sand transport at this station. In section 5.5.3, it was explained that there are 62 diversion dams in place on the Kukhuri-Andheri system diverting channelised runoff for *khet* irrigation. This elaborate indigenous system is fully operational in the monsoon season, diverting extensive streamflow. At high flow, a large proportion of the sand fractions are moving in saltation on the stream bed and are therefore preferentially diverted by the irrigation dams. The lack of a seasonal effect in Kukhuri basin (see Figures 6.6a and 6.6b) suggests that its steepness and extreme channel roughness is adequate to completely mix the streamflow for sampling and the steep topography renders the diversion dams less effective than in the larger basin.

Figures 6.15 and 6.16 show change in silt and clay relations with basin area. Both fractions exhibit a weakened dependence on discharge than the sands at Kukhuri station. The sensitivity to Q at Kukhuri may be caused by the erosion of loamy agricultural soils: during the pre-monsoon season these soils are highly erodible so the coefficient is big and the exponent small. The clay relations show a reduced coefficient with scale except for Dhap (3). This is the result of the degraded state of the clay-rich soils in this basin: when the heavy rains of the monsoon season arrive, clay recruitment *increases* while at the other basins, the enhanced vegetative *reduces* the amount of clay available.

Figure 6.15 Seasonal functional relations for suspended silt contrasted by basin area.

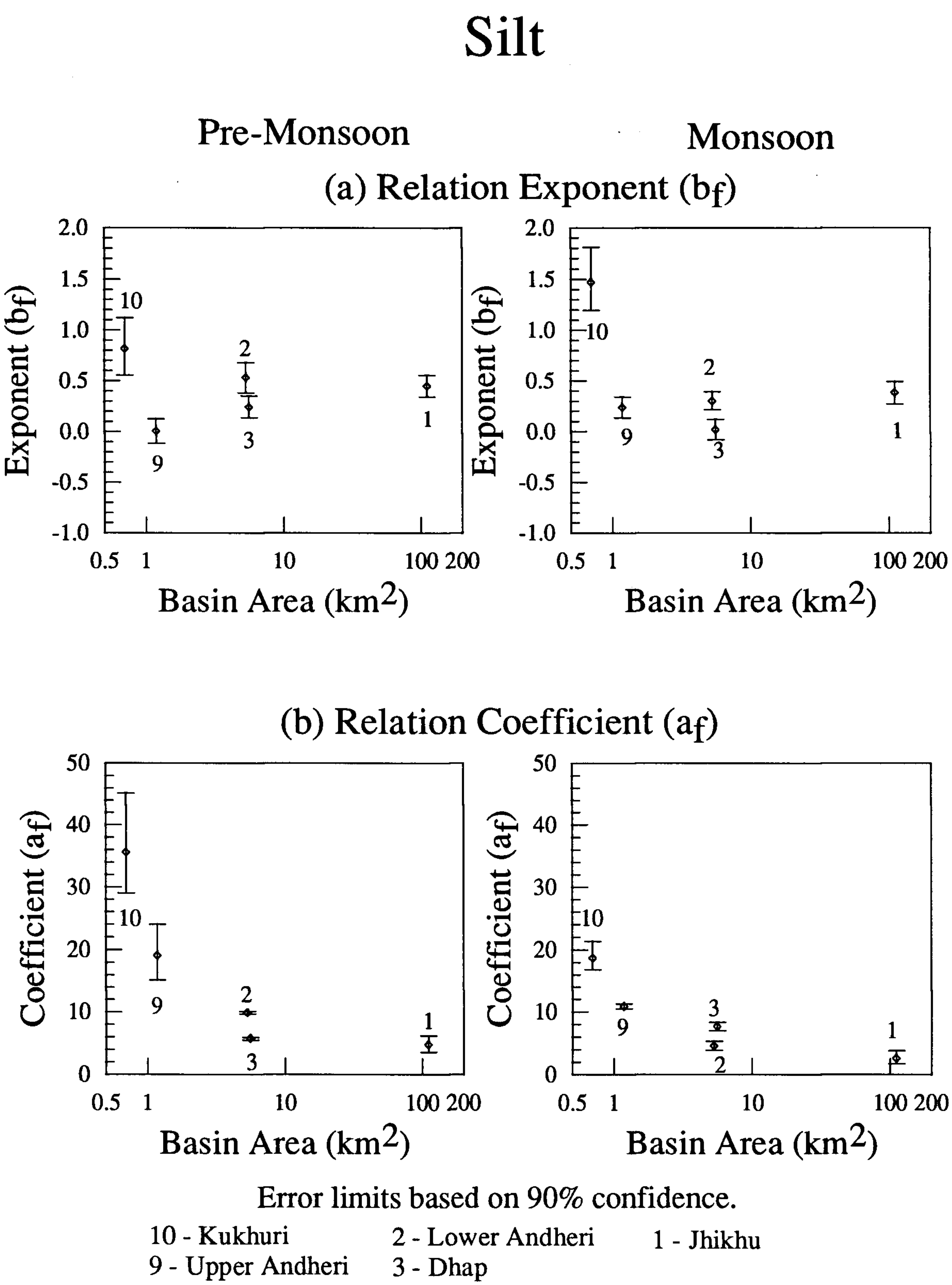
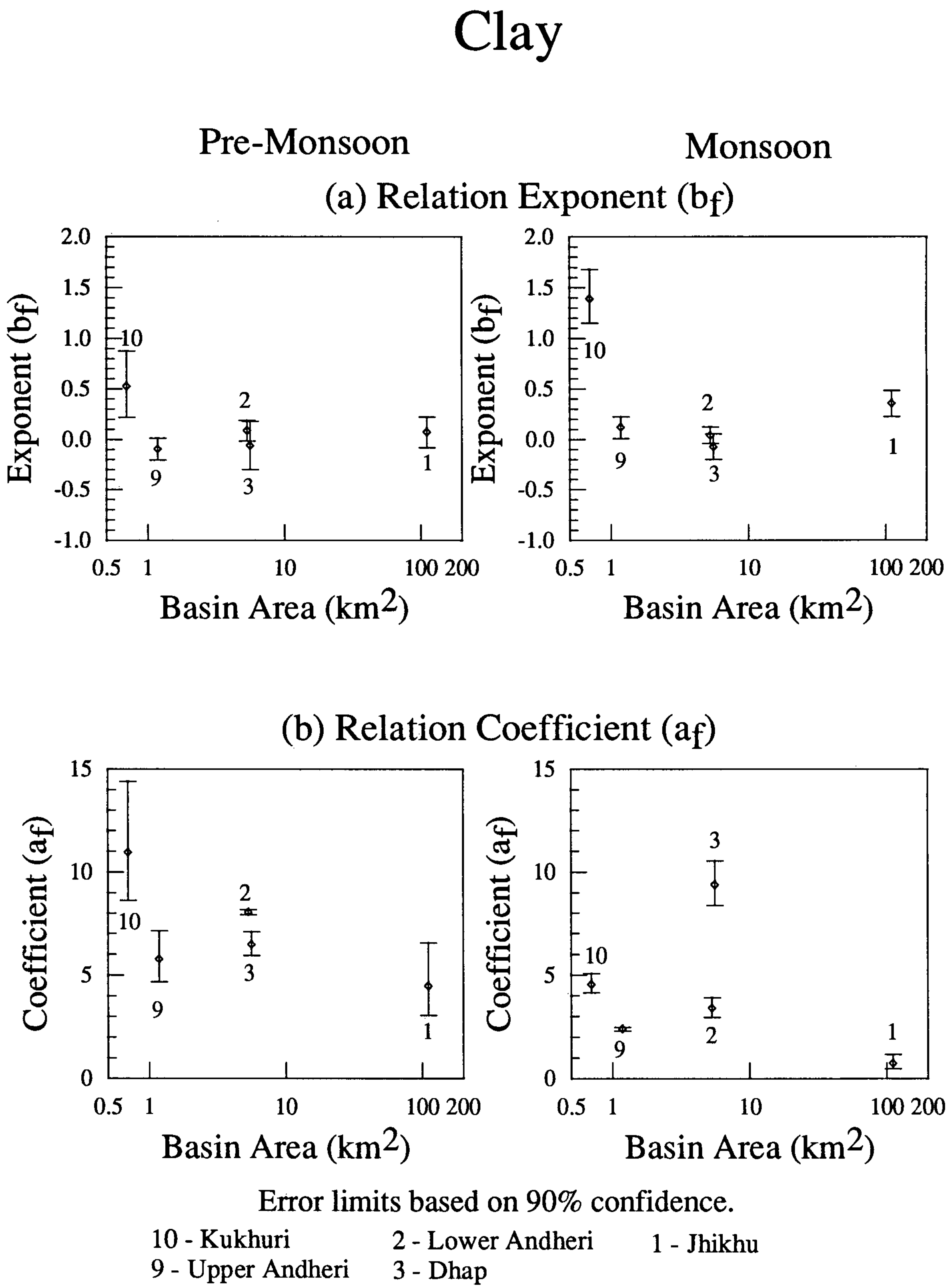


Figure 6.16 Seasonal functional relations for suspended clay contrasted by basin area.



Particle-size comparison by basin

In Figures 6.17 through 6.21, the relations for the particle-size classes are assembled for each basin and season. It is clear from a_f in Figures 6.17 and 6.18 (Kukhuri and Upper Andheri basins) that silt recruitment is responsible for the high concentrations of suspended sediment during the pre-monsoon season.The lowlands of Lower Andheri also contain clay-rich soils and the signature of these soils is seen in Figure 6.19: the relative proportion of clay in the suspended load increases beyond that of the upland Kukhuri and Upper Andheri basins. Suspended sediments in the larger Dhap basin (Figures 6.20) - dominated by degraded clay-rich soils - are dominated by both clay and silt. Suspended sediment sampled at Jhikhu station (Figure 6.21) during the pre-monsoon season is almost entirely absent of sand due partially to deposition in the large meanders several kilometres upstream. Presumably, the same effect occurs during the monsoon season but evidence is obscured by the measurement limitation discussed earlier.

6.4.3 Hysteresis

Particle-size data can be used to investigate the role of sediment texture in hysteresis by plotting on one set of axes the C-Q graphs for the four individual classes of an individual flood. This has been done for eight flood events and the results presented seasonally in Figure 6.22 (pre-monsoon/transition) and Figure 6.23 (monsoon). These graphs suggest that the hysteresis observed in the overall result is also well reflected in hysteresis of all four classes. Season appears to determine which class dominates. During the pre-monsoon season, the hysteretic effect appears driven by the silt content of the suspended sediment. In contrast, the hysteresis observed during the monsoon season is driven by the fine sand - due to the magnitude of silt content transported during the pre-monsoon season, hysteresis in silt transport shapes the hysteresis observed in this season's total sediment transport. These findings are consistent with a change in sediment sources from surface erosion off cultivated agricultural fields in the pre-monsoon season to streambank and streambed erosion and

Figure 6.17 Seasonal functional relations for Kukhuri basin for four particle-size classes.

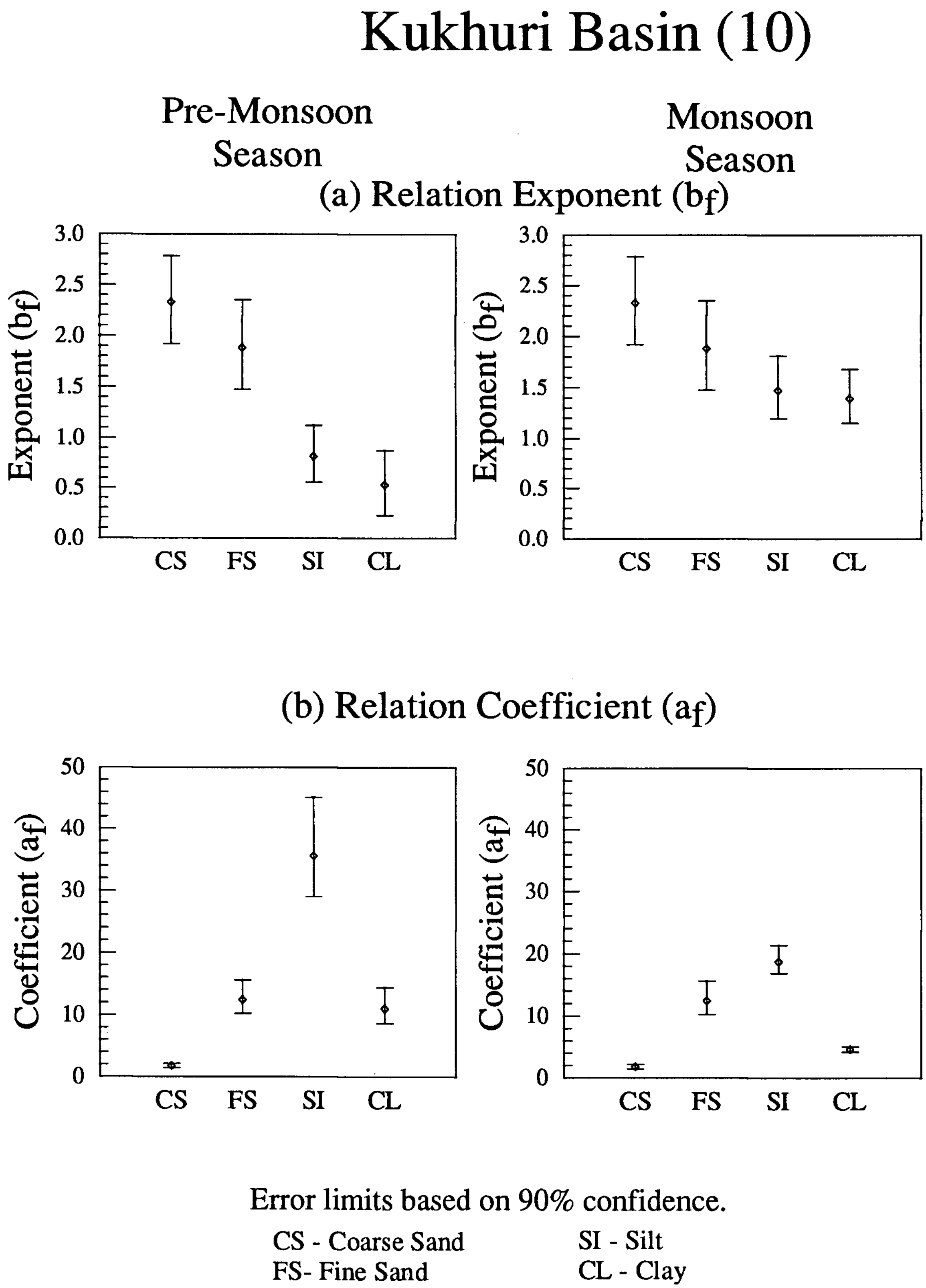
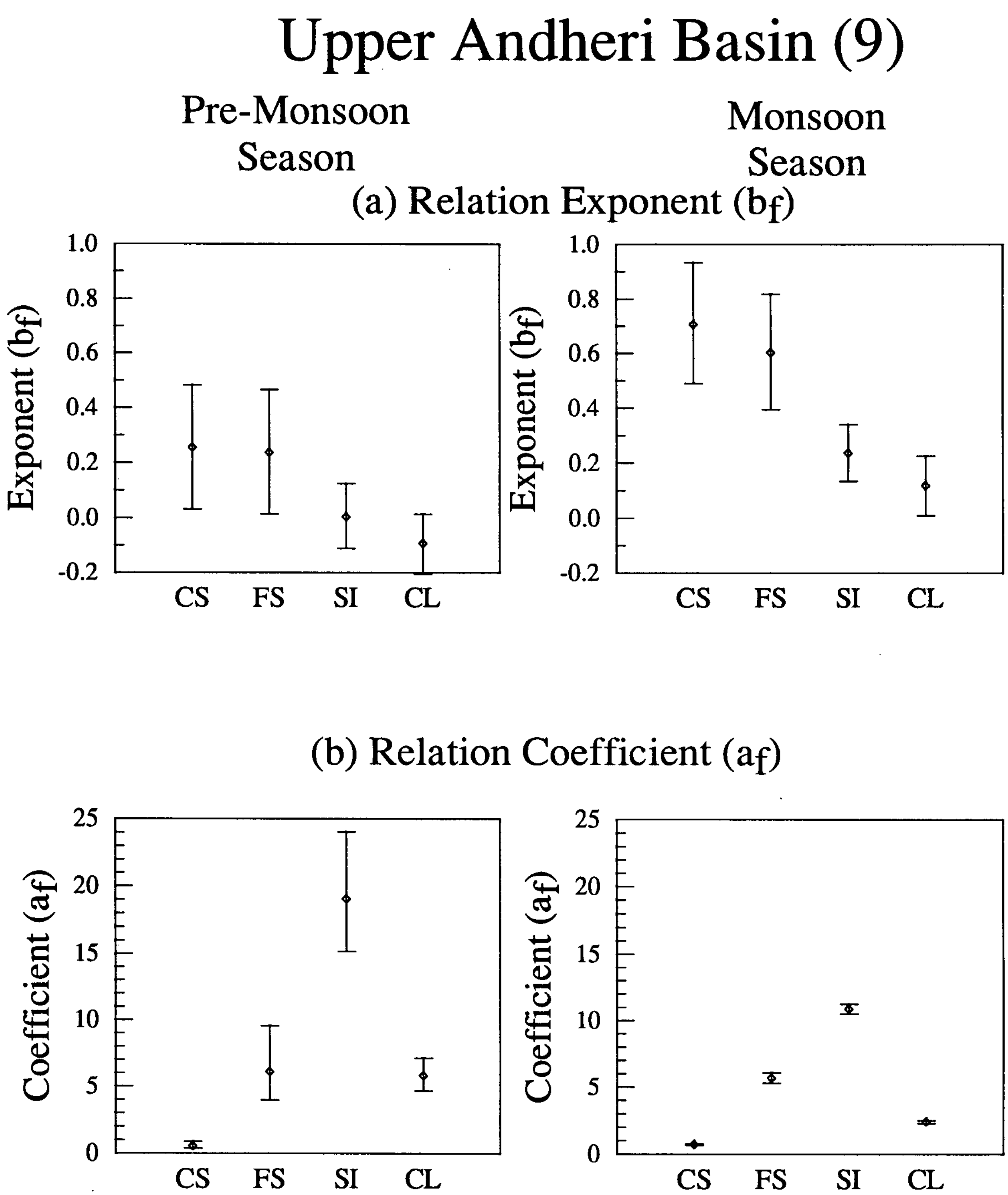


Figure 6.18 Seasonal functional relations for Upper Andheri basin for four particle-size classes.



Error limits based on 90% confidence.

CS - Coarse Sand
FS- Fine Sand
SI - Silt
CL - Clay

Figure 6.19 Seasonal functional relations for Lower Andheri basin for four particle-size classes.

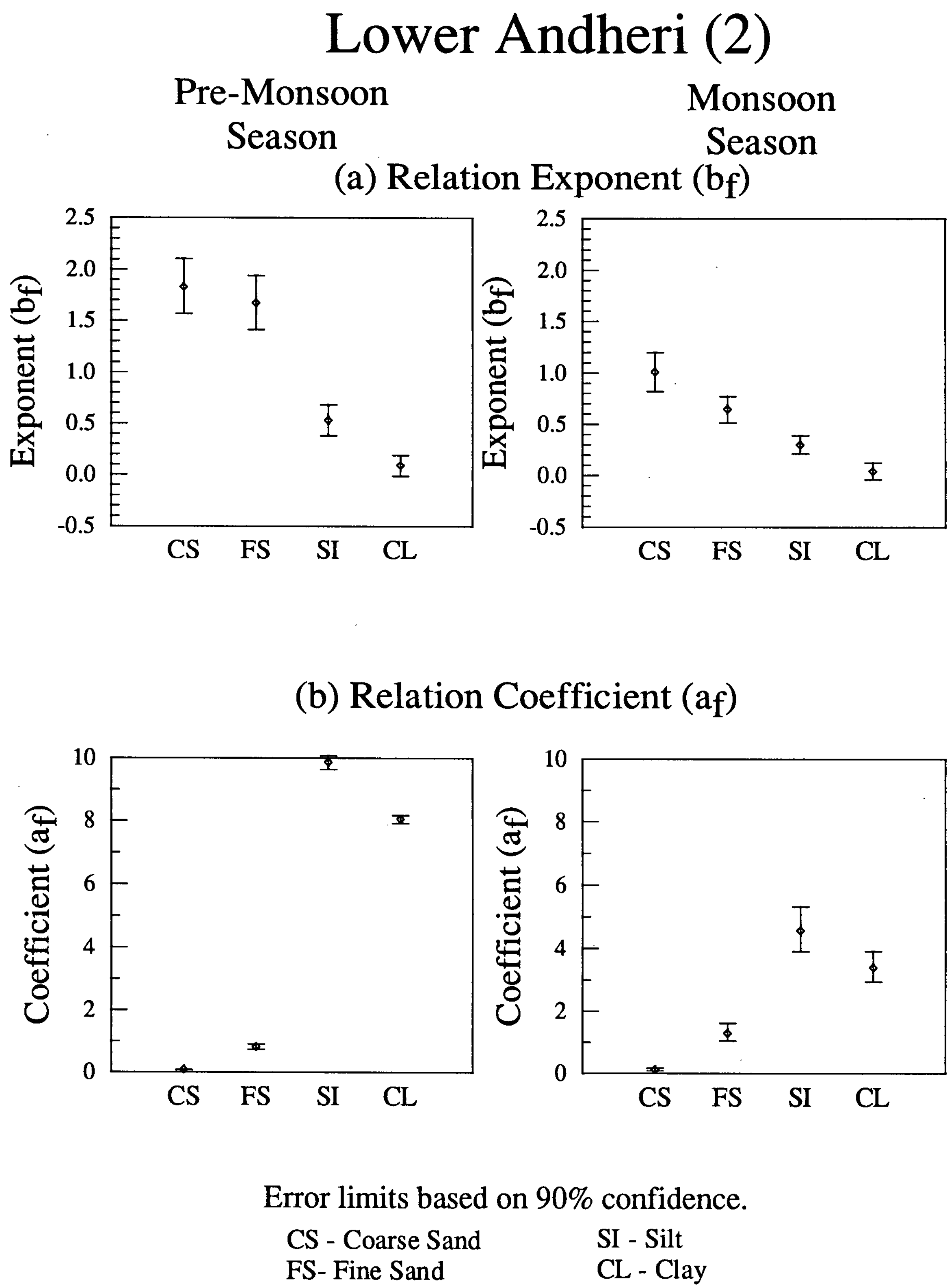
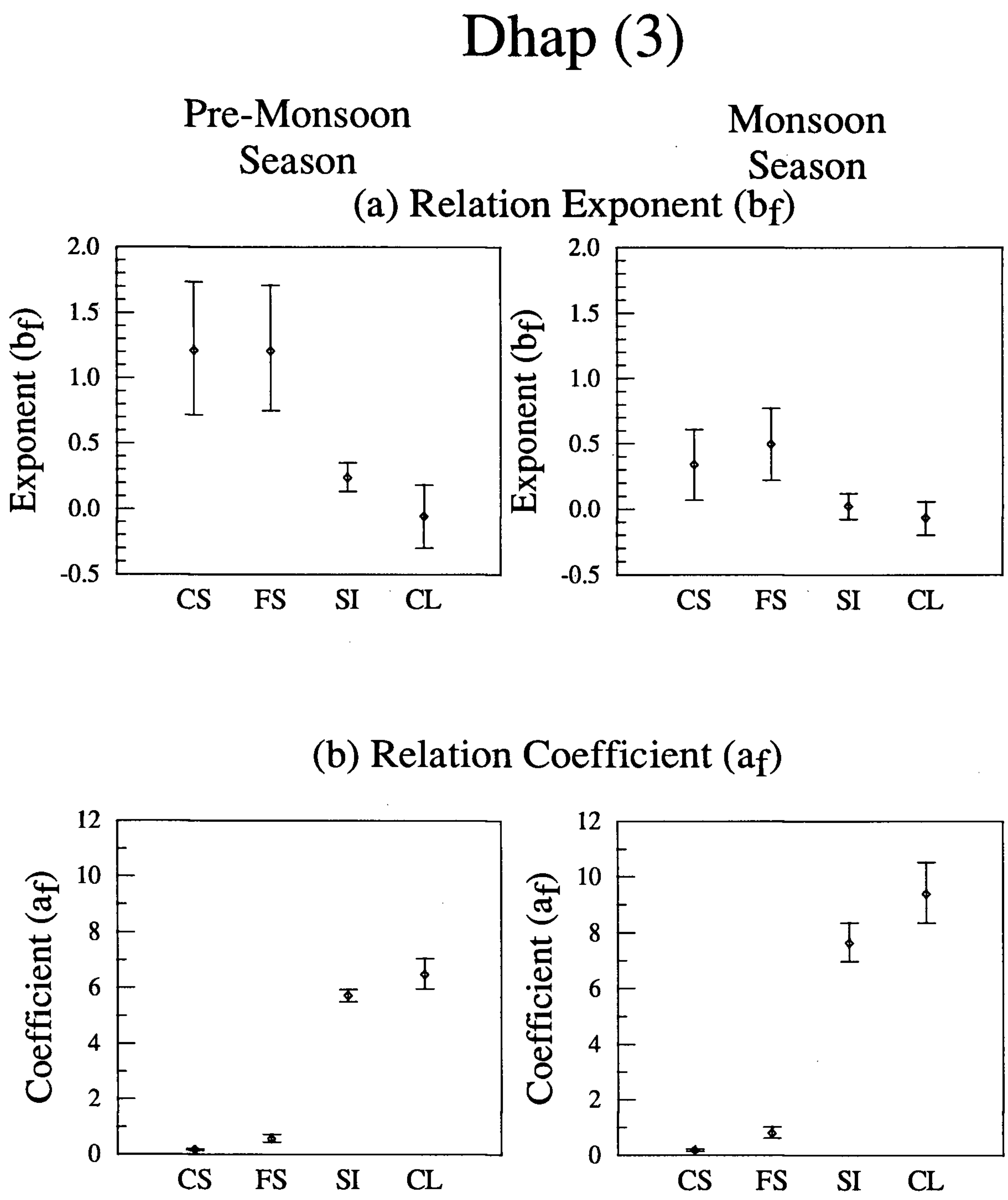


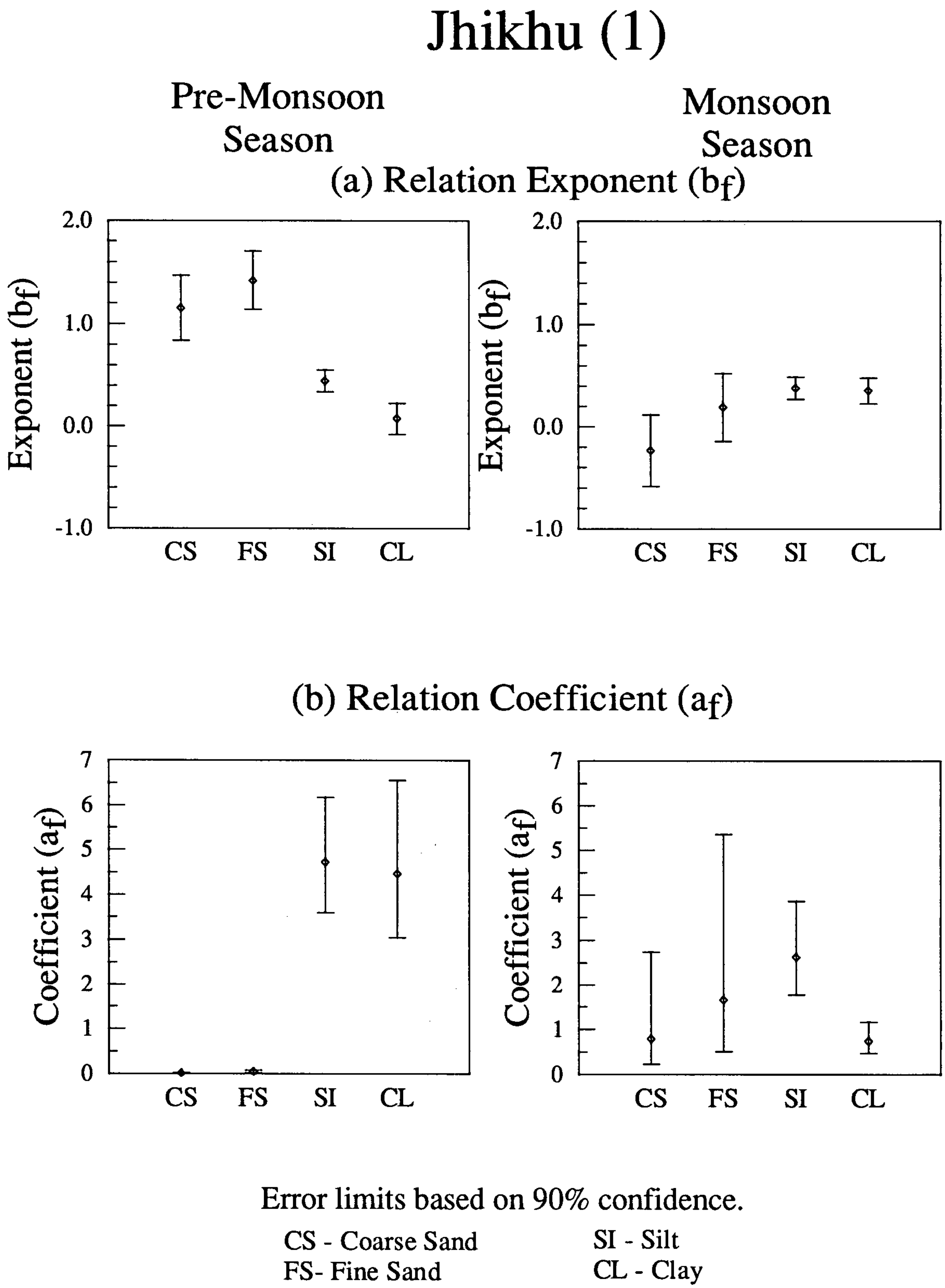
Figure 6.20 Seasonal functional relations for Dhap basin for four particle-size classes.



Error limits based on 90% confidence.

CS - Coarse Sand
FS- Fine Sand
SI - Silt
CL - Clay

Figure 6.21 Seasonal functional relations for Jhikhu basin for four particle-size classes.



terrace slumping in the monsoon season.

Figure 6.22a shows the detailed data for the large pre-monsoon event at Lower Andheri station (2) discussed earlier in Figure 6.2a. It is clear from this C-Q graph that it is the pulse of silt arriving from the upland which undermines the predictive effectiveness of the rating curve in this instance.

6.5 Fingerprints of suspended sediment

Techniques used to trace the provenance of suspended sediment were identified in section 6.2.3. The chemical and physical properties of surface soils within the Andheri basin show marked contrasts with landuse and as such provide an opportunity to identify the origin of suspended sediment. In particular, the degraded gullied lands discussed in section 5.5.2 are formed on soils and parent materials low in available phosphorus and red in colour. These soils represent the oldest and most-weathered soils in the Jhikhu basin. The intensively-cultivated, upland soils, in contrast, are high in available phosphorus and are largely brown in colour. These contrasts are used here to link the sediment data to its erosional origin.

As explained in section 6.2.3, sediment properties are inherently weak in expressing the provenance of suspended sediment and the fingerprints chosen in the present study are no exception: colour is qualitative in its determination and simplistic in its quantitative representation; phosphorus, though strictly quantitative, is not a unique identifier and can be misleading. Hence, the two properties are considered simultaneously. A total of 1649 sediment samples has been analysed for colour and 598 samples for phosphorus as summarised in Table 6.12. These data provide the basis for the following examination.

6.5.1 Sediment properties

In using sediment properties to determine erosive origin, it is necessary to establish them as

Figure 6.22 C-Q graphs by particle size for pre-monsoon and transition season events at four stations.

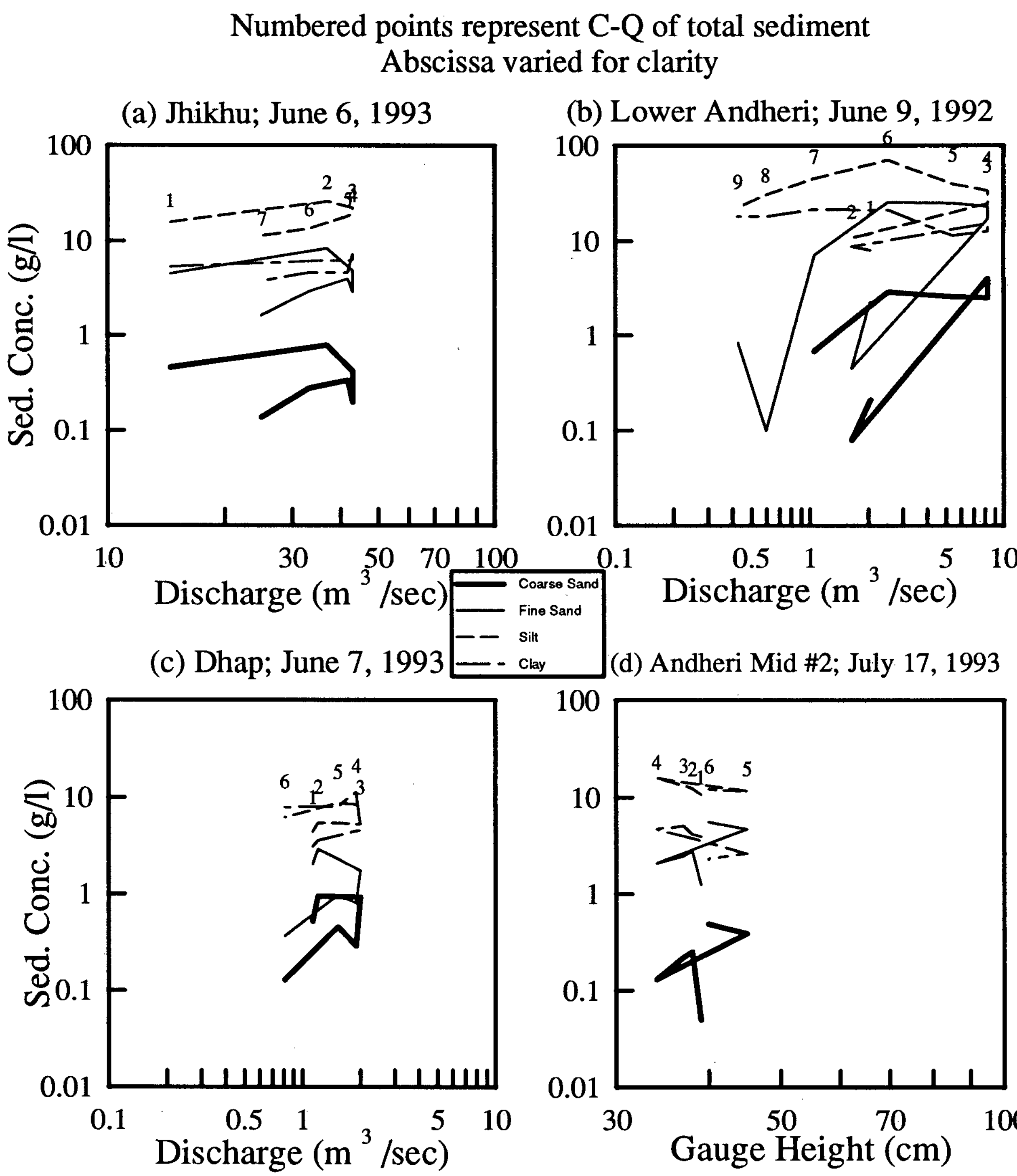


Figure 6.23 C-Q graphs by particle size for monsoon-season events at four stations.

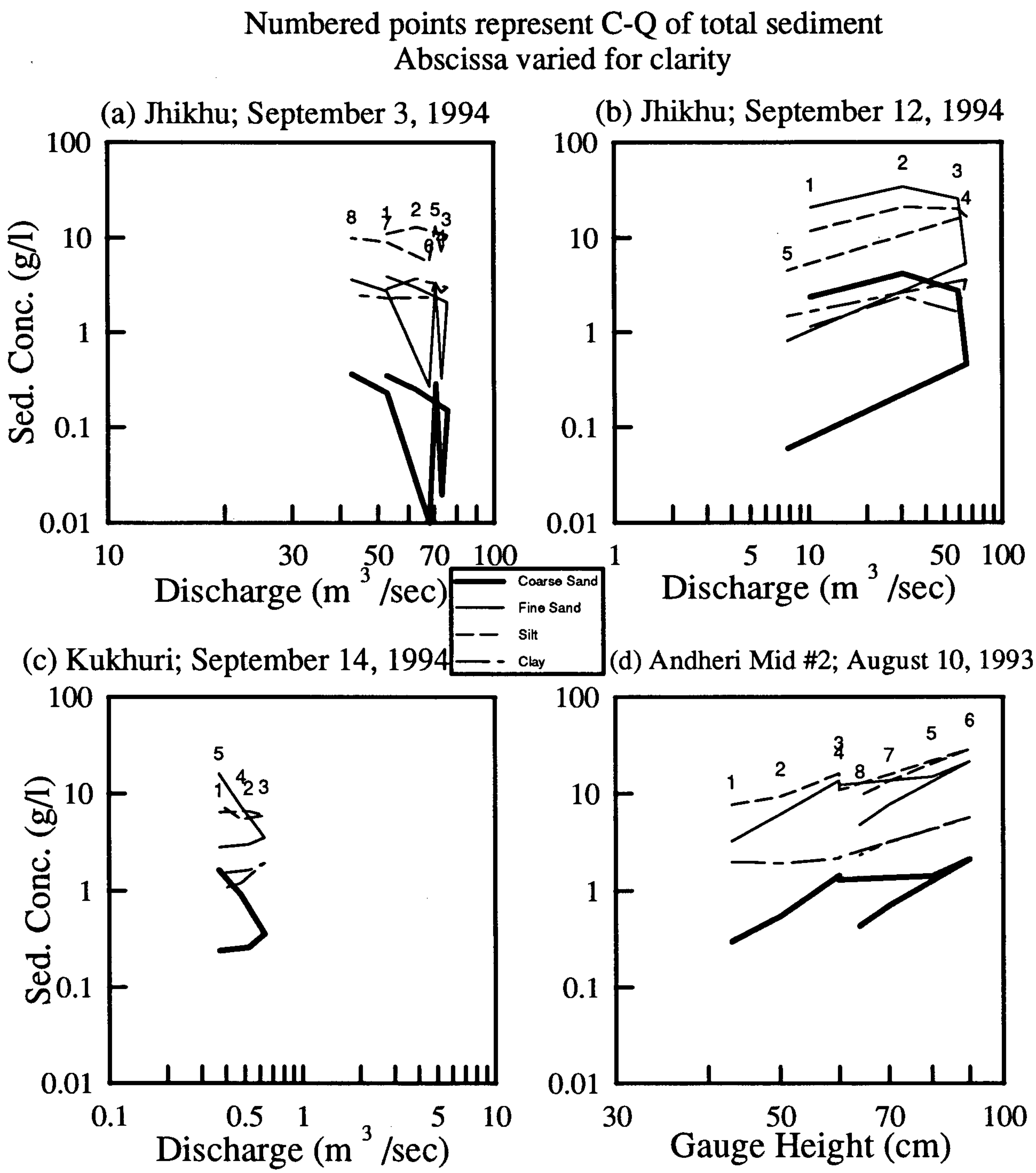


Table 6.12 Number of sediment samples analyses for colour and phosphorus by station and season.

St. No.	Colour					Phosphorus				
	No. events	All	P	T	M	No. events	All	P	T	M
1	55	407	106	48	253	49	201	72	32	97
2	65	471	155	67	249	131	140	56	23	61
3	27	235	62	30	143	23	62	19	18	25
9	36	188	47	25	116	19	45	17	11	17
10	39	157	42	25	90	22	56	19	12	25
11	20	131	61	22	48	10	31	13	7	11
12	11	60	8	20	32	11	63	8	22	33
Σ	n/a	1649	481	237	931	n/a	598	204	125	269

P - pre-monsoon season; T - transition season ; M - monsoon season

objective quantities. This is easily done with phosphorus (orthophosphate - see section 3.2.1) but is not as straightforward with sediment colour. Four classes of sediment colour are recognised on the basis of Munsell soil colour charts: red, yellow, brown, and light brown. Yellow soils, though infrequent in the Jhikhu River landscape are associated generally with degraded soils and exposed parent material. Red soils are common as are brown soils. Pale brown sediments result from mixtures of various soils and occur infrequently. Red and brown dominate overwhelmingly the colour of suspended sediments and conveniently provide starkly-contrasting colour for objective description. "Red" sediments possess a chroma of at least 6, a value of at least 5, and a hue of 2.5YR, 5.0YR, or 7.5YR (10YR and 2.5Y are yellow). Otherwise, if either the chroma or value does not meet this criterion, then it is brown unless the value is at least 7 in which case it is light brown.

These properties have been determined for the surface soils of the Andheri basin to yield colour and phosphorus reference maps as shown for Andheri basin in Figure 6.24 along with the locations of the hydrometric stations under consideration in this section. These maps illustrate that the lowland of this basin is dominated by degraded red soils, low in phosphorus. In contrast, the soils in the upland of Kukhuri basin are almost entirely brown in colour, typically with elevated phosphorus content. These distinctions are typical of the Middle Mountains and these differences also exist elsewhere in the Jhikhu River basin (*e.g.*, Dhap basin - see Figure 6.25).

6.5.2 P-Q relations

Figure 6.26 shows the sediment-colour and seasonally-stratified sediment-phosphorus rating curves for Kukhuri basin. The sediments sampled during the three years of this study are uniformly brown and dominantly high in phosphorus, consistent with the source material provided in this basin. In the pre-monsoon season, the sediments possess a higher phosphorus content than their monsoon-season counterparts, with those of the transition season being intermediate.

Figure 6.27 relates the same variables for the Upper Andheri basin (9). This basin is very similar to the Kukhuri basin but contains isolated pockets of degraded soils, dominantly red in colour. This difference is evident in the rating curves: a few of the sediments are light brown and red revealing the effect of the presence of these degraded soils and the phosphorus content is slightly lower than that of this basin's neighbour.

The properties of sediments sampled from these two upland basins present a stark contrast to those sampled at the Lower Andheri station (2) where only 34% of all sediments sampled were brown in colour as evident in Figure 6.28a. In Chapter 4 it was shown that isolated rainfall events are more common over these degraded lowlands than over the upland and more of the sediments are red suggesting that in this basin the red soils are eroded more often. Figure 6.28a also shows that the red samples tend to dominate low-discharge samples whereas the brown samples tend to dominate at high discharge. This discrepancy may be partially explained by the diversion of low discharge samples into *khet* fields so that they are not available for sampling at the Lower Andheri station. There are also far more red sediments during the pre-monsoon season than there are brown sediments. Red and brown soils of the transition season show intermediate behaviour.

Figure 6.24 Soil colour and available-phosphorus maps for Andheri basin.

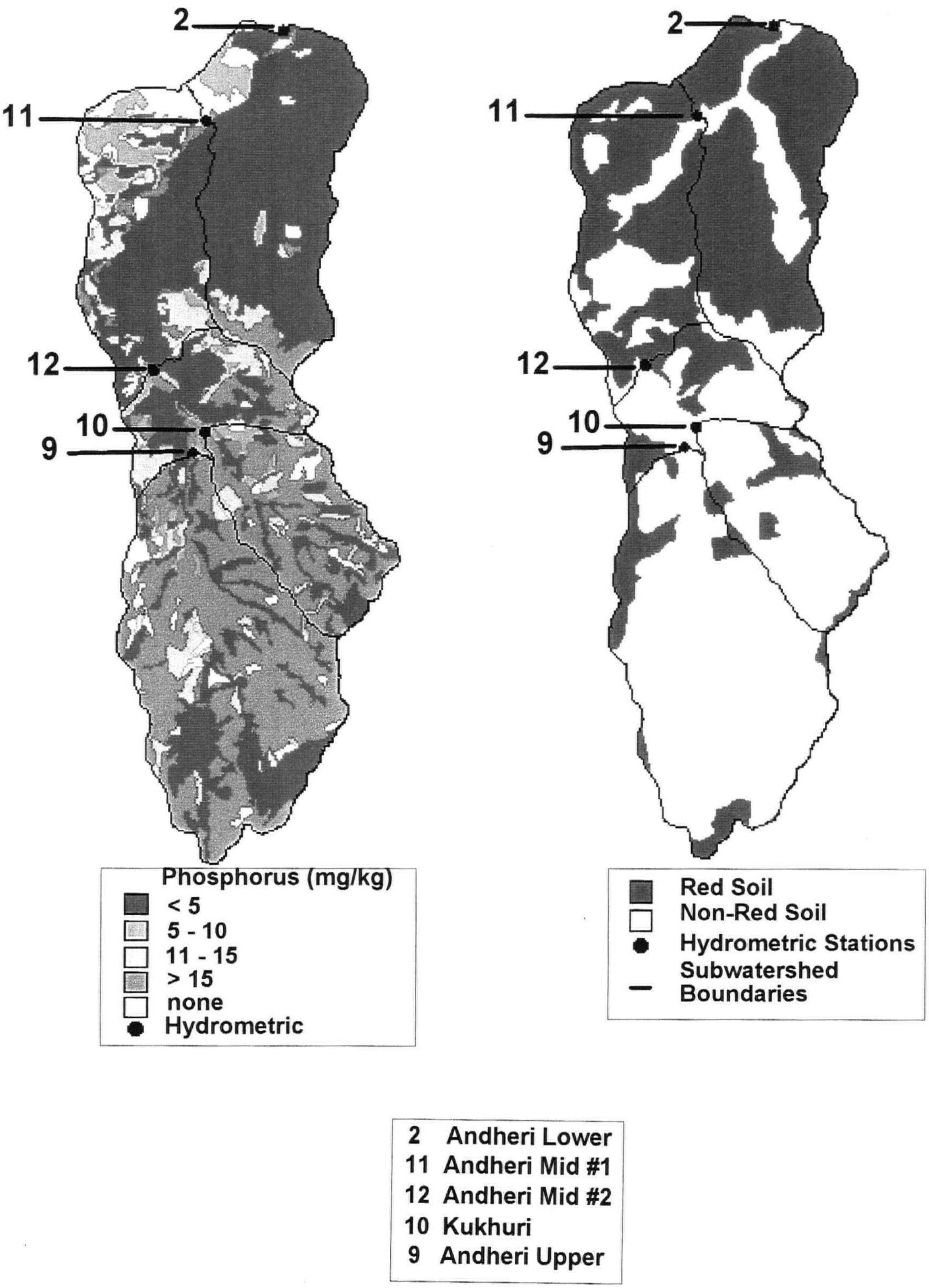


Figure 6.25 Soil colour map for Jhikhu basin.

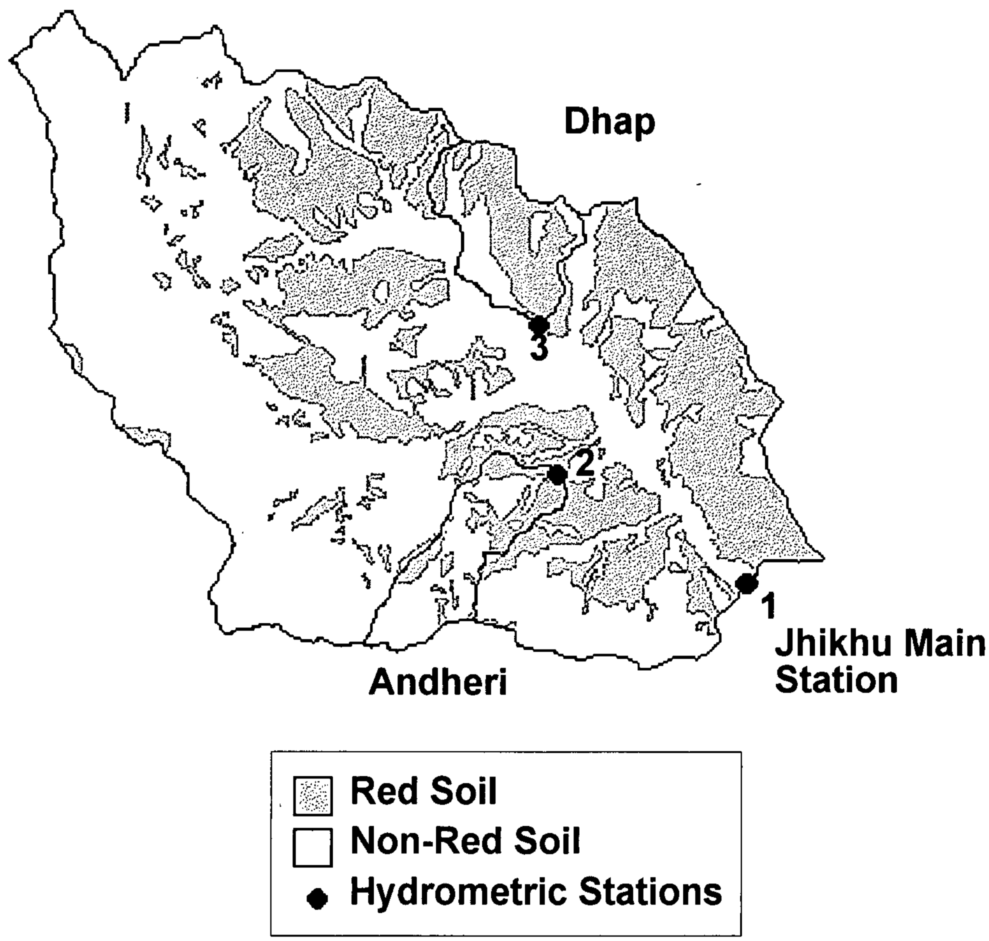


Figure 6.26 Sediment rating curve stratified by colour and sediment-phosphorus rating curve stratified by both colour and season for Kukhuri basin (10).

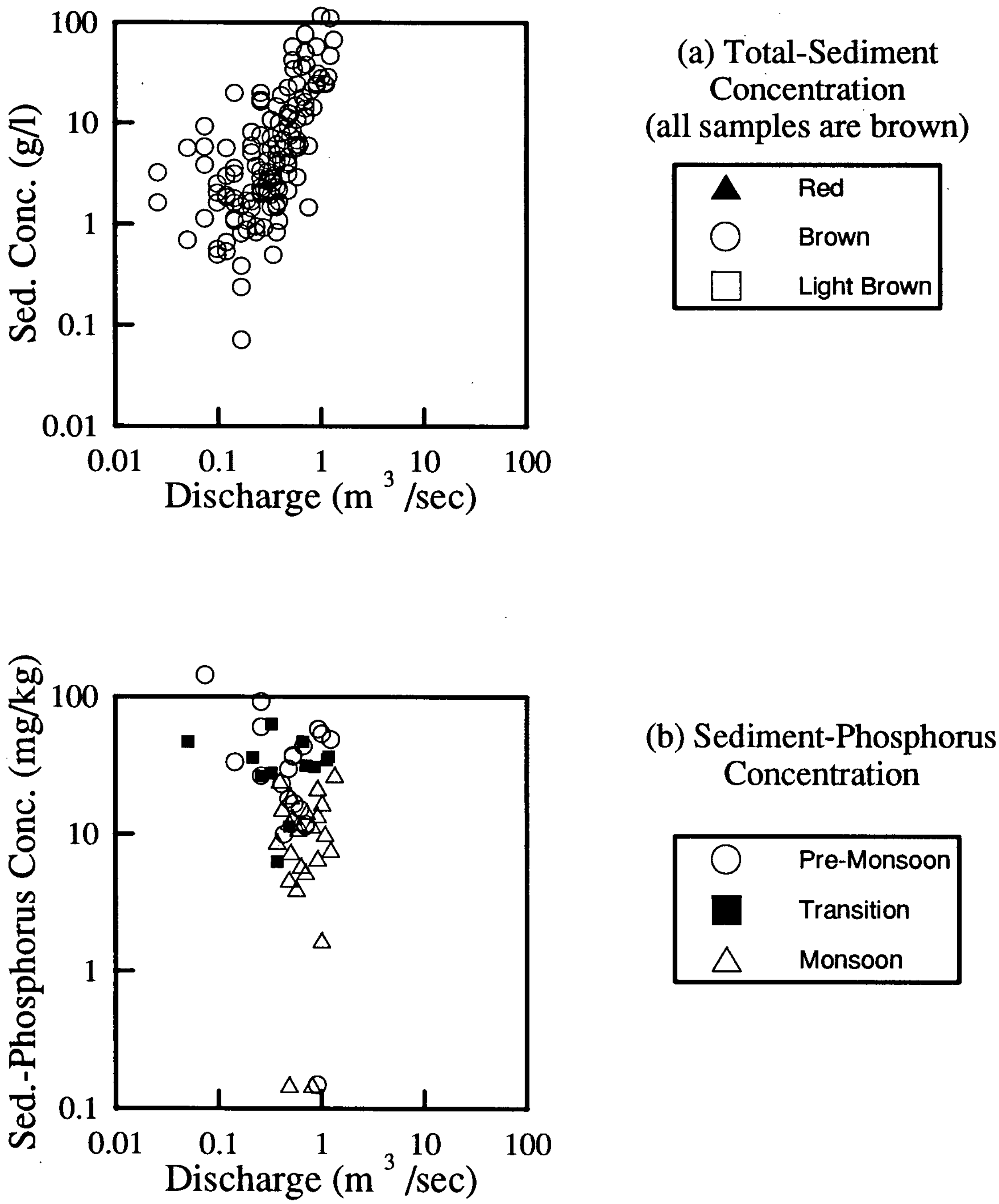


Figure 6.27 Sediment rating curve stratified by colour and sediment-phosphorus rating curve stratified by colour and season for Upper Andheri basin (9).

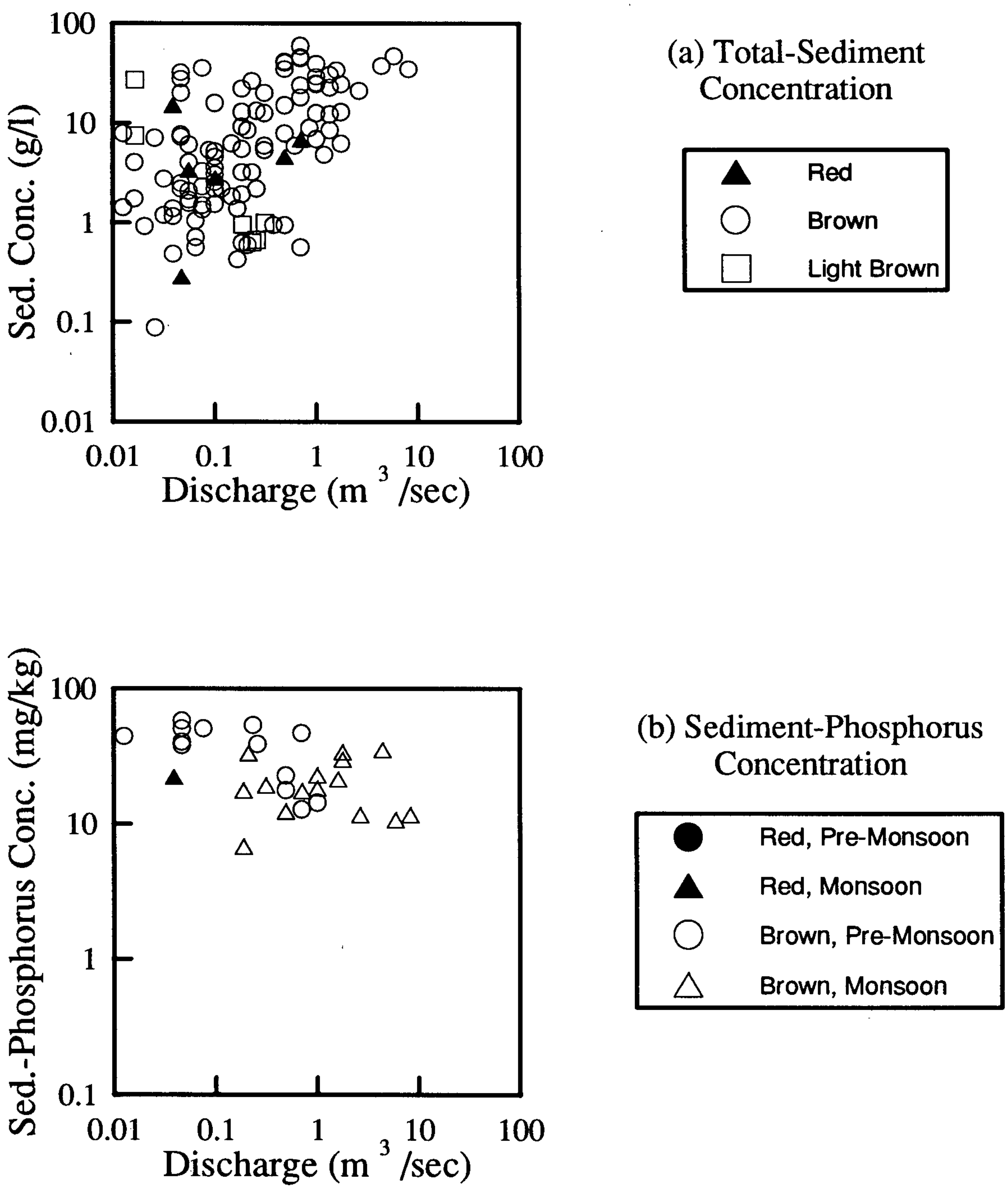
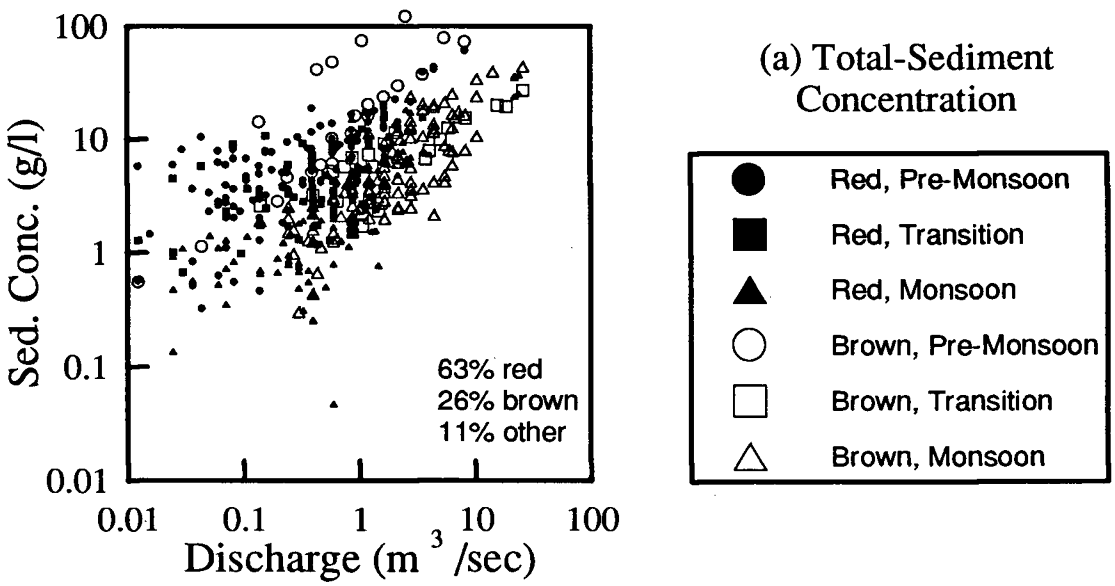
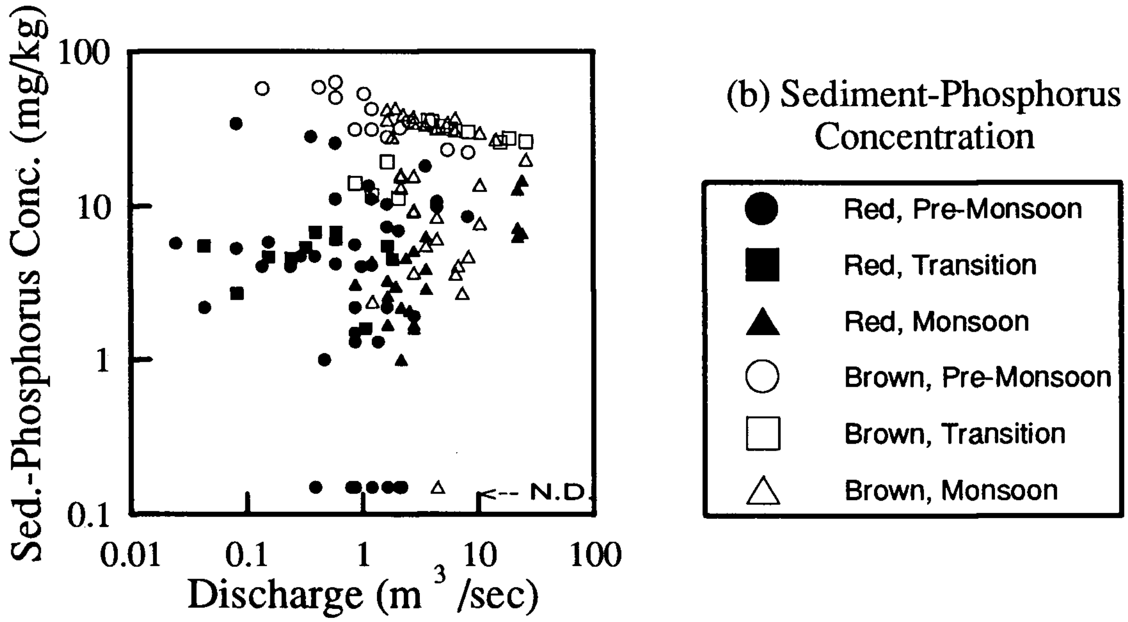


Figure 6.28 Sediment and sediment-phosphorus rating curves stratified by colour and season for Lower Andheri basin (2).





The trends observed in the Lower Andheri sediment-colour rating curves are echoed in the sediment-phosphorus rating curves shown in Figure 6.28b. The range of phosphorus measured in the sediments at this station is much greater reflecting the wider diversity in sediment sources. The monsoon season yields sediments with a lower range of phosphorus than that of the pre-monsoon season while the sediments of the transition season are once again intermediate. Sediments with a high phosphorus content (above 40 mg/kg) tend to be brown while red sediments possess generally low phosphorus (below 10 mg/kg). In addition, phosphorus content is insensitive to season for red samples but depends on season for brown samples.

Figure 6.28b suggests an upper limit to phosphorus content in relation to discharge. Below a ceiling, phosphorus content in relation to discharge is seasonal. During the monsoon season, there is a weak positive relation with discharge due to increased recruitment of clays and silts with the more aggressive rainfall events generally associated with higher stream discharge. Relatively, this increase in nutrient content is large and able to offset the increase in sand which is carried at these higher flows. In contrast, sediment-phosphorus content shows a negative relation with discharge during the pre-monsoon season. High-phosphorus soil is available readily at low flows in this season - as sand transport increases with discharge, this low-nutrient component serves to dilute the high-nutrient clays and silts thereby causing the negative relation. The ceiling can be seen at Kukhuri (Figure 6.26b), Upper Andheri (Figure 6.27b), Dhap (Figure 6.31b), and Jhikhu (Figure 6.34b). This finding has important implications for the agricultural system and in particular monitoring of nutrient loss. It is discussed further in section 8.6 within the context of the *relative* seasonal nutrient loss between the pre-monsoon and monsoon seasons.

These findings can be further examined by repeating the graphs of Figure 6.28 for only upland and lowland rainfall events. Figure 6.29 shows the rainfall distribution for an example pre-monsoon upland event and a lowland monsoon event overlaid on the soil colour map for Andheri basin. Lowland events fall largely on red soils and upland events impinge dominantly on non-red soil.

Recall also that sediment phosphorus content was used as a fingerprint indicating when suspended sediment derives dominantly from either the upland or the lowland (section 5.5.2).

The C-Q and P-Q graphs shown earlier in section 5.5.2 are presented here, stratified additionally by sediment colour. Figure 6.30a shows that sediments from upland events are largely brown whereas those of the lowland events are almost uniformly red. Consistent with Figure 6.28a, red sediments dominate at lower flows while brown samples dominate at higher flows. If this is applied to the phosphorus content, the difference in behaviour of the two areas becomes clear as shown in Figure 6.30b. Essentially all brown sediments originate in the upland and form the envelope of phosphorus content for the plot. Red sediments, whether from upland or lowland events, are consistently low in phosphorus. In fact, all the low-phosphorus sediments during upland events are red in colour. The lack of such sediments at station 10 and station 12 (see below) points strongly to these sediments being re-entrained from bed deposits, originating from the gullied lowlands.

These figures also provide insight into the extent of storage within the channel system. The presence of red sediments from upland events suggests that upland events are re-entraining red soils deposited in the lower reaches of the Andheri River. Local rainfall events over the lowland mobilise considerable material from the active gully headwalls and carry it to the channel. However, many of these smaller events are often unable to carry this material out of the basin, depositing it in the stream channel. Subsequent upland events show this: the first samples are red due to re-entrainment of this material and then the brown samples from recent surface erosion in the upland arrive. Why is the opposite not observed? The irrigation system may be the reason why little sedimentation of brown particles occurs in the lower reaches: the diversion dams effectively truncate the low flows of the sediment rating curve.

Figure 6.31 presents the sediment and sediment-phosphorus rating curves for Dhap basin (3) stratified by sediment colour and season. Red sediments dominate, particularly at high-sediment and high-discharge samples consistent with the prevalence of degraded red soils throughout this basin.

Figure 6.29 Rainfall distribution over Andheri basin for an upland and a lowland pre-monsoon event, overlaid on the soil colour map.

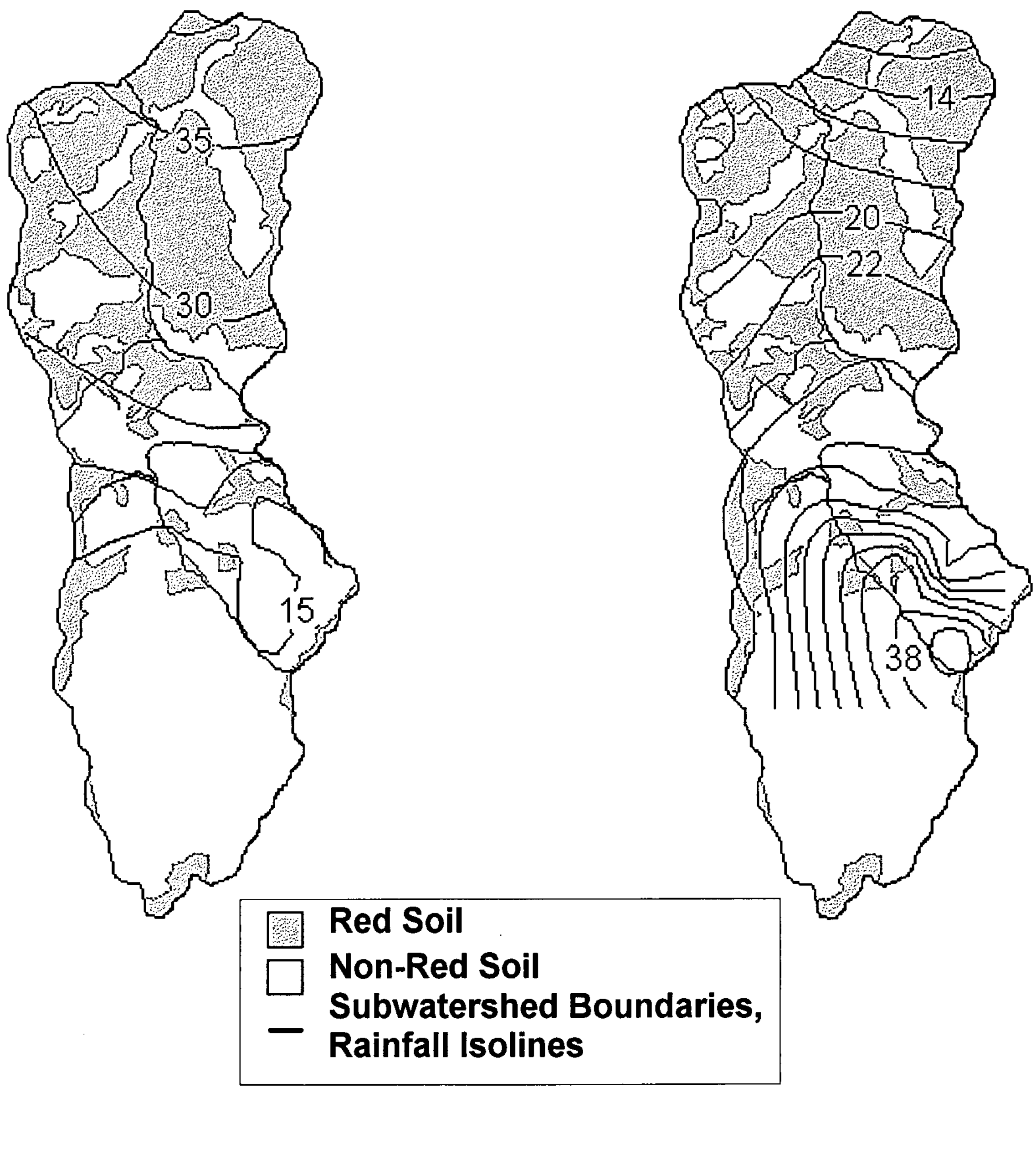
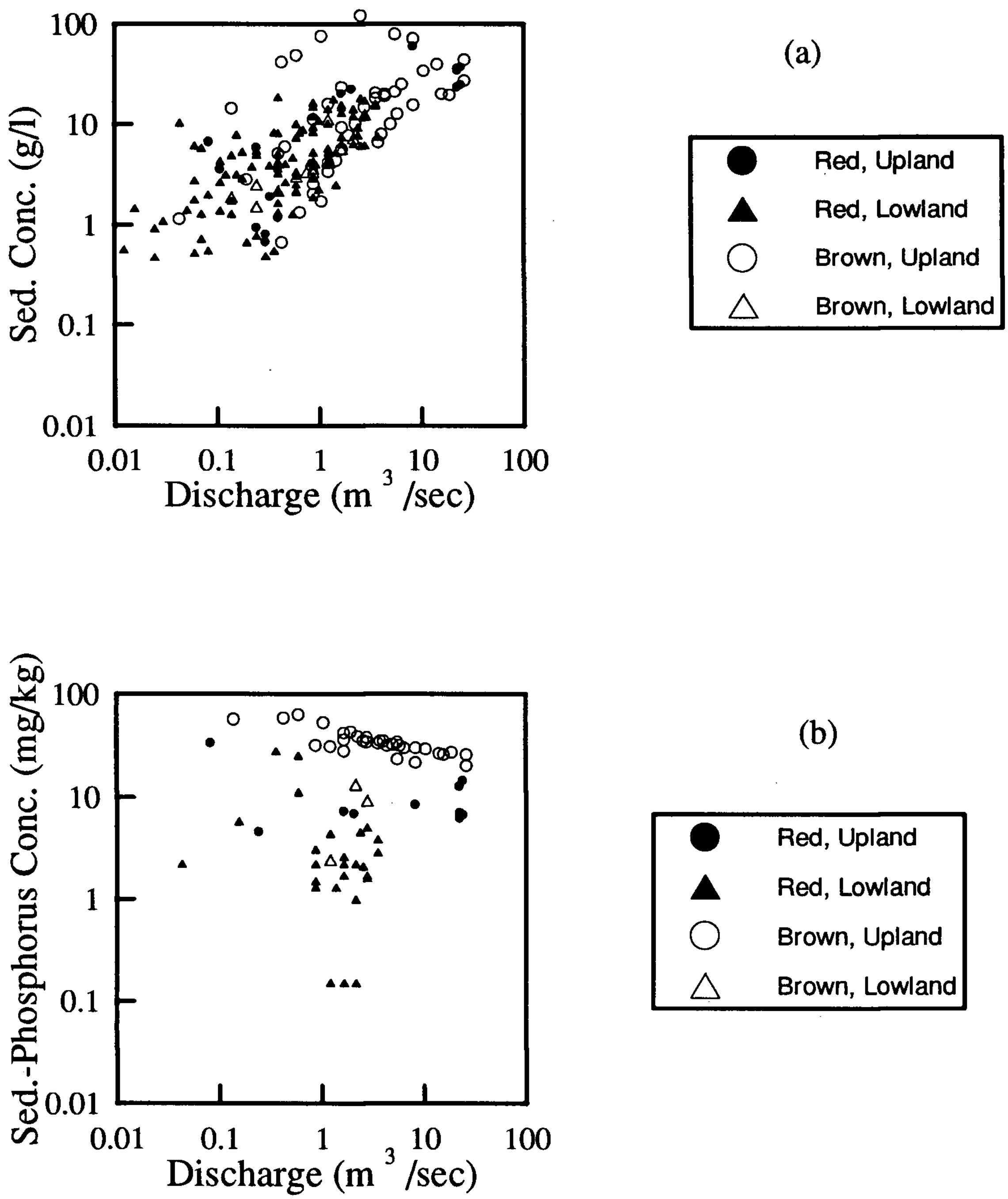


Figure 6.30 C-Q (a) and P-Q (b) graphs stratified by rainfall location (upland and lowland) and sediment colour (red and brown) for Lower Andheri basin (2).



Sediment phosphorus content is consistently low for both red and brown sediments. These findings are also consistent with the lack of a seasonal change in sediment output from this basin.

Rating curves from the mid-reach Andheri stations provide further information about sediment delivery along this channel. Figure 6.32 shows the sediment and sediment-phosphorus rating curves for the higher mid-reach station (12) stratified by sediment colour and season. At this point in the stream, the sediments remain non-red and high in phosphorus. The phosphorus content has declined a small amount due to contributions from degraded forest and shrub land near this station. This is in contrast to the rating curves shown in Figure 6.33 for the other mid-reach station (11) which lies just below the onset of tributary inflow from degraded (red) lowlands. The presence of red sediments is obvious and shows the effect of these tributary contributions. The effect of mixing of brown sediment from the upland with inflow sediment from the lowland is seen in the lower phosphorus content of the brown sediment. The mid-reach stations provide substantial support for the statements made in Chapter 5 regarding the role of these degraded lowlands because they serve to narrow the entry point of red sediment input to the fluvial system.

There is little evidence to suggest that soil colour and phosphorus content lose their effectiveness as sediment fingerprints between 0.7 to 5.3 km^2 in the Andheri basin. Figure 6.34 shows proportionally fewer red sediments at the 100-km^2 scale, in keeping with the smaller proportion of red soils in this basin in comparison with the Andheri and Dhap basins. The strong seasonal shift in sediment concentration noted earlier (in section 5.4) is shown here to be driven by the brown sediments. In addition, the phosphorus rating curve shows that at this large spatial scale, the high-phosphorus sediments continue to be dominated by brown sediments, particularly during the pre-monsoon season. Clearly, the source material has a greater effect than does season on phosphorus output.

Figure 6.31 Sediment and sediment-phosphorus rating curves stratified by season and colour for Dhap basin (3).

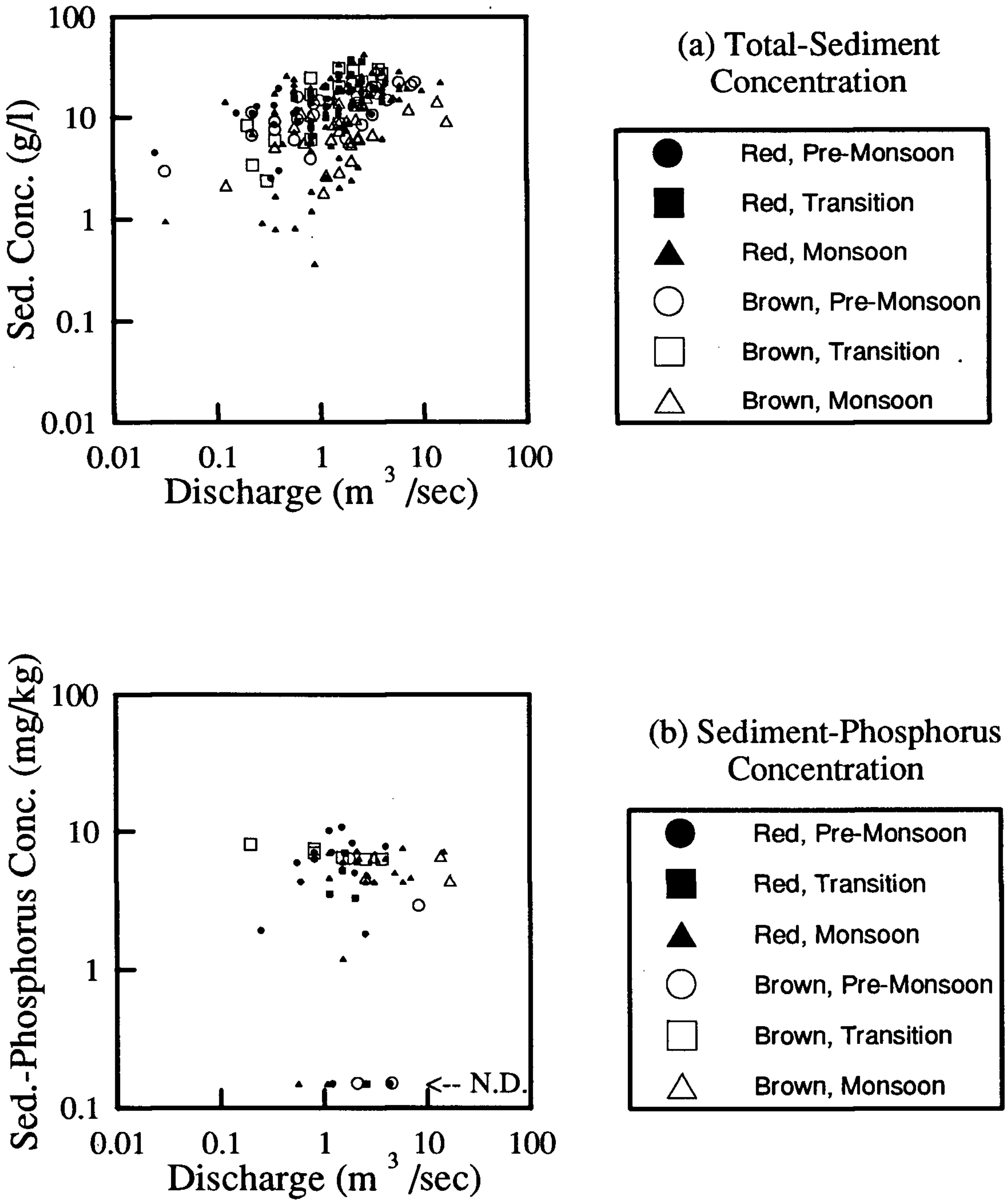
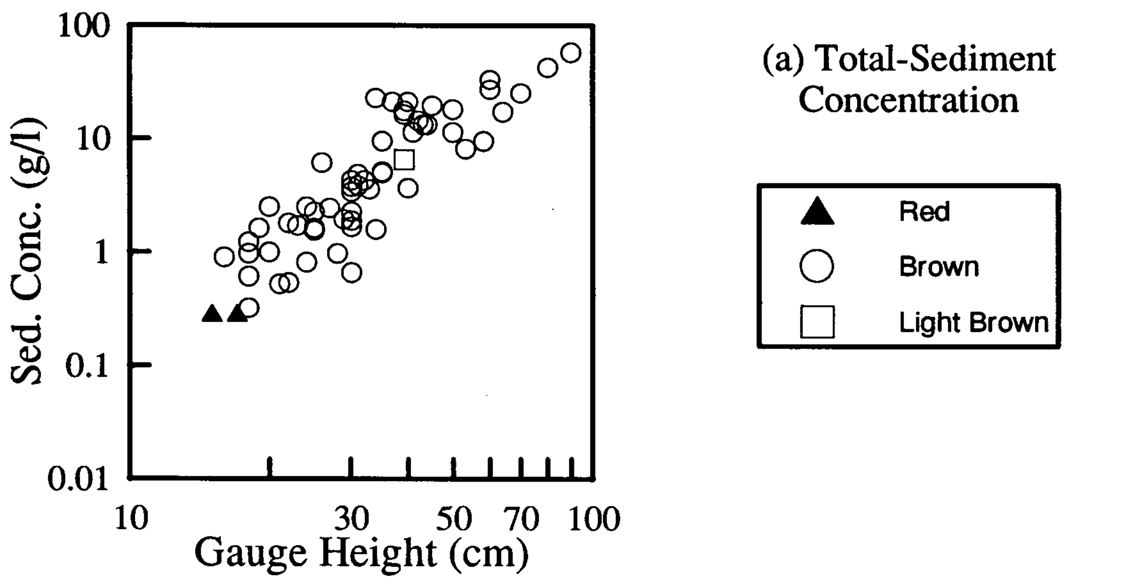


Figure 6.32 Sediment and sediment-phosphorus rating curves stratified by season and colour for Andheri Mid #2 basin (12).



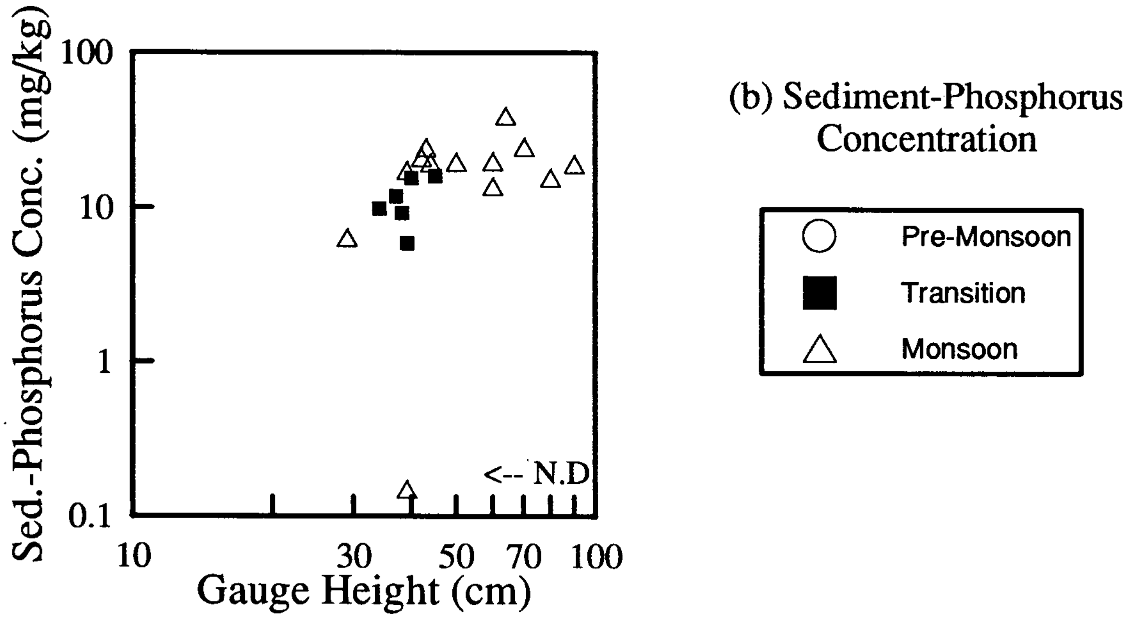
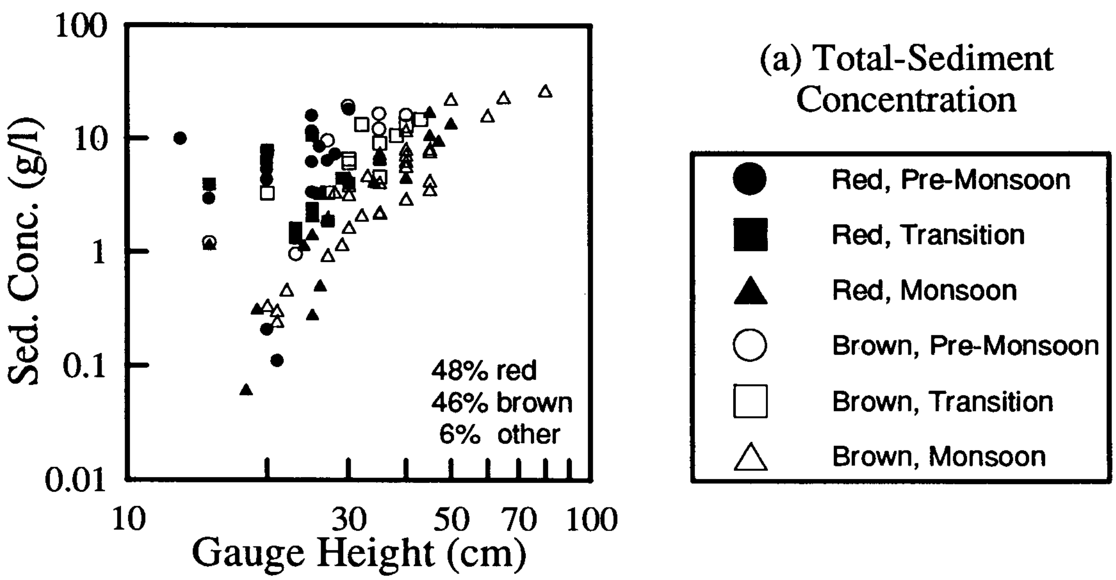


Figure 6.33 Sediment and sediment-phosphorus rating curves stratified by season and colour for Andheri mid #1 basin (11).



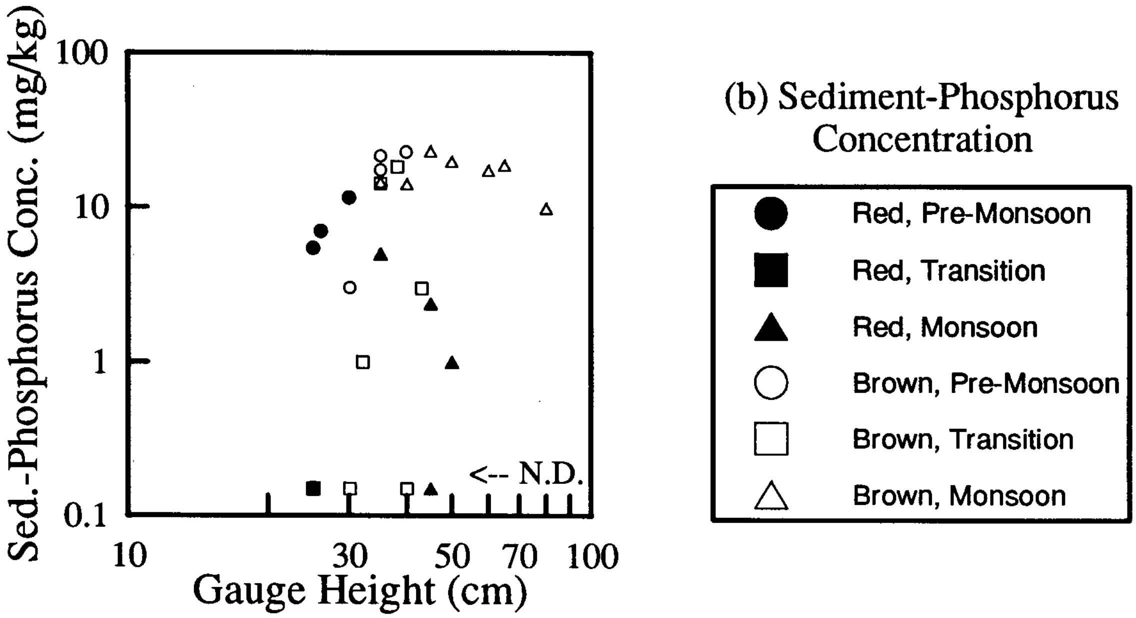
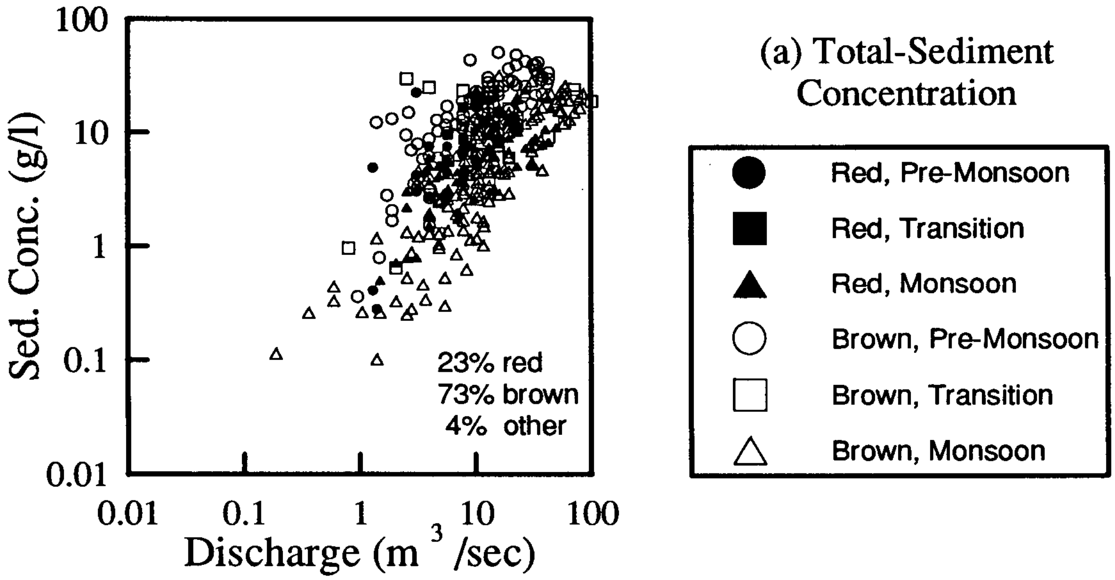
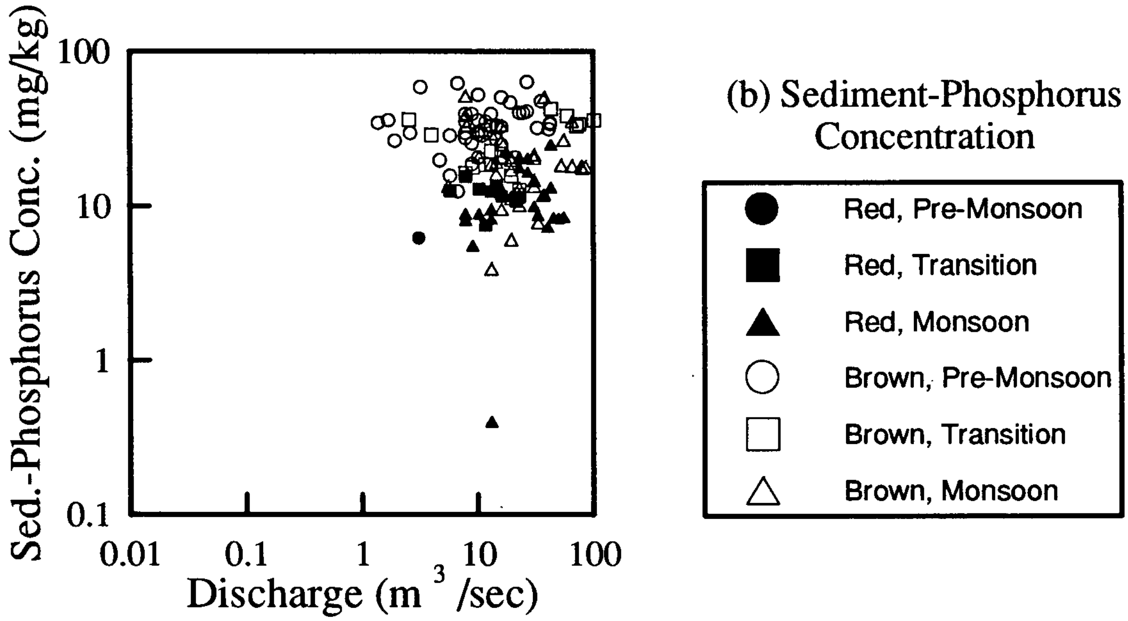


Figure 6.34 Sediment and sediment-phosphorus rating curves stratified by season and colour for Jhikhu basin (1).





6.5.3 Implications

Sediment concentration is not a sufficient indicator of nutrient output from these basins. Table 6.13 presents descriptive statistics by station and season using the sediment phosphorus data. This summary indicates that stations 9, 10, and 1 show higher sediment phosphorus during the pre-monsoon season than during the monsoon season. The stations which are heavily influenced by degraded soils (stations 2 and 3) show an overall lower phosphorus content in the sediment sampled at those stations. These numbers show that when considering nutrient output from the basins, it is important to also consider the relative content of the sediment (see Section 8.6).

Nutrient content is particularly sensitive to the source type and texture of the suspended sediment. Colour is a useful indicator of the source type and discharge implies texture. The seasonal effect on total sediment identified in Chapter 5 is accentuated by these added controls: during the pre-monsoon season, clay and silt export is highest and suspended sediment is dominated by brown upland soils. These nutrient controls enhance strongly the general seasonal control making the nutrient loss during the pre-monsoon season far greater relatively than total sediment loss. Thus, whereas net sediment export is dependent strongly on season, net nutrient export is affected by **both** season and source material.

The fingerprints have also indicated the way in which sediment is redistributed during its passage through the Andheri basin. The lack of brown sediments at low and medium flows at the Lower Andheri station suggests that the diversion dams essentially truncate these flows moving this material into permanent storage in the *khet* fields. The measurements point to limited deposition of upland sediment on the bed and minor re-entrainment by subsequent flows. The evidence also suggests a minor (but greater) level of stream-bed deposition of red soils within the lower reaches of Andheri basin. This information is used when calculating basin sediment budgets in Chapter 8.

The sediment fingerprinting technique is a useful addition to the present study. Taken alone, measurements of erosion and sediment transport can be inconclusive. The techniques chosen here -

Table 6.13 Mean sediment phosphorus content by station and season.

Station Name	Station No.	Season	N	Mean (mg/kg)	Standard Deviation
Jhikhu	1	P	72	28.9	15.2
		M	97	19.3	10.7
Lower Andheri	2	P	56	14.2	17.3
		M	61	13.9	13.4
Dhap	3	P	19	4.7	3.4
		M	25	5.0	2.0
Upper Andheri	9	P	18	39.1	13.9
		M	17	20.5	8.3
Kukhuri	10	P	20	38.5	32.4
		M	35	11.0	7.0
Andheri Mid #1	11	P	13	8.2	7.5
		M	11	11.4	7.8
Andheri Mid #2	12	M	13	18.4	8.8
Jhikhu	1	All	201	23.3	13.3
Lower Andheri	2	All	144	13.9	14.9
Dhap	3	All	62	5.0	2.8
Upper Andheri	9	All	46	27.4	15.9
Kukhuri	10	All	57	25.4	24.5
Andheri Mid #1	11	All	31	8.7	7.9
Andheri Mid #2	12	All	19	16.2	8.2

especially measuring colour - are simple to carry out and they build confidence in the diagnosis. Its application in this study suggests that the fingerprinting approach is most informative when it incorporates multiple methods. The techniques used here emphasise the importance of isolating the sediment sources when planning the sampling program. However, without the quantitative sampling program, the insights from the fingerprinting study would remain largely qualitative.

6.6 Conclusions

This chapter has used sediment properties and sediment behaviour during individual flood events to identify sources of the residual "unstructured" variance within seasonal ratings. Discharge exercises a strong direct effect on coarse- and fine-sand concentration through hydraulic controls and a weak effect on silt and clay concentration through an induced change in supply associated with heavy rain. Season modifies the extent of discharge-induced changes in supply - differences in sand concentration are greatest in high-order basins whereas differences in silt/clay concentrations are greatest in low-order basins. During the pre-monsoon season, all size fractions are readily available hence an increase in discharge has a limited effect on silt and clay concentrations in comparison with the monsoon season. The high sediment concentrations of the pre-monsoon season are associated dominantly with high silt losses from intensively-managed rainfed agricultural fields and high clay losses from degraded red soils (where they occur).

In addition to these differences in the availability and transportability of sands, silts, and clays, spatial and temporal synoptic variability cause further decoupling of the C-Q relation. Hysteretic sediment transport behaviour was observed within all basins and seasons. In most cases, the effect is inadequate to persist in seasonal ratings and single-value relations result. Clockwise hysteresis indicative of a supply-exhaustion effect is common, particularly during the monsoon season. The signature of counterclockwise hysteresis was found in one pre-monsoon rating and indicates a combination of plentiful supply, travel-time effects, and storage into the irrigation system. Though seasonal corrections to ratings are possible given adequate basin characterisation, they do not make successful the application of seasonal ratings to single events: spatial and temporal variability in rainfall-runoff response during single events overwhelms the predictive accuracy of seasonal ratings.

These findings suggest difficulty in the prediction of suspended sediment output in the Middle Mountains. Extremely limited data combined with variability over small spatial and temporal scales limit the likelihood of developing broadly applicable relations. Integrating these findings into specific guidelines for monitoring in the Middle Mountains is an area of useful applied research. Several possible responses are suggested here:

1) Always carry out seasonal sampling.

2) Plan to sample in a nested "hierarchical" design.

3) Sample differently for sand and clay/silt fractions. Sands may be predicted hydraulically with limited sampling to calibrate to seasonal supplies. Clay and silt may require repeated sampling at any discharge to compute mean and variance of expected response. Collect sufficient sample volume to leave open the possibility of particle-size analyses.

4) Plan monitoring strictly in accordance to the goals of the project. For example, if basin nutrient loss is to be determined, then sampling should be focused on those fractions (clay and silt) that carry most of the economically important nutrients.

5) Identify all site-specific information available which can be used to improve rating calibrations (*e.g.*, soil colour and soil nutrient status as fingerprints of sediment origin).

6) If sand sampling is required, be careful to select a sampling site and method which can successfully characterise suspended sand concentration.

PART II Management and Implications

7. The Influence of Indigenous Management on Sediment Dynamics

7.1 Introduction

Farmers throughout the tropics and subtropics practise subsistence agriculture on steep slopes. In many instances, high population growth rates have forced them onto previously uncultivated slopes, marginal for agriculture. Stories of high rates of soil erosion and plummeting productivity in these areas are well known. For example, Hurni (1985) explained how recent population increases in the Ethiopian Highlands are threatening the ability of the country to feed itself even in normal years. However, to characterise all developing countries in this way would be a simplification overlooking a broad, empirically-derived indigenous body of knowledge about land management. In this chapter, indigenous management is examined to identify the nature and extent of its influence on sediment dynamics within the study basins.

7.2 Research Background

Interest in research on indigenous knowledge and management has grown enormously over the past two decades. Increased populations and changing patterns of agriculture have brought about landuse intensification and, in some cases, land degradation, causing alarm worldwide. Recent work has emphasised changes as being simply a spiral of cause and effect as population increases amidst a limited agricultural resource base. Other assessments have emerged integrating the history, culture, political and socioeconomic reality of resident populations (*e.g.*, Gupta and Ura 1990; Thapa and Weber 1991), and above all the traditional knowledge present within indigenous societies. Also, Western integrated rural development programs have had a dismal record of success - people continue to get poorer while populations increase. This apparent inability to reverse cycles of degradation and impoverishment has sparked the explosion of interest in indigenous knowledge and management.

This review looks at specific indigenous agricultural knowledge relevant to the management of sloping, cultivated land within Nepal with a focus on environmental perception, soil classification, and soil and water management techniques. The term "indigenous" is defined following Warren (1989) to refer to a localised system developed over time based on a knowledge system expressed in the local language. Such a system is viewed to be in dynamic equilibrium with the environment, influenced by not only innovations emerging from within the system but also by those adopted from other indigenous systems and occasionally also from national and international communities.

Caution should be exercised in not deifying indigenous capabilities. As Reij (1991) pointed out with respect to indigenous knowledge in Africa, management resulting from only indigenous knowledge may not always be efficient enough for today's demands; and indigenous knowledge is developed within a socioeconomic context which is generally different than that of today. He suggested that a marriage of the old and new may be necessary but until more is known about the "old", it is difficult to design progressive and successful project interventions.

7.2.1 Indigenous knowledge

Contemporary worldwide interest in indigenous knowledge has been particularly important in Nepal. Eckholm's condemnation of the future of Nepal (Eckholm 1975) implied that the Nepalese hill farmer was nothing more than an ignorant accomplice in the demise of the mountain agroecosystem. As awareness increased about the unjustified assertions of Eckholm and others, investigation increased into the management regimes of hill farmers themselves and knowledge underpinning their techniques (Johnson et al., 1982; Schroeder 1985; Bjonness 1986; Ives 1987; Gurung 1989; Metz 1989; Brower 1990; Zurick 1990; Muller-Boker 1990; Muller-Boker 1991; Schweizer 1992). Also, if outsider support in environmental planning is to be successful, then ethno-specific knowledge must be known because differences and problems of understanding between western scientists and local populations occur repeatedly (Muller-Boker 1992).

Gurung (1989) described a rich environmental knowledge held by the farmers of the Kakani-Kathmandu area in the Middle Mountains. She described an extensive vocabulary expressing an understanding of landscape, landuse, soil types, and erosional processes present in the region. The farmers' environmental perceptions are based on the visual, tactical, and verbal context and the challenges they have to face. The evidence of the effectiveness of their knowledge is their ability to transform the entire landscape into an agricultural one.

Schweizer (1992) distinguished between indigenous knowledge and the psychological motivation expressed through actual behaviour. In studying the motivation and practice of farmers in the Bamti-Bhandar area of the High Mountains, Schweizer found that farmer *knowledge* of conservation practices was higher than their *attitude* to implement these practices. She noted, however, that conservation behaviour did not depend in all cases on possessing the relevant knowledge because it was also influenced by tradition.

Systems of soil classification

Indigenous people throughout the world have long developed utilitarian soil classification systems to address specific applications (Wilken 1987). Farmers' systems are orientated toward practice whereas modern scientific systems provide widely-applicable models (Sikana 1993). Due to the many applications of soils in traditional societies, many groupings are possible (Wilken 1987). This discussion looks at soil classification exclusively in agricultural applications.

Indigenous classification systems typically use colour and texture as primary characteristics in distinguishing between soil types (Weinstock 1984; Wilken 1987; Dvorak 1988; Muller-Boker 1991; Tamang 1992; Sikana 1993; Turton *et al.* 1994). A wide variety of other soil characteristics provides secondary (or further primary) modifiers. For example, Conklin (1975) described the Hanunoo's system in the Philippines which also uses moisture content, sand content, rock content, firmness, and seasonal (wet/dry) structure.

In conjunction with a larger investigation of indigenous methods of soil management (Tamang

1992), Tamang (1991) examined the indigenous system of soil classification in the Middle Mountains of Nepal. She stated that soil colour and texture are primary distinguishing characteristics. Farmers use the terms *chimtay* (clay-rich), *dumuth* (loamy), *balautay* (sandy), and *dhunge/patray* (stony) to represent the dominant textural classes with broadly different characteristics. Tamang (1992) identified depth, consistency, internal drainage, moisture retention capability, soil temperature, and location as secondary physical descriptors; management parameters used included the availability and source of water, labour requirement, terrace construction, and compost and synthetic-fertiliser requirement.

Muller-Boker (1991) compared the dominant soil types mentioned by farmers in the Gorkha Region of the Mid Hills to the FAO soil classification and pointed out that the two systems can be reconciled. She emphasised that the main difference between western and Nepali soil classification systems is that indigenous systems reflect the soil characteristics relevant for agriculture whereas scientific systems are based primarily on morphogenetic criteria. Beyond texture and colour, soil depth, susceptibility to erosion, and organic matter content are also of concern to the farmers.

Turton *et al.* (1994) described the soil classification system of farmers in Eastern Nepal. They described detailed characteristics of *chimtay raato maato* and *phushro raato maato* and calibrated their observations to Soil Taxonomy (1975). *Chimtay raato maato* is equivalent to a Rhodudult, Rhodustalf, or a Haplustalf whereas *phushro raato maato* is equivalent to a Ustochrept or a Dystochrept. These indigenous soil types are very different in characteristics and the calibration to soil types of Soil Taxonomy is subject to overlap: the indigenous system relies heavily on surface soil structure and workability which can change under management or slope conditions. Great Groups in Soil Taxonomy are less able to change under management.

Indigenous systems vary regionally and with the experience of individual farmers. It is contextual, relative, and site specific (Sikana 1993). For instance, farmers using valley-bottom soils likely possess a different body of knowledge than their nearby hill-farming counterparts. The system is not encyclopedic - an individual's knowledge varies with practical experience. It is through the collective knowledge of many farmers in a region that the indigenous classification system is constructed.

As pressure mounts to increase productivity, researchers seek to establish the relative potential contributions of both modern and traditional systems of soil classification in agricultural development. Efforts to calibrate them conclude that the two are generally consistent (Wilken 1987; Dvorak 1988; Turton *et al.* 1994; Shah 1995) though exceptions occur (Sikana 1993). The indigenous classification system essentially provides the site-specific interpretation needed when applying a universal system. The local system can be used to enhance the effectiveness of an interpretation based on a Western system; if the outcome is re-interpreted back to the farmers' system it will be even more effective.

7.2.2 Indigenous management

Techniques of indigenous soil and water management are documented worldwide (*e.g.*, Wilken 1987 - Middle America; Mountjoy and Gliessman 1988 - Mexico; Reij 1991 - Africa; Alemayehu 1992 - Ethiopia). Studies documenting Nepalese examples are described here - many of the Middle Mountain examples are also found in the study area. Additional techniques observed in the study area are documented in section 7.4.1.

Pakhribas Agricultural Centre (1990) provided a summary of indigenous approaches for soil and water management used by Middle Mountain farmers in the Koshi Zone of Eastern Nepal. Small bamboo mat structures are erected across slopes of wide *bari* terraces to check runoff and trap sediment. Gullying on public land is the greatest problem in the area and check dams of stone within the gully are built to halt the gully growth. Various plants including fodder trees, bamboo, banana, thatch grasses, and Napier grass are used to rehabilitate gully sidewalls. Bamboo is also planted on old landslide scars. Fodder trees are planted along the edges of terraces to stabilise the risers. Mixed cropping, the collection of runoff, and the use of waterways or ditches to act as cut-off drains for run-on are all reported to be in use in Eastern Nepal. Sthapit *et al.* (1988) and Subedi *et al.* (1989)

described their observations of traditional methods used to maintain crop productivity in the Mid and High Hills of Western Nepal. These techniques include green manuring, mulching, composting, *in situ* manuring, mixed cropping, using legumes in crop rotations, short fallowing and early ploughing, shifting cultivation, and the use of farmyard manure and kitchen wastes. Cutting of the terrace riser and trapping of floodwaters are cited as further fertility management techniques. These methods can all help to reduce the soil's erodibility.

Zurick (1990) described *kanlo* built by farmers in the High Mountains of Western Nepal. These vegetated barriers between cultivated fields mitigate channelisation and capture entrained soil particles. Rainfall is lower in the High Mountains so terracing is often avoided. The *kanlo* technique, in widespread use, is in contrast to the labour-intensive terracing system of the Middle Mountains where rainfall is heavier. The farmers in this area acknowledge readily the importance of *kanlo* for soil conservation on their sloping cultivated fields.

The intimate relation between farming and forestry in Nepal (Mahat 1987) has recently brought about a closer scrutiny of indigenous methods of forest management (*e.g.*, Fisher 1989, Gilmour 1989). While the benefits of indigenous techniques are being discovered, the advantage of having the farmers who use the resource put in control of the forest resource has also been amply demonstrated (Bajracharya 1983; Gilmour 1984; Moench and Bandyopadhyay 1986; Messerschmidt 1990; Pardo 1993). "Community forestry" combines many indigenous approaches to forest management with input and experience from other countries (Sattaur 1987; Gilmour and Fisher 1991; Hausler 1993).

7.3 Environmental perceptions and system of soil classification

Any diagnosis of sediment dynamics within Middle Mountain basins must incorporate the actions and motivations of the farmers. This section examines farmer knowledge with respect to physical aspects of soil management. Depth and breadth of erosion and erosion-control knowledge is examined along with the understanding of erosion and soil classification underpinning these technical skills.

7.3.1 Farmer attitudes and perceptions

In 1991, five detailed, open-ended interviews were carried out with ten farmers to examine their awareness, knowledge, and priorities in erosion control and soil/water management (see Appendix A3). These findings are combined with insights gained from *impromptu* discussions with farmers (generally while in their fields working) over the course of the study (1991-1994). The open-ended questions were designed to:

a) encourage the farmers to elaborate as much as possible; and

b) enquire beyond what they can reasonably *know* to test their perceptions of their agricultural environment.

The findings are presented in three sections: awareness, knowledge, and management techniques.

Awareness

Farmers were asked if they were aware of the flooding problem in Bangladesh and its causes. All the respondents indicated an understanding of the regional issue and that it was a controversy. Their responses were generally well-informed, ranging widely on the spectrum of explanations.

Basic Knowledge

Technical farming knowledge varies widely according to farmer age, caste, tenure, and location. Select individuals with exemplary farming skills were easily cited by each respondent - these people were middle-aged males prominent in the community. Tenure - often confounded with caste - also affected knowledge: the individuals actually farming a specific piece of land knew in more detail its soil characteristics and management requirements than did the owners of the land, even when the owners were also farmers themselves. All castes demonstrated comprehensive knowledge about soils though the lower castes possessed an increased level of practical knowledge relating to soil properties perhaps because they work more closely on the land (often being tenant farmers) and cannot risk poor production. Throughout the study area and its nearby regions, a wide variety in level of commitment to good farming practices was readily observed. For instance, while some farmers actively go to the *bari* during heavy rainfall to study patterns of surface runoff and investigate how best to avoid slope failure, others will go only after the rain has ended.

Location was another important factor in determining the level of farmer knowledge. Farmers were almost uniformly uneasy about commenting on soil properties and management requirements of land only a few kilometres away. For instance, valley-bottom farmers who cultivate flat *khet* with no concern about slumping and landsliding were unable to comment on the experience of farmers cultivating *khet* on steep slopes. Yet, these were areas directly up the hillside and were farmed by people with whom they frequently interacted. Similarly, farmers living on steep, hot and exposed south-aspect sites had no idea about the management constraints on the other side of the Jhikhu River valley on steep, north-facing sites. I commented that I had observed different conditions and techniques in the other area and still the farmers showed no knowledge of these constraints. It remains unclear the extent to which they were unaware of conditions elsewhere or unwilling to discuss this openly.

Interviews revealed a thorough understanding by the farmers of the processes of soil erosion and soil redistribution with a rich, associated vocabulary. They demonstrated a detailed knowledge about sites of accumulation and erosion and all farmers were explicit in stating that *bari* soil becomes *khet* soil through processes of soil erosion. At the field scale, they were able to discuss specific locations of accumulation and loss in both *khet* and *bari*. Mass wasting and surface erosion are understood and the farmers responses suggest a detailed classification system of erosion types based on its location in the agricultural landscape. The farmers referred to weak soils and strong soils, analogous to western geotechnical terminology. The erodibility of soils according to texture was clearly understood (sandy soils erode the fastest, clay-rich soils much less so, etc.).

Applied Knowledge

The wide variety of erosion-control methods described by the farmers reveal a long tradition of empiricism. Both structural and vegetative techniques were described (see section 7.4.1 for more details). Walls are effective but labour intensive. Tenacious native plants are exploited where appropriate. Small runoff channels are constructed to decrease channel volume, often during heavy rainfall, and armoured with stone micro-check-dams. If rills are discovered during heavy rain, stones may be placed in them for armouring. Leaves and branches are located below drop points to lessen the flow's erosivity. Trees, though generally considered desirable, are also the source of many production constraints (shading, neighbour conflicts, inability to cut back the terrace riser which provides new soil for the upper part of steep *bari* fields etc.). Notably, the poorest farmers interviewed explained their inability to sacrifice production today for growing trees for tomorrow (for food and soil protection): "the production of this year has to be eaten this year; the production of next year has to be eaten next year". Wealthier farmers, though possessing more options, still indicated that they planted trees primarily near their homes.

The need of farmers to integrate their erosion-control techniques into a complex management system is further emphasised by considering the range of concerns outside of production which they consider before implementing (or not) further action (Muller-Boker 1992). For instance, though they are effective, native erosion-control plants in use and available to them for further use, may not be placed in many locations because of the difficulty of working quickly and effectively amongst some of these plants. They must protect their own physical safety because "the farmers must live within these cultivations". Such safeguards may conflict with erosion-control. The farmers must manage their activities within close proximity to their neighbours and often share resources (*e.g.*, water); the potential for conflict is present requiring frequent compromise.

A major concern mentioned by all farmers was the need for additional labour. The agricultural system in the Middle Mountains, especially in the steeper areas, is extremely labour intensive. Many farmers are poor and live from year to year in growing what they need to eat. Any proposed changes which place further demands on their time - for instance for improved erosion control - must yield dividends quickly if they are to be implemented. Otherwise, only the wealthier farmers are able to accept the associated risks.

Despite all these constraints, every farmer interviewed expressed a willingness to learn new techniques. Old and young farmers alike, they wanted to innovate further but were cautious and unsure of how to achieve further improvements in production and farm sustainability without outside support.

7.3.2 Soil classification

Farmers in the study area rely overwhelmingly on colour and texture to distinguish soil types (see section 7.2.1). However, informal discussions undertaken during 1991/1992 indicated inconsistency in how these terms are used, implying inconsistency in how the soils are managed. Hence, interviews were conducted in 1992 and 1993 to describe the basic terms used in the indigenous soil classification system, to explore consistency in their application, and to investigate soil-management constraints by soil type according to the farmers.

Eleven farmers were asked (see Appendix A3) to select a soil which they know well from their own fields and describe its characteristics and management constraints. The physiographic locations of these 11 sites are summarised in section A3.7 in the Appendix and Table 7.1 summarises the farmers' responses. The responses are generally consistent with the laboratory data also shown in Table 7.1. The farmers' textural description correlates well with clay content - 4 of the 5 soils described as fine textured had more than 36% clay. Stickiness follows clay content though the correlation is less consistent. Coarse-fragment content corresponds poorly with stoniness as does infiltrability. Fertilizer requirement is medium to high for all the soils which is supported by laboratory data indicating low pH and low carbon throughout. *Kaalo* (black) soil is identified as the only soil with high yield regardless of irrigation. This, too, is supported by lab data - this soil's nutrient status is the best of all the soils in this set. Overall, there is reasonable but not excellent correspondence between the farmers' descriptions and the laboratory data. Clay content (and attendant characteristics - *e.g.*, nutrient capacity) appears to be the best single indicator linked to the farmers' descriptions.

Based on the interviews, the lab data, other informal discussions, and the literature (see

Table 7.1 Farmer descriptions of selected soils (1993).

No.	Soil Type	Farmer Descriptions											Laboratory Data							
		Physical Characteristics						Management Characteristics					Physical				Chemical			
		a	b	c	d	e	f	g	h	i	j	k	S	Si	C	Texture	CFC	P	C	pH
1	*khorani*	ash	1	3	1	3	2	2	3	1	1	3	35	33	52	SiL	18	77	0.6	4.7
2	*phushuro*	red-light brown	3	1	1	3	3	1	1	1	1	3	42	48	10	L	16	25	0.4	4.5
3	*balaute-seto*	white, pale grey	3	1	1	3	2	3	1	1	3	2	38	48	14	L	28	14	0.3	4.8
4	*chimtilo*	red-black	1	1	3	3	1	3	3	1	3	3	27	37	36	CL	11	10	0.7	5.1
5	*raato*	red	1	2	3	3	1	2	3	1	3	3	37	42	20	L	6	40	1.1	5.3
6	*raato*	red	2	1	3	3	3	1	1	1	3	2	11	58	30	SiC	6	18	0.8	4.4
7	*phushuro*	dull	2	2	1	3	3	1	1	1	2	2	20	54	26	SiL	35	10	0.9	4.8
8	*balaute*	dark	2	2	1	3	3	2	1	2	1	?	30	50	20	SiL	32	58	0.9	4.4
9	*pahelo*	whitish-yellow	3	2	2	1	1	3	3	1	1	3	21	60	19	SiL	35	13	0.2	4.6
10	*raato-phushuro*	red	1	1	3	1	1	3	1	2	3	3	14	39	47	C	31	0.1	0.5	5.1
11	*kaalo (khet)*	black	1	1	2	?	?	1	1	3	3	2	11	49	40	SiL	17	40	1.2	5.6

Column information:
(a) colour
(b) texture: 1-fine, 3-coarse
(c) stones: 1-few, 3-many
(d) stickiness: 1-low, 3-high
(e) water-holding capacity: 1-low, 3-high
(f) infiltrability: 1-low, 3-high
(g) wet workability: 1-easy, 3-difficult
(h) dry workability: 1-easy, 3-difficult
(i) yield with little water: 1-low, 3-high
(j) yield with irrigation: 1-low, 3-high
(k) fertilizer requirement: 1-low, 3-high

section 7.2.1), the dominant terms used in describing soil types are defined in Table 7.2. While some of these soil names imply detailed soil chemical and physical characteristics and associate closely with certain Great Groups (Turton *et al.* 1994), other soil names involve only one soil characteristic and can occur over a wide range of sites and soil Orders (*e.g.*, *dhoran* - stony soils). Soils are interpreted as mixtures determined by the relative feel and colour of the soils. Colours include red (*raato*), black (*kaalo*), white (*seto*; *kamero*), yellow (*pahelo*), ash-like (*khorani*), brown (*khairo*). Most farmers explain that "loose" (*phushuro*) soils are also colourless. Some farmers choose to provide one colour descriptor for a particular soil whereas another will provide a colour/texture, colour/colour, or texture/texture combination.

In 1992, 16 surface and sub-surface soils from within the study area (see Appendix A3.7) were chosen for identification by 12 farmers. Farmers were selected to represent a variety of villages, geographic locations, wealth (caste), and experience. The respondents were asked to identify the soils (using their indigenous classification system) and indicate which are favourable and unfavourable for erosion and crop production. These 1992 interviews were purposefully designed to be difficult for the farmers to respond to accurately in order to improve my understanding of how they reach their determinations: the soils were provided out of context and included some B and C horizons. Some farmers were unable to provide a soil type partly as a result of this constraint.

Table 7.3 provides the distributions of names used by the farmers to describe each of the 16 soils. We see large variability in farmer response; rarely do half of the terms refer to one soil type. This variance is undoubtedly driven not only by the effects of caste, experience, etc. but also by its contextual and empirical derivation. *Raato*, *kaalo*, *phushuro*, and *balaute* were the most common terms used to describe these soils.

Table 7.3 also presents the results of field and lab analyses of these soils for comparison with indigenous assessments. Given the inherently high level of variability, there is reasonable consistency between the dominant names used, the definitions of these indigenous soil types (Table 7.2), and the

Table 7.2. Definitions of primary terms of indigenous soil classification system.

Soil Name	Symbol	Description
Balaute	B	sandy
Charchare	Ch	very fine stone particles; no stickiness
Chimtiya	C	clay rich; hard when dry; sticky; not red in colour; difficult to work; low infiltrability
Dhumuth	Dh	sandy loam
Dhungen-Dhoran	D	high in stone content
Kaalo	K	black soil - rich in organic matter; loamy
Khorani	Kh	ash colour
Pahelo	Pa	yellow colour
Phangye	Pg	depositional soil near river (high silt/sand content); mixture of soil types
Phushuro	Ph	low in clay and possessing no distinguishing colour; little sand and few stones; loose & easy to work (wet and dry); high infiltrability; low yield
Raato	R	red colour stains fingers; high clay content and little sand; soft and sticky
Seto	S	white in colour

objective analysis indicating that the indigenous system has a basis in soil properties. For example, *balaute* and *phushuro* soils lack clay; *raato* soils are red in colour; *dhoran* soils have a high coarse-fragment content. *Kaalo* soils are not consistently of high nutrient content. The exceptions suggest that there is a large degree of inconsistency making "widespread application" of the system problematic.

Table 7.3 also shows how the farmers manage these soils. Informal interviews and discussions with farmers carried out throughout the study period in their fields, indicated that there is widespread consistency in how they manage specific soil types. These data, however, indicate that it is the exception for the farmers to agree on two of the most important management constraints, namely

Table 7.3 Distribution of terms used by farmers to name specific soils (1992).

Soil	No.	Name used by farmers to describe soil (% of total)													Management				Physical									Chemical		
															Erosion		Prod.		S	Si	C	Text	CFC	BD	Col	I_{10}	I_{basic}	P	C	pH
		B	C	Ch	D	Dh	K	Kh	P	Pa	Pg	R	S	Other	Y	N	L	H	%	%	%		%			cm/hr		ppm	%	
1	19	5	0	11	0	0	0	0	26	0	0	58	0	0	6	6	8	9	23	35	42	C	1	1.3	R	32	7	-	0.1	4.6
2	19	5	16	5	0	0	11	0	5	0	0	0	53	0	18	6	0	21	19	24	57	C	1	1.3	dk R	21	10	-	0.5	4.8
3	17	18	0	0	0	0	12	12	47	0	12	0	0	0	6	0	15	9	40	50	10	SiL/L	7	1.5	YB	5	2	3	0.7	4.5
4	16	25	13	0	0	6	0	0	25	0	19	0	6	6	19	13	8	9	39	46	15	L	8	1.5	dk YB	3	2	18	0.6	4.6
5	16	19	19	0	0	0	13	0	0	0	0	44	0	6	0	0	0	13	37	33	30	CL	3	1.5	dk R	47	16	-	0.4	4.6
6	15	7	13	20	0	0	0	0	33	0	20	7	0	0	13	0	0	4	44	35	21	L	2	1.3	str B	42	32	6	0.7	5.1
7	17	0	0	6	0	0	0	0	35	0	0	47	0	12	0	13	15	0	36	42	22	L	5	-	R	17	5	-	0.6	4.7
8	15	0	20	7	0	7	7	0	13	13	0	0	0	0	0	6	0	0	32	41	27	CL	1	1.5	str B	5	2	-	0.6	4.6
9	18	30	0	0	0	6	0	0	33	6	6	17	6	11	0	25	31	0	47	42	11	L	15	1.5	YR	17	5	4	1.5	4.8
10	16	6	6	6	0	0	44	0	6	0	0	25	0	6	6	6	0	13	28	52	20	SiL	1.2	1.4	RB-YR	21	10	4	0.8	4.6
11	20	25	0	5	0	5	0	0	25	15	0	20	25	5	0	6	0	0	48	33	19	L	0.6	1.4	R	42	32	-	0.1	4.8
12	17	29	6	0	0	18	18	0	18	6	6	0	0	0	13	6	0	9	39	46	15	L	10	1.6	dk YB	3	2	-	0.3	4.8
13	17	0	6	18	0	0	35	0	0	0	0	35	0	6	0	0	0	9	21	41	38	CL	1	1.5	dk RB	21	10	-	0.6	4.6
14	17	29	6	0	0	0	0	0	6	0	0	47	6	6	6	0	0	0	37	34	29	CL	4	1.2	YR	47	16	3	1.0	4.7
15	14	14	0	0	0	57	0	0	14	7	0	7	0	0	13	13	23	0	52	37	11	L-SiL	46	1.3	YR	68	20	22	1.1	5.2
16	17	12	6	6	12	0	35	0	18	0	0	12	0	0	0	0	0	4	39	48	13	L	12	1.3	RB-YR	40	15	4	1.6	4.9
Σ															16	16	13	23												

1) Refer to Table 7.2 for definitions of abbreviations used for soil types.
2) Under management, Y/N means yes/no when asked if the soil presents erosion concern for management whereas L/H means low/high when asked the level of productivity expected from the soil.

S - sand; Si - silt; C - clay
Text - texture; CFC - coarse fragment content
BD - bulk density; Col - Munsell Colour
I_{init} and I_{basic} - infiltration rates
P - phosphorus (mg/kg); C - carbon(%)

erosion and productivity. Inherent in these responses is the variability in the names given the soils. Only 7 of the soils had over 15% of the farmers' responses in agreement. These consistent responses centre around clay content and soil colour: low clay content generally relates to low erosion potential *e.g.*, *balaute/phushuro* (soil 9) has a low erosion concern and low productivity (though soil 4 is an exception) and red soil with high clay content corresponds to the culturally important *raato maato*. The findings from the second set of soils agree with those of the first: there is correlation between farmer description and objective field and laboratory analyses but it is often weak.

The indigenous system of soil classification demonstrates a basis in soil properties as they relate to management. For example, when asked if soils change with time, there were only two different answers amongst all respondents - red soils turn black when compost is regularly added and soils go looser with the steady application of chemical fertilizers.

In summary, this indigenous system can be useful in providing an overview assessment of soil properties as they relate to management concerns. The high degree of variability means that one should be careful in reaching conclusions from limited sampling. In addition, because of regional variation, it is wise to calibrate the terms regionally or locally before making decision based on this information.

7.3.3 Significance

The observations in this section reveal a detailed knowledge by the Middle Mountain farmers of erosional and depositional processes. The farmers are technically competent, enquiring, and willing to innovate and integrate new ideas into their farming system. Farmers' techniques are empirical based on a long tradition. Such technical literacy provides a strong basis for the successful implementation of prescriptions developed from this study's diagnosis.

The section also reveals considerable variability in farmer knowledge and applied skills. Age, caste, tenure, and location are the main factors which influence the awareness and particular knowledge held by individual farmers. The most effective prescriptions will be the ones which are developed and interpreted within the framework of the farmers' knowledge base. Hence, it is important to calibrate the local indigenous classification systems so that any proposals for change within the farming system can be expressed in these terms during extension activities.

7.4 Techniques of water management and erosion control

An overview is presented of indigenous erosion-control methodologies used within the Jhikhu basin on *khet* and *bari* to prevent erosion and mitigate its consequences.

7.4.1 Description of some techniques observed in the Jhikhu basin

Western soil conservation has traditionally focused on preventing erosion on the field. Consequently, interest in indigenous methods has been oriented toward this aspect of soil erosion. However in the study area, farmers use on-field methods as only a part of their overall strategy to contain soil losses to an acceptable level. They employ many methods to recapture eroded material once it has left the field. This differentiation between on-field and off-field methods forms the basis for the following classification of indigenous techniques.

On-field methods

On-field approaches attempt largely to prevent upland erosion through terracing and the use of runoff ditches; mixed cropping and fertility maintenance were described in section 7.2.2.

The myriad terraces seen throughout the hills of Nepal clearly facilitate cultivation but are also their most well-known example of water management. Farmers in Indonesia, China, Thailand, and many other countries (Lal 1988) have developed similar terraced farming systems. Rainfed terraces enable the farmer to control how water moves over the agricultural landscape. Irrigated terraces are flat and bunded to retain water for rice growing. In conjunction with the terraces, trees may also be found on the terrace risers. However, their use is subject to many constraints (shading, production, neighbours) and hence this agroforestry practice is not widespread in the study area.

As Carson (1992) describes, there are many different types of rainfed terraces in Nepal reflecting the full range of physical and socioeconomic conditions. They tend to be outward or sideways sloping to join with other nearby terraces. Some are large, flat terraces with high stone-reinforced risers while others are steeply-sloping with steep (60° to 75°), vegetated risers. Farmers modify terrace characteristics empirically to accommodate local slope and climate demands. In each case, the terrace type reflects the specific topography, climate, and soil type of the site and also the overall productivity and cropping practices of the farming system developed there.

Terraced farming is an activity with a high labour requirement. Without regular maintenance, terraces are barely visible within only a few years (Carson 1992). Although terrace failures obviously need immediate attention if further damage is to be contained, terrace-riser maintenance and ditch clean-out are also essential. Risers are cut back semi-annually to both maintain the structural integrity of the terrace itself (by deterring rodent activity) and improve the thin soil which results at the top of terrace slopes (see section 7.4.3).

Whatever the terrace type, a thorough control of surface-runoff pathways is essential for successful cultivation on steep slopes. In the Jhikhu River basin, permanent and temporary ditches - *bhaal* - are constructed throughout the terraced landscape to remove runoff from the steep fields and direct it quickly to the larger drainage network. Without these small ditches, terraces and hillsides would routinely fail. The ditches are located within the fields to quickly evacuate runoff from a steep slope or above the field as a cut-off drain to prevent excessive run-on to a field from a neighbour's above. Where infiltration rates are low, terrace slope must be high to prevent moisture build-up in the terraced soil which might be unacceptable for crop growth and slope stability.

This human-made extension to the fluvial system acts to make flashier an already rapid hydrological response. For example, in the 0.72-km^2 Kukhuri basin, the time to peak flood discharge after the onset of the peak rainfall is often only a few minutes. Such a rapid removal of surface runoff helps permit cultivation but can in turn also lead to higher rates of downstream bank erosion.

Off-field methods

Off-field methods focus on the management of runoff, the sediment that is carried with it, and the frequent accumulation of this sediment during its passage out of the basin. They either protect against erosion due to concentrated flow or attempt to recapture previously-eroded sediment. These techniques include runoff canals, streambank protection, the irrigation system (dams and canals), and silt traps.

Large volumes of runoff routinely need safe evacuation from these basins. Runoff canals are a necessary extension to the system of runoff ditches in the terraced slopes. These canals are vegetated and permanent and take swollen upland streams of runoff to the natural drainage network. The fast hydrological response of the Middle Mountains causes streams to swell rapidly and be prone to bank erosion. Farmers also protect streambanks and other areas of channelised runoff using tenacious vegetation (Gill 1991) and stone walls. Though originating from outside the area, erosion-control gabions are adopted by the farmers where economically feasible. Gill (1991) also describes several water management techniques, such as the "inverted siphon" related to those employed for erosion control.

The irrigation system captures streamflow, directing it into canals and ultimately irrigated *khet* fields where previously-eroded soil is deposited and often held indefinitely. Diversion dams and irrigation canals are extremely common throughout most streams in the Middle Mountains. With these dams, farmers are able to provide water for rice production and simultaneously capture fertile sediment eroded from upland rainfed terraces. This practice is of particular utility in the pre-monsoon season when a high amount of nutrients is leaving the uplands.

Manipulation of surface-runoff is also pursued to directly influence the fate of the fertile sediments carried by the runoff. In the wider valley bottoms, silt traps are built of stone to admit floodwaters upstream and slowly release them as the flood recedes (Gill 1991). Silt traps enhance the deposition of sediment so that it can be purposefully reincorporated into a productive field (Tamang 1993). In the uplands, where the microtopography is favourable, farmers direct runoff away from one terrace to have it flood directly on to another, depositing its sediment. These practices are particularly important in the pre-monsoon period when sediment quantity and nutrient status are high. Such detailed manipulations require a thorough familiarity with the landscape and a high labour input.

Like the terraces, the networks of canals and ditches need regular maintenance. If deposition in the upland ditches is not removed, the channelised water spills out creating rills and gullies throughout the lower terraces. The soil is removed throughout the year and put on the nearby terrace. Deposition in the irrigation canals must also be removed to allow sufficient water to flow to the irrigated field. Farmers use this soil to build/repair the canal sides.

7.4.2 Irrigated lands

During 1992 and 1993, farmers within the Andheri basin were asked to describe their management of the irrigation system. The questionnaire, given in Appendix A3, includes questions about the diversion dam, the irrigation canal, and the *khet* fields. Thirty-two farmers were interviewed, involving 36 dams. A summary of the quantitative results of this questionnaire is provided in Table 7.4.

Farmers within the Jhikhu basin maintain extensive irrigation systems to grow paddy rice. Networks of canals are built and maintained - often cooperatively - to deliver reliable quantities of runoff to terraced *khet* fields. Diversion dams are built within the steep mountain channels to divert stream runoff into these irrigation canals. The entire system serves as a vast sediment trap and requires constant maintenance throughout the rainy season to function correctly.

Farmers put a large amount of effort into constructing and maintaining the irrigation diversion dams (*baandh*). On average, they spend 7.2 person-days to build a dam on the Kukhuri River (>6°) and 21.9 person-days to build a dam on the lower reach of Andheri River (2-6°) where the dams

Table 7.4 Summary of quantitative results from farmer interviews about the irrigation and *khet* system.

	Diversion Dam								
	Area Irrigated (ha)			No. Days to Build			Soil Placed Behind Dam (kg)		
	x	σ	N	x	σ	N	x	σ	N
Gentle	0.92	1.09	17	21.9	19.0	16	4000	3800	16
Steep	0.12	0.07	18	7.2	3.4	17	380	710	15

	Canal					
	Depth of deposition (cm)			No. Cleans Per Year		
	x	σ	N	x	σ	N
Gentle	12.3	9.0	15	2.2	0.8	17
Steep	15.3	6.2	14	1.7	1.3	14
Combined	13.8	7.9	29	2.0	1.1	31

	Khet												
	Riser Cutback (cm)			No. Cuts Per Year			Reasons Cited for Cutback						
	x	σ	N	x	σ	N	Tot	So	Sh	C	A	St	R
Gentle	3.7	1.5	18	1.7	0.5	17	15	15	9	6	4	3	0
Steep	3.3	1.3	17	1.4	0.5	17	17	16	2	4	3	2	4
Combined	3.5	1.4	35	1.5	0.5	34	32	31	11	10	7	5	4
							%->	97	34	31	22	16	13

Note: gentle = 2-6°; steep = 6-30° + (slope of stream where diverted)
So = Provide soil for fertility and levelling
Sh = Reduce shading
C = Reduce root competition by grasses
A = Indicate that terrace is active to discourage through traffic
St = Improve riser stability
R = Discourage rodents from deteriorating the riser structure

must be much larger. A dam on the Kukhuri River requires that, on average, 710 kg of soil be transported and placed behind the dam after initial construction. The larger dams on the Andheri River require about 6 times this amount. They generally repair these dams within a few days of any damage though availability of stone can limit the repairs. In 1992, every dam within the entire Andheri basin was destroyed by a large runoff event on July 10. This vast expenditure of labour is a reflection of the value placed on the rice crop grown in the *khet*. It also serves as a mechanism to divert eroded soil into long-term storage as a result of deposition in the irrigation system.

Farmers say that it takes only a few floods for the area immediately behind these dams to become filled and the dam to become strengthened by sediment deposition; if the flood is large, it fills up with only that event. Dams on steep streams do not generally fill up with soil. The farmers prefer several smaller floods after construction so that the newly-constructed dam is not damaged before it has strengthened. Each year, up to four or more visits may be required to repair flood damage, depending on the extent of heavy flooding during any given rainy season. Unfortunately, when a dam is destroyed, this soil and sediment is lost from the basin unless it is recaptured by other dams further downstream. The importance of these dams to the Middle Mountain farmers is indicated by the fact that only 3 of the 62 dams within the Kukhuri-Andheri system are less than three years old: the irrigation capacity of this stream using indigenous techniques has been fully exploited for almost a century. The recent pressure on the land base is reflected in the recent additions of diversion dams. The potential for conflict is also heightened as the level of diversion is raised beyond what the stream can provide.

As sediment-laden runoff flows through the irrigation canals, considerable deposition occurs in advance of the water's arrival in the *khet*. Table 7.4 reveals that the canals, whether high or low in the basin, receive the same level of deposition and frequency of cleaning: an average of 13.8 cm of sandy soil (*paango maato*) is deposited on the canal bed and is cleaned out twice a year. Farmers indicated that the canals are generally 20 cm in width at the base (the sidewalls are vertical). This material is either placed on top of the canal sides to build and re-strengthen them, is placed in the *khet*, or is thrown directly into a nearby stream. Which choice is made is highly variable and depends on the particular situation locally, but overall about half of this deposition goes into the stream and the other half is stored on canal sides or in the *khet*. Given the density of canals present (Nakarmi 1995), this work represents a further substantial labour commitment.

In the *khet*, the farmers direct the water through a maze of pathways designed to maximise the travel time of the water. Farmers visit their fields daily (in most cases) to ensure that this flow through their fields is operating as needed. Considerable deposition also occurs in the *khet* (see Chapter 5 for a discussion of the extent). Before transplanting, great care is taken to ensure that each field is level. A board is dragged and ridden behind a cow or oxen to achieve a level terrace.

The terrace risers in the *khet* are cut back as part of the regular maintenance of the field. The labour required for riser maintenance is substantial and is an essential component of the irrigated agricultural system. They are cut back, on average, twice a year though risers are generally cut back in proportion to the number of crops grown annually in the *khet*. The riser is cut back by 3.5 cm and this soil is almost always put into the *khet* directly below. Over time, this riser cutback serves to advance the *khet* into its hillslope and to widen the valley bottom, modified by frequent adjustment of terrace lay-out and the constant recruitment of fines into the *khet*. Though Table 7.4 indicates many reasons cited by farmers for this practice, soil fertility and soil levelling is almost unanimously held (97%) as justification.

The indigenous irrigation system involves highly sophisticated, labour-intensive techniques. The capabilities of this indigenous technology and the input in labour it requires serve to redirect a portion of sediment within floodwaters out of the stream and into long-term storage, encouraging the redistribution of soil that is eroded from the *bari*. The extent of this redistribution is examined further in Chapter 8 within a sediment-budget framework.

7.4.3 Rainfed lands

In 1992 and 1993, interviews focused on the extent and kind of management used to maintain production on *bari*. Questions were chosen to investigate the farmers' understanding and description of soil and water dynamics. A summary of the interview is provided in Appendix A3. Measurements of soil deposition and drainage lay-out were made within *bari* fields for use in the sediment budget of Chapter 8 (see Table 7.5).

Table 7.5 *Bari*-management data based on farmers interviews and detailed measurements.

Aspect	No. of areas	Interviews						Measurements					
		Riser Cutback		Soil Accumulation				Soil Accumulation			Ditch Dimension		
		cuts/yr	amount/cut (cm)	depth (cm)		cleaning per year		soil depth (cm)			ditch width (cm)		
				x	σ	x	σ	N	x	σ	N	x	σ
N	16	0.96	9.1	7.1	3.81	1.67	0.745	36	4.71	6.67	42	19.67	7.102
S	5	<1	?	10.8	6.56	1.67	0.943	5	3.00	3.29	8	23.52	4.65
All	21	-	-	7.9	4.73	1.67	0.789	41	4.50	3.59	50	20.29	6.915

The farmers interviewed in the Kukhuri basin say that, on average, they cut back the terrace riser 9 cm (Table 7.5), once a year, always depositing the cut soil on the terrace below. They identify two dominant reasons for this practice. First, the upper part of sloping *bari* terraces become soil- and nutrient-poor and the riser soil replenishes this deficit due to erosion, helping to keep the entire terrace productive. Second, they cite less competition for the crop when the riser grasses are cut away. The risers on the south-facing slope are commonly not cut back and, instead, tall vegetated risers and large flat terraces are commonplace. This is possibly due to tradition or because of the hotter microclimate and rocky soils on this slope.

The *bhaal* is a ditch constructed within the rainfed terraces to quickly remove runoff from sloping fields (see section 7.4.1). Farmers said that they started with a depth and width between about 20 and 50 cm. Then, through experience they would modify the dimensions to suit the slope and the size of the *bari*. A few farmers said that they went out at night during heavy rain to investigate what changes were needed in the ditch dimensions. One farmer explained that *bari* size and slope were most important in determining the capacity of the ditch. Presumably, soil infiltrability and "design" rainfall are taken into account empirically when the ditch dimensions are adjusted after construction.

Many farmers direct the runoff onto suitable, lower *bari* fields to recapture previously-eroded soil and nutrients. In these cases, some amount of the soil eroded from *bari* fields is retained within the *bari* and would not be measured by the pins or at any point downstream. It is difficult to assess how widespread is this practice. Some ditches are permanent, vegetated canals, providing a reliable source of fodder. Other ditches are temporary and are reconstructed each time a crop is planted. One farmer reported that he has started using the ditches on some *bari* to capture water for his cattle!

Farmers report that, on average, 7.1 cm of sediment accumulates in the ditches between cleaning and that they are cleaned out 1.67 times per year. The farmers say that this deposition is returned to the terrace or is used to build the side of the permanent ditches (canals). One farmer cleans his ditches after every major rain event. Measurement of total annual accumulation using 138 pins indicated that in the ditches of the Kukhuri basin 4.7 cm of deposition accumulates between cleanings (in 42 ditches). This figure is used in the sediment budget of Chapter 8 because it should more accurately represent accumulation in the year of measurement (1993). It is reassuring that the extent of accumulation reported by the farmers is consistent with the amount measured. Measurements also indicate that the ditches have an average width of 19.7 cm and density in *bari* of about 500 m/ha.

When surveying the damage from heavy rainfall events which occurred in 1992, it was observed that some of the greatest damage occurred in new *bari* fields. This is consistent with the empirical approach followed to determine the ditch dimensions. Once a hillslope is initially converted to *bari*, many farmers will need some significant runoff events before they can adequately size the ditch system on that land. If a particularly heavy rainfall occurs during this initial period, then the new *bari* is susceptible to damage from excessive runoff whereas adjacent *bari*, with ditches sized according to years of experience, remain undamaged.

7.4.4 Significance

The Middle Mountain farmer is extremely active in manipulating soil and sediment dynamics within these headwater basins. From the sediment's origin to its transport and potential deposition downstream, the farmer is an active participant in the process of soil erosion and redistribution. This fact holds important implications for the quantitative component of the present study. The sediment budget and its components discussed in the next chapter must quantitatively reflect the findings presented in this chapter.

The interviews and observations indicate that the farmers are one of the best sources of information on soil dynamics within these headwater Middle Mountain basins. If soil loss is to be reduced, it will be accomplished only with the full participation of the farmers themselves since they are so influential in shaping the fate of soil in the Middle Mountains. Because the farmers' motivation is driven by productivity and not soil conservation *per se*, any effort at improving the effectiveness of indigenous management techniques should incorporate economic considerations as well as creative, technical, soil-conservation innovations.

7.5 Implications of quantitative study for indigenous management

The quantitative study makes estimates of the rate of erosion from *bari* land and the subsequent transport and/or deposition of this material on its passage through the study basins. These analyses suggest that indigenous management modifies the prevailing sediment regime. This section briefly summarises these findings.

On-Field

In Chapter 5, it was determined that surface cover is a primary control limiting surface erosion throughout the rainy season. The sparse vegetative cover of the pre-monsoon season permits huge soil losses in comparison with those incurred from similar rainfall events of the monsoon season. During the monsoon, the indigenous cropping systems aggressively facilitate a complex and strong crop/root protection. Unfortunately, the approach to cultivation during the pre-monsoon season does not equivalently address the significant hazard posed by bare soil on sloping ground subject to intense rainfall present during that season. With the enriched nutrient content during the pre-monsoon season, sediment nutrient losses of the pre-monsoon season are 75-95% of annual total sediment nutrient loss (see Chapter 8).

It was demonstrated that gullied, degraded land within the Andheri basin contributes an equivalent amount to the basin's annual soil loss as does the upland *bari* - the *bari* provides its contribution largely during the pre-monsoon season whereas the degraded land contributes its portion steadily throughout the rainy season.

Off-Field

In Chapter 5, it was determined that basin water delivery was highest during the monsoon season. Though the saturated conditions present during the monsoon season contribute to this seasonal change, it may also be true that the irrigation system is more effective during the pre-monsoon season in diverting and capturing runoff. The irrigation system diverts vast amounts of soil and nutrients with the irrigation water, preventing it from leaving the basin. Hence, the entire indigenous *khet* system serves as a significant sediment trap.

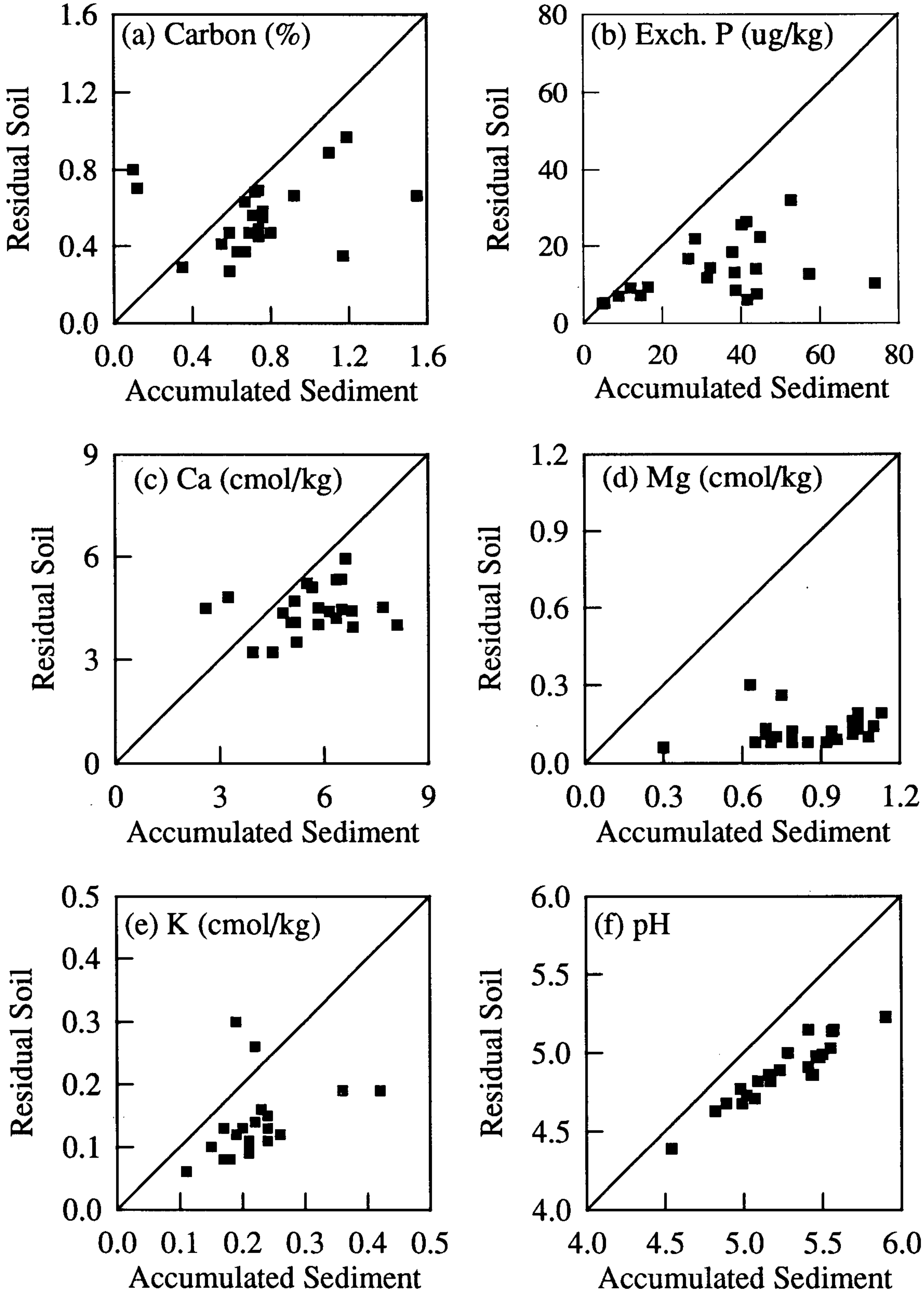
Figure 7.1 shows that sediment deposition consistently enriches *khet* in all nutrients analysed. This material is dominated by clay- and silt-sized particles and a large amount is deposited in the *khet* during the pre-monsoon season.

7.6 Conclusions

Knowledge

- The farmers have a long tradition of empiricism used to apply their knowledge to solve soil-management problems;
- The indigenous system of soil classification is utilitarian and reflects its applied agricultural-

Figure 7.1 Nutrient enrichment in *khet* fields due to annual deposition.



management context; it is a system based in soil properties - correlation to laboratory and field analyses is noticeable but inconsistent.

- The farmers are receptive to new ideas and willing to modify their farming practices using new and useful technologies;
- The application of principles of erosion control must be successfully integrated into a complex farm management system because the farmers' concerns go far beyond those of only soil erosion; and
- Labour is identified as a major constraint to the farmers' abilities to innovate.

Effect on Sediment Dynamics

- The activities of Middle Mountain farmers profoundly alter the sediment regimes of these headwater basins;
- While some practices aggravate soil erosion (*e.g.*, bare fields during the pre-monsoon season), most management activities mitigate basin soil loss resulting in a significant extent of soil recapture; and
- Headwater basins in the Middle Mountains can be interpreted as systems of soil redistribution due to ongoing farmer intervention in the fate of mobilised soil.

8. Sediment Budgets: Implications for Landuse Management

8.1 Introduction

The sediment-budget technique is used to integrate this study's findings to provide a better understanding of the net effect of soil loss and redistribution *within* these basins. Using the sediment-budget approach, this chapter apportions soil loss and soil accumulation according to landuse and calculates net basin loss over contrasting temporal and basin scales. Implications for nutrient redistribution within and loss from these basins are also suggested.

8.2 Research background

The harvest of temperate forests and the increased awareness of sediment-related environmental effects resulting from these activities has led to an urgent need to better understand the effects on sediment regimes of different management practices. The need to identify how sediment is moving within forested basins led to the development of the sediment-budget technique. A similar need is identified in tropical and subtropical agricultural basins where downstream inhabitants are questioning upstream landuse practices when evaluating water quality and quantity issues. However, without an adequate understanding of sediment routing and fluxes *within* the upstream areas, it is not possible to evaluate how changes in agricultural practices in the uplands can modify sediment regimes in the lowlands.

A sediment budget is a quantitative description of the movement of sediment through a single landscape unit (Swanson *et al.* 1979). Dietrich *et al.* (1979) explained that a sediment budget for a drainage basin is a quantitative account of the rates of production, transport, storage, and discharge of detritus and requires:

- recognition and quantification of sediment production and transport processes;
- recognition and quantification of storage elements; and
- identification of linkages among transport processes and storage elements.

To accomplish this, it is necessary to know the detailed dynamics of transport processes and storage sites, including such problems as defining the recurrence interval of each transport process at a place. Management activities can affect each component of the sediment budget and should be considered in each of these steps.

8.2.1 The sediment-budget technique

Formal erosion studies originated in agricultural applications, particularly with the USA Soil Conservation Service during the early part of the twentieth century. Decades of research in soil physics and in field trials have yielded management tools (e.g., the USLE) effective in many environments for evaluating soil erosion at the field scale (see Chapter 5). Due to the relative simplicity of production and delivery processes within many agricultural basins, concepts like the sediment delivery ratio have enabled reasonably successful basin-scale extrapolation of these field-scale rates.

This empirical approach is far less successful in basins with complex sediment regimes. For example, steep forested basins of British Columbia and the USA Pacific Northwest subjected to road building and forest harvesting present significant challenges due to the wide range present in spatial and temporal variability in sediment production and delivery. Agricultural basins of the humid and subhumid tropics and subtropics present similar difficulties to sediment-budget studies. These basins possess landuse heterogeneity rarely found under temperate agriculture. Steep basins in the tropics and subtropics under terraced agriculture, subject to extreme rainfall, suffer from the episodic nature of sediment production similar to their forested, temperate, humid counterparts.

Budget Components

Sediment-source identification requires understanding of sediment-production processes operating within the basin (Pearce 1986; El-Swaify 1990). In forested basins, this can be difficult because of the wide variety of active hillslope processes able to produce sediment (Dietrich *et al.*

1979) but in agricultural environments, diversity is generally lower. Management activities can alter severely the range of sediment-producing mechanisms present. Because processes of sediment production operate continuously, seasonally and episodically (Swanson *et al.* 1979), it is necessary to stratify the sediment budget exercise accordingly.

Burt (1989) emphasises the importance of understanding basin hydrology due to its direct influence on sediment production. For instance, Keller and Weibel (1991) attributed large differences in specific sediment yield between paired catchments in the Swiss Prealps to a difference in the basins' runoff behaviours. Increases in peak flow resulting from management activities such as channelisation and changes in vegetative cover can increase sediment availability from within channels (Swanson and Frederiksen 1979).

Sediment storage elements in the landscape are the medium through which transport processes act and as such their quantification is an essential part of a sediment budget (Dietrich *et al.* 1979). Reid (1979b) emphasised the need to understand temporary storage to evaluate management impacts such as on spawning gravels and pool in-filling. Conversely, storage can mitigate impacts of management - for instance, a landslide depositing on a bench above a stream can result in no detrimental effect on water quality. Storage is frequently the least understood component of a sediment budget (Swanson *et al.* 1979).

The identification of linkages among processes and storage elements is an essential component of the basin sediment budget (Dietrich *et al.* 1979). These linkages can be used to distinguish amongst the continuum of storage and transport processes such as some clast sizes which move infrequently along the stream bed. Some changes within the basin, for example recent climatic changes, can convert a storage element into an active source (Reid 1979b). Though Harden (1990) recognised the spatial heterogeneity in steepland agricultural basins in the Ecuadorian Andes and stratifies the landscape before extrapolating the units using the USLE, her procedure is in need of a routing and storage analysis provided by a sediment-budget framework.

Reid (1979a) described how flowcharts are used to diagram relations among transport and storage sites during analyses of sediment routing. The operations which are selected depend ultimately on the level of understanding of system function, the amount of relevant information available, and the use to which the flowchart will be put. The flowchart - initially qualitative - becomes increasingly quantitative as understanding increases and can be used to expose conceptual holes in understanding of relations within a system and to pinpoint critical rate-controlling steps.

Scale

The degree to which one process affects another and the importance of a transport process to the sediment budget are both dependent on the magnitude of the process and its frequency of occurrence (Dietrich *et al.* 1979). Wolman and Miller (1960) proposed that the largest portion of the total load in a river is carried by flows which occur, on average, once a year or every two years (bankfull discharge) and that channel morphology is associated with this discharge, not with that of infrequent episodic events. Brunsden and Thornes (1979) agreed that morphology within a landscape unit is heavily influenced by frequent events but suggested that change in *landscape* morphology is associated with extreme, episodic events. Thresholds for change may limit which episodic events can be geomorphically effective (Lewin 1989). Others have emphasised the importance of identifying which scale is of interest in a given analysis of magnitude-frequency (Kelsey 1979; Pearce 1986; Lewin 1989).

Perhaps the greatest limitation of Wolman and Miller's original ideas is that the conclusions were based on independence of successive events (Swanson *et al.* 1979). In other words, the magnitude-frequency of climatic events is not equal to that of geomorphic events because the response of the land surface (geomorphic event) to the force (climatic event) is often affected by the conditions which preceded the event (Kelsey 1979). Each has a different magnitude-frequency relation which, in turn, depends on the spatial and temporal scales under study. Extreme events which weaken the surface and landuse and fire which alter the surface's erodibility can both affect the subsequent susceptibility of the surface to erosion (Lehre 1979).

Given the range of factors which control the effectiveness of a given climatic event on mobilising sediment and influencing the basin sediment budget, climatic factors really dictate the **potential** for catastrophic response rather than its actual occurrence (Baker 1977). For instance, Lyons and Beschta (1983) found that the greatest damage brought by a 100-year flood in Oregon was caused by the increased supply of sediment than by the increased flow *per se*. Baker (1977) found that high-magnitude flood response is also promoted by physiographic factors such as hillslope morphology, soils, rock type, and drainage density. In addition, the relative proportion of overland flow versus interflow and groundwater flow appears to integrate both the climatic and the physiographic influences on the potential for catastrophic floods.

Geomorphic recovery is defined as the time it takes for a basin to lose memory of an event (Wolman and Gerson 1978) and provides an alternative approach to pursuing magnitude-frequency analyses. A given event provides a disturbance to which the basin relaxes: the larger in magnitude and more frequent the disturbance, the longer it takes for the basin to respond sufficiently to have lost memory of the event. Only if the disturbance is of a sufficient size can the landscape pass a threshold for change (Schumm 1979), creating a permanent record of its occurrence until another event of threshold-order magnitude occurs. This approach to episodicity has, built-in, a recognition of the distinct geomorphic behaviour of extreme events. It is also an important subject in determining the minimum sampling necessary for episodic events.

While the sediment budget requires stationarity, the landscape is constantly adjusting to change - for instance, landuse modification transforming a forested landscape into a terraced agricultural one (Swanson and Frederiksen 1979), poor agricultural practices which cause increased floodplain aggradation (Reid 1979b), and the process of deglaciation (Church and Slaymaker 1989). Even the agent of change is likely not constant in magnitude. Nordin (1985) pointed out that most long-term records of stream sediment transport are non-stationary because of response of the sediment regime to landuse change or to a catastrophic event. Douglas (1967) examined basin specific sediment yields concluding that contemporary rates outside the humid tropics cannot be used to reconstruct past rates of sedimentation because human interference has led to an increase. Kelsey (1979) suggested ending interest in magnitude-frequency estimation above 10^2 to 10^4 years due to non-stationarity resulting from climate change and tectonic influences.

Techniques

An impressive array of techniques for measuring the movement of soil and sediment is available for use in sediment-budget research. Their use is guided by an understanding of dominant processes of sediment production and delivery. Reid (1979b) summarised techniques used to evaluate and map sources and storage areas of sediment. Field mapping and aerial-photo interpretation are standard techniques for discrete sources such as landslides. One field season may yield sufficient information about landsliding because evidence remains long after its occurrence (Reid *et al.* 1981). Analysis of sequential aerial photographs and even historic ground photographs, if available, can be useful to determine frequencies and recovery times. However, it is generally desirable to quantify these photographic methods to avoid subjective conclusions (e.g., Brizga and Finlayson 1994). Photogrammetric methods in conjunction with techniques using Geographic Information Systems can be used to quantify sediment production and storage. Portable seismic units can be important in determining the location of wedges of deep soil indicative of long-term sediment storage.

Dispersed sources require a more process-oriented approach to analysis (Reid 1979b). Erosion pins, erosion plots, Cesium-137 dating and other fingerprinting methods at sites of sedimentation, and the measurement of sediment transported in channelised water are commonly used (see Chapter 5). The truncation and burial of soil profiles can be used to indicate the presence of erosional and accumulation sites and can sometimes be available on soil maps (Harden *et al.* 1979). Multiple measurement approaches may be used to address the variety of sediment-producing mechanisms (e.g., Loughran *et al.* 1992).

Integrated approach

Though there has been considerable progress in developing sediment budgets, the technique remains slow to develop. Studies using paired-catchments and representative basins have long suffered from being expensive or of short duration, lacking measurement of storage, and yielding inconclusive results (Reid *et al.* 1981; Dunne 1984). Dunne (1984) suggested that because the sediment-budget approach suffers from being labour intensive, a few days should initially be spent mapping sources, pathways, and grain-size distributions within the study basin. Start with an approximate budget using field techniques and then use these results to design a long-term study (Dietrich *et al.* 1979). Multiple approaches should be used to build confidence in the extrapolations incorporated within the sediment budget. Dunne recommends using basin sediment yield as a check on the other forms of erosion prediction.

Dunne (1984) stressed the need to get away from the separation between field-based research and theoretical modelling to avoid having to document rates of erosion and sediment transport on a case-by-case basis. He suggested retaining the field-based emphasis on the varied forms, spatial distribution, and interconnectedness of sediment mobilisation, transfer, and storage but incorporating simple mathematical models for various steps in the budget. Reid *et al.* (1981) explained that the isolation of individual sources makes possible the evaluation of each sediment production process over a time and space scale applicable to its distribution and frequency regardless of the confines of a single basin. For example, Reid and Dunne (1984) used the unit hydrograph method for runoff prediction combined with the sediment rating curve at culvert outlets to predict sediment yields from forest roads under a range of traffic intensities. Reid *et al.* (1981) pointed out that if the relation between production rates and controlling variables is understood, then reasonable estimates can be made of the effects of changing management practices.

Another promising development is the coupling of erosion studies with rigorous hydrological investigations (Dunne 1984). Water budgets apportion water inputs in a similar manner to the sediment budget technique (Rawat 1987) and as such provide a consistent basis for analysis. A coupling of hydrology and sediment studies makes available to sediment-budget studies a wide range of field hydrological techniques (eg tracers and fingerprints - see Chapter 6).

Swanson *et al.* (1979) presented sediment budget/routing as an analogy to hydrology and nutrient cycling and indicate that they provide a useful framework for a holistic analysis of drainage basin function. Interactions between vegetation and sedimentation systems are numerous and complex: sediment transport and storage constrain terrestrial and aquatic ecosystems while vegetation and fauna influence sediment transport and storage. Sediment-budget and sediment-routing offer great promise in studying drainage basin evolution and the impacts of management practices on sedimentation and on forest and stream ecosystems.

8.2.2 Sediment-yield calculation methods

The Einstein Procedure (Einstein 1950) calculates the total sediment output of sediment sizes which are found in appreciable quantities in a stream bed. Colby and Hembree (1961) simplified Einstein's complex bedload transport formulae, enabling the calculations to be based on only one cross-section. Because this Modified Einstein Procedure derives from first principles, extensive data are required as shown in its application to the Niobrara River (Colby and Hembree 1955) and to Georgian streams (Kennedy 1964). Equivalent predictive relations for suspended sediment loads are unavailable because, unlike the bedload, washload is generally supply-limited and not controlled by hydraulic variables. Hence, washload determinations are based on calculations using limited measurements of discharge and suspended sediment concentration (or a surrogate).

The sediment budgets determined in this study rely heavily on calculations of total suspended-sediment flux at various nested-stream locations. Ideally, when calculating sediment loads from actual records of discharge and sediment concentration, one has available continuous measurement of these variables as a function of time; the product of these two variables is integrated over time increments much smaller than that which causes changes in these variables. Of course, such measurements are a rarity so "direct" computation (Walling and Webb 1981) is generally replaced by estimation procedures.

Walling and Webb (1981) identified two types of indirect load calculation methods. They reported variation of up to five times in load estimates depending on the method chosen. Interpolation procedures are required when the actual discharge and concentration change significantly beyond what is suggested by the continuously-recorded values. In these instances, they found results are more accurate from calculations which weight each concentration value by its discharge at the time of sampling.g., that is, exploiting the complete degree of resolution available in the data.

Extrapolation procedures are the focus of the present study and are emphasised in this discussion. The basic extrapolation procedure involves developing a rating curve relating sediment concentration to discharge based on limited sampling and then applying this relation to a continuous flow record. These relations exhibit typically large scatter in sediment concentration, restricting the accuracy of load calculations. Most efforts directed at improving load calculations involve improving the way that these sediment rating curves are used to predict sediment concentration as a function of discharge.

Load-calculation errors resulting from use of the rating curve technique derive overwhelmingly from error in the concentration variable. Many researchers have recommended careful stratification of the rating curve to reflect the way concentration varies with discharge (Walling 1977a; Walling 1977b; Walling and Webb 1981; Parker 1988; Singh and Durgunoglu 1992). For example, rating curves are frequently stratified by season and hydrograph limb. It is also recommended that separate curves be determined for different ranges of discharge if the data suggest that a single average relation is inappropriate (Singh and Durgunoglu 1992).

Hysteretic behaviour decouples the sediment-discharge relation reducing the accuracy of load calculations based on application of a rating curve. In perhaps the earliest documented example of the rating curve method, Johnson (1942) built a time-of-lead relation as a function of discharge and imposed it on the rating curve. His approach was successful because the direction of hysteresis was constant. Because hysteresis can quickly reverse, no generalised method is available which addresses this error - adjustments based on sampling information must be made on a case-by-case basis (Porterfield 1972).

The lack of high-flow sampling data coupled with the method of log-transform linear regression used to develop the rating curve typically leads to an under-prediction of load (Walling 1977b; Singh and Durgunoglu 1992). The best response to this situation is to improve the sampling at high flow!

Several approaches have been proposed to avoid the under-prediction of the least-squares regression transformation. A variety of corrections have been derived based on statistical arguments (Baskerville 1972; Beauchamp and Olson 1973; Wiant and Harner 1979; Sprugel 1983; Miller 1984; Snowdon 1991; Lee 1994). A multiplicative factor of $\exp(\frac{1}{2}\sigma^2)$ where σ is based on the least squares estimator for the original model appears to be the most accepted statistical response to this source of error. Singh and Durgunoglu (1992) suggested the use of non-linear regression techniques. Loughran (1976) suggests using a Model II regression when there is significant uncertainty in *both* the concentration (dependent) and discharge (independent) variables.

Variants on the rating curve approach involve manipulation of the discharge record before application of the sediment rating curve. Walling and Webb (1981) assessed two forms which are more straightforward to carry out than the conventional rating curve method. Development of flow-duration curves involves a loss of resolution in discharge (it is lumped into classes) which inevitably undermines the net accuracy of the calculation procedure. The load-interval method assembles classes of sediment *load* (in lieu of discharge); the result is predictably more accurate because the classes include variation in both relevant variables rather than in discharge alone.

Rakoczi (1977) has advocated a common-sense approach to dealing with uncertainty in the extrapolation method when calculating long-term sediment loads. He recommended applying the sediment rating curve to selected floods (from a long-term flood record) the magnitude of which make them dominant within the annual sediment load. Then provide ranges of sediment output corresponding to the ranges of flow considered as an "average year". The key to his method is to determine sediment loads for individual floods because the averaging process often obscures understanding of what is really happening. Such an approach works well with a continuous flow record and with a flow regime where sediment transport occurs in discrete identifiable flood events - the situation present in this study.

8.2.3 Case studies

Dietrich and Dunne (1978) stressed the importance of storage and of identifying linkages in the system before beginning the sediment-budget exercise. They computed a sediment budget for a 16.2-km^2 basin in Oregon's Coast Range which emphasises the storage capacity of the valley floor sediments. Due to the high storage capacity of tributary debris fans, a small interannual variation in accumulation in these fans can modify basin sediment discharge without a concomitant change in hillslope condition. Such a change would not be predicted by sediment transport formulae. Similarly, Walling *et al.* (1986) found that 28% of the sediment delivered to a 13-km reach of the River Culm in Devon, UK during November 1982 through May 1984 was deposited within the reach and on the floodplain.

Page *et al.* (1994) assembled a sediment budget for a 32.1-km^2 basin on New Zealand's North Island after a major cyclonic storm. Of the 1.35×10^6 m^3 of sediment production, only 6% was discharged from the basin. Although the rainfall event was the largest of the 93-year record, it produced less sediment than an earlier event in 1938. These comparisons underline the importance of combining climatic magnitude-frequency analysis with an assessment of prior basin condition when determining how extreme or infrequent is a geomorphic event.

The fate of sediment produced by agricultural disturbance is examined by Trimble (1983) in the Coon Creek basin in Wisconsin, USA. He found that 50% of historic, agriculturally-derived, upland sediment production has gone into storage in channels and in the floodplain. Sediment was being subsequently recruited from channel storage bringing about a downstream increase in specific sediment yield.

Lehre (1979) found that landslides in colluvium-filled swales are the dominant erosional agent in a 1.74-km^2 basin near San Francisco. During the measurement period, only 53% of all sediment production was discharged from the basin, the remainder being temporarily stored on slide scars, footslopes, and in gully and channel banks and beds. Sediment was remobilised from this storage only by events with at least a 10-year recurrence interval.

Kelsey (1979) contrasted the residence time of sediment storage on hillslopes versus storage within stream channels in the 160-km^2 Van Duzen basin in north-coastal California. He determined that sediment remains stored on hillslopes during a period of about 1 to 2 orders of magnitude longer than within channels. Infrequent, high-intensity storms trigger debris slides that sculpt the landscape and set in motion the redistribution of sediment stored in channels. He hypothesised that more-persistent, smaller storm events are responsible for transporting the greater volume of sediment in channels. He suggested that infrequent, episodic events are responsible for the major shifts in sediment storage and therefore these events provide the catalysts for significant changes in channel morphology occurring on timescales of thousands of years.

Loughran *et al.* (1992) developed a sediment budget for the 1.7-km^2 Maluna Creek catchment dominated by vineyards in New South Wales, Australia. Of the 2.2 $t \cdot ha^{-1} \cdot yr^{-1}$ overall basin sediment yield during 1971-1986, they found that 96.6% was derived from the vineyards occupying only 10% of the catchment area. Also, only 56% of sediment produced during the study period was transported out of the catchment.

Roberts and Church (1986) used the sediment-budget technique to evaluate the effects of logging practices in four severely-disturbed basins in the Queen Charlotte Islands, Canada. They found that disturbance from logging and road building has increased sediment production from hillslopes but not invariably. Damage to riparian areas due to obsolescent logging practices have initiated sediment wedges within the fluvial system. Once these storage elements are developed, they are persistent and diminish aquatic habitat.

Reid *et al.* (1981) developed sediment budgets for the 375-km^2 Clearwater basin on the western slopes of the Olympic Mountains to assess the importance of road-surface sediment production to overall basin yield. They isolated the road surface component of the sediment budget and measured its contribution over time and space scales applicable to its distribution and frequency regardless of the scale of the basin. They found that road-surface sediment production contributed only 20% to the total sediment budget and of this amount only 80% is attributable to roads along which logs are being transported. It is the fraction less than 2 mm which most affects water quality and fish habitat so they calculated a partial sediment budget of only this fine fraction. In terms of this partial fine-sediment budget, road surface sediment contributed over 35% of total production, an amount equivalent to the fine-sediment production from landslides. The approach used in this study is useful in evaluating management options for decreasing basin sediment production.

Himalayan region

Table 5.1 presented measurements of surface erosion and stream sediment yield available from Himalayan studies. Unfortunately in this region, these production and delivery components are rarely provided within a sediment budget framework. However, these measurements and other related findings can be generalised to provide regional estimates of denudation and yield, useful to developing and interpreting the sediment budget of the present study.

The Himalaya provide a regionally-high geomorphic context for the present study. Major rivers transport large volumes of sediment from the mountains to the Indian Plains. The capacity of this young mountain range to produce sediment is important for rivers with direct connections to the

High Mountains. For instance, glacial-lake outburst floods (GLOF) destabilise channels and deliver tremendous volumes of sediment to the fluvial system. Vuichard and Zimmerman (1986) described, amongst other consequences, how all suspension bridges were destroyed from Namche Bazaar to the Sun Kosi from a GLOF which drained 8×10^6 m^3 of water within four hours into the Dudh Kosi. Sharma *et al.* (1991) documented myriad sediment sources within the snowmelt-dominated Sutlej basin in northwestern India, shaping the development of its sediment-rich, braided river. Goswami (1985) examined both recent (1971-1979) and historic sediment storage (aggradation) within the lower reaches of the Brahmaputra and found that about 70% of suspended sediment delivered is deposited within this 145-km reach. He pointed out that the Brahmaputra has the world's second highest sediment regime and he attributes the high rate of suspended-sediment delivery into this reach to rapid uplift of the Himalaya and the consequent instability and river downcutting. Froehlich and Starkel (1993) hypothesised that under natural conditions, the disturbance from rapid uplift in the Darjeeling Himalaya causes rivers to incise. Their observations suggested to them that disturbance from human activities is causing net aggradation in the channels of this region because the rivers cannot rework all the material delivered. During July 19-20, 1993, heavy rainfall (over 500 mm in 24 hours) in the area southwest of Kathmandu in the Middle Mountains and Terai of Nepal (Dhital *et al.* 1993) produced a sediment yield of 500 t/ha to enter the Kulekhani reservoir which provides most of the electricity for the city of Kathmandu (Galay *et al.* 1995). This event provides a graphic, recent example of the sediment production potential of the Middle Mountains: extensive landsliding damaged severely farming operations and caused the reservoir to lose 6% of its remaining life in one event (Galay *et al.* 1995).

Linkages between landuse activities and downstream sediment regimes are weakened as a result of the dramatic contrasts in scale present in the Himalaya. Lauterburg (1985) suggested that only within the microscale (basins smaller than 50 km^2) does human activity have a direct and visible effect on basin sediment regime. At the mesoscale (basins 50-20 000 km^2 in area), one cannot distinguish the effects of human influence from natural processes whereas in basins larger than 20 000 km^2 (macroscale), natural factors outweigh the importance of human activities. Though his scale distinctions are useful, he appears to have assumed that all human activity is negative; sediment budget studies carried out within the microscale could assist in identifying the sediment consequences of upland farming systems. Hamilton (1987) agreed with Lauterburg and stressed that conservation activities in the headlands will not modify the sediment regime of the distant lowlands but can be very important for the farmers within this "microscale".

Hillslope hydrologic behaviour appears significant to sediment regimes in these upland farming areas. Hamilton (1987) pointed out that forested hillslopes do not intrinsically yield low sediment regimes in comparison to agriculture. The difference depends fundamentally on the quality of the forests and the type of conservation activities that are incorporated into the agricultural system. Loshali *et al.* (1990) found minor levels of overland flow from erosion plots within steep (30°), non-degraded, forested hillslopes in the Kumaun Himalaya. Singh *et al.* (1983) hypothesised that since these forested hillslopes are subsurface flow systems, that the major pathway of soil loss is by landsliding. These hydrological observations can be useful for identifying sediment source mechanisms and routing linkages when combined within a sediment budget framework.

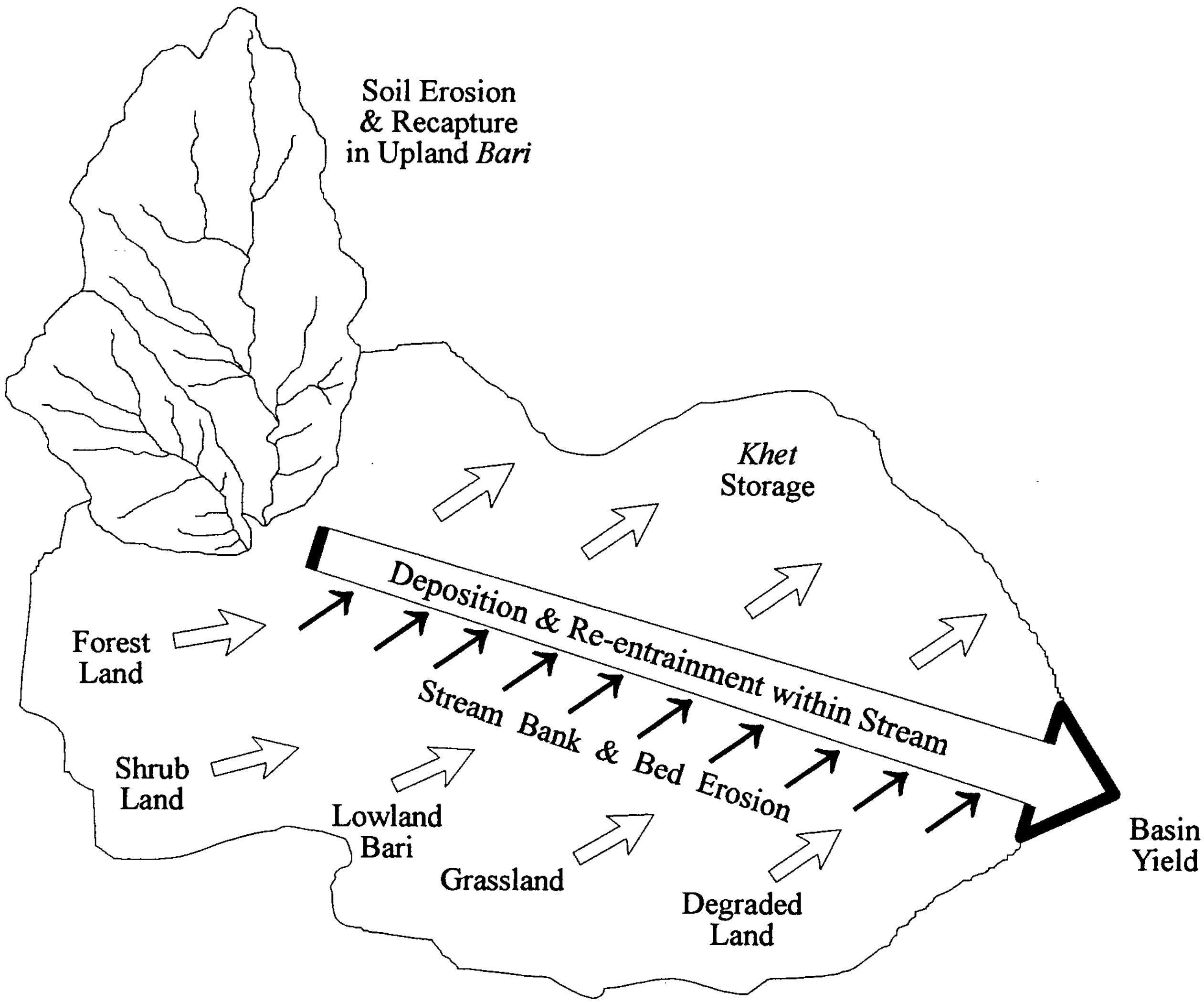
Although sediment budgets for entire basins are not available, several studies have assembled sediment production measurements and estimates for small catchments, spatially extrapolating these rates according to landuse. Combining measurements of soil loss from their erosion-plot study, Overseas Development Agency (1995) calculated an average of 3.2 t/ha sediment production in the 2.6-km^2 Dees catchment of the Middle Mountains. The basin did not contain gullied land and one-third of its area was occupied by *khet*. Carson (1985) used measurements and estimates of sediment production found in the literature to compare overall rates of production within a 0.63-km^2 partially-degraded basin in the Middle Mountains to help guide soil conservation activities. He concluded that mass wasting is a large component of the annual sediment yield from the basin and production from degraded shrub land and abandoned terraces is also significant. Euphrat (1987) carried out detailed measurements of sediment production rates by landsliding within the 0.55-km^2 Pipal Chaur basin in Kabrepalanchok District, near the site of the present study. An average of 10.7 $t \cdot ha^{-1} \cdot yr^{-1}$ was produced by landsliding during a five-year period and 40% of this amount was estimated to be induced by human activity. He noted that it is not unusual for one landslide to dominate the sediment regime of small basins in the Middle Mountains. Using values of surface and trail erosion from other studies, he calculated that landsliding was dominant in only forested areas and streamside zones and, overall, surface erosion was the dominant mechanism of sediment production. Though these three studies did not attempt to identify pathways and linkages and quantify storage, such sediment-production comparisons can be used to improve the effectiveness of soil conservation projects.

8.3 Sediment sources and pathways

Figure 8.1 illustrates the major fine-sediment sources and pathways operating within the Andheri basin and important fine-sediment storage areas. Six important sources of fine sediment are identified: persistent (moderate) surface erosion from *bari* land, mass wasting and severe rill/gully erosion from *bari* and *khet* fields, mass wasting from streambanks, and surface and gully erosion from degraded land, both shrub and grassland. Mass wasting and severe rill/gully erosion from bari and khet fields occurred together episodically and are considered together for measurements purposes. Surface and gully erosion from degraded land is calculated together using an empirical relation. Hence, production is distinguished for four components in the sediment budget.

Chapter 5 showed that surface erosion from *bari* land is of concern during the pre-monsoon season. Conversely, mass wasting from within the cultivated terraced areas (*bari* and *khet*) occurs less frequently and is of greatest practical concern during large monsoon events. An exceptionally large pre-monsoon or late-monsoon event would activate both source types during these seasons; such an unusual event did not occur during the study period. Large monsoon events also undermine the

Figure 8.1 Sediment routing within the Andheri River basin including sources and opportunities for storage.



stability of channel banks and cause slumping directly into channels.

Degraded lands have been shown to be important sediment sources. Degradation takes several forms in the Andheri basin. Large tracts of unvegetated, gullied land are present in the lowland. These areas contribute large amounts of sediment directly to the fluvial system. Shrub land throughout the basin is frequently without adequate cover and suffers losses due to surface erosion. Also, some forested land at lower elevations has a degraded canopy permitting further surface losses.

Short-term storage occurs in the channel system of the Andheri River and other Jhikhu River tributaries. Sediment concentration in runoff is high during the pre-monsoon season and accumulation in the channel occurs largely within the channel's lower reaches. As the monsoon season takes effect, flows typically increase and sediment is less widely available. During this period, the short-term bed storage is re-entrained and removed from the channel. Occasionally (as happened on July 10, 1992), a major rainfall event occurs which drastically reorganises the lower channel reaches. The clastic content of bed material is strongly affected. Changes in production and storage of fine-sediment result from an increase in streambank erosion, and less so by released storage from within the coarse bed. Considerable long-term storage opportunities result within the system of rainfed and irrigated agricultural fields from a high degree of manipulation and maintenance by local farmers (see Chapter 7 for more details).

At larger spatial scales within the Jhikhu River basin, sources remain the same but their relative abundance and the temporal duration of storage opportunities change. Large meander bends of the Jhikhu River near Baluwa store sediment for longer periods than can the tributaries. The large bars present in the lower reaches of the Jhikhu River are also capable of retaining a greater amount of material than can their tributary counterparts. The mix of landuse and topography within the larger basin is different than the Andheri basin which contains a higher proportion of degraded land than is found in the Middle Mountains in general and in the Jhikhu River basin in particular.

8.4 Components of sediment budget

Budgets are computed and presented for the three nested basins - Kukhuri, Lower Andheri, and Jhikhu. A complete flow record is available for these basins along with well-established sediment rating curves. Nested basins provide an excellent basis for contrasting the effect of spatial scale on sediment dynamics. The presence of large gaps in the flow record at the other stations and the lack of stage-discharge relations at the mid-Andheri stations render them unsuitable. Sediment budgets are assembled by considering separately the production, yield, and storage components. The sediment budget for the Jhikhu basin is limited to a basin-yield analysis due to a lack of adequate measurements to address variability within this 100-km^2 scale.

In constructing the sediment budgets, it is necessary to distinguish between normal-regime and episodic-regime behaviour in order to make use of the measurements available in this study. The "normal-regime" is defined here to include erosional mechanisms which occur persistently throughout the entire rainy season: sheet erosion and moderate surface erosion (*bari*, shrub, forest, and grazing) and chronic gully erosion (degraded areas). "Episodic-regime" erosion is defined to consist of erosional mechanisms which occur infrequently - mass wasting and severe levels of rill and gully erosion.

Several significant figures are retained in the estimates presented in order to avoid excessive round-off error. In section 8.5, final budget quantities are rounded to a reasonable number of significant figures.

8.4.1 Normal-regime behaviour

Normal-regime sediment production, and combined normal and episodic-regime storage are presented. Rates are based on measurements from this and other studies and a Geographic Information System is used to extrapolate these components spatially according to landuse. Yield is computed by applying the relation developed in Chapter 5 to measurements made at the hydrometric stations.

Production

Normal-regime sediment production from persistent surface erosion is calculated for each landuse type in proportion to the seasonal and event erosion rates established for *bari*. Most studies to date (see Table 5.1) including this study have presented rates of surface erosion in the Middle Mountains ranging between 0 and 35 t/ha. During 1992-1994, annual soil loss at erosion plot 1 averaged 21.4 t/ha while that of erosion plots 2 and 3 was 24.2 t/ha. However, the hillslopes where these plots are located is slightly steeper than the average (65% overall) and particularly for *bari* fields on red soil. Annual rates of soil loss from erosion plots 4 and 5 were measured to be less than 3 t/ha due to the high infiltrability of their surface soils. These plots help to explain why some studies measure negligible soil loss from agricultural fields on steep hillslopes. Soil loss is sensitive to terrace slope, as evidenced in the results of Overseas Development Agency (1995). In that study, rates of soil loss at five plots averaged 4.8 t/ha because the terrace slopes were between 1.5° and 6.5°, much lower than those of this study (18° at plot 1; 23° at plots 2 and 3). It is concluded that due to the steeper-than-average hillslope where the erosion plots are located in the Kukhuri basin in this study, the average annual soil loss rate for the basin is less than 24 t/ha. In addition, the red soil of the plots may erode more easily than the prevailing brown rainfed soils. Further, the slope of the terraces is steeper than average (based on observation) and results from Overseas Development Agency (1995) reveal the importance of terrace slope. Discounting 24 t/ha by 2 t/ha for each effect leaves 18 t/ha. A 4-t/ha confidence limit allows for the full range of possibilities for the average rate of soil loss from *bari* within Lower Andheri basin. The rate is thus established as 18 $\pm$ 4 t/ha.

Rates of soil loss from landuse under grassland, forest, and shrub are determined proportionately to the rate established on *bari*. Overseas Development Agency (1995) presented rates of erosion measured during 1992-1993 from plots under forest, degraded shrub, grassland, all of similar steepness to those present within the Lower Andheri study basin. Their results suggested that forested land loses soil at a rate of about 10% of the *bari* whereas shrub land - because it is generally degraded - erodes at about 50% of the *bari* rate. Grassland with a complete surface cover, is almost free of soil loss. However, if grassland is degraded, it produces high rates of soil loss - higher than the losses on *bari*. These findings are consistent with visual estimates established independently through observations made throughout the Lower Andheri basin and are used in the sediment budget calculations. Sediment production from severely degraded areas cannot be computed with this approach because these rates can be much higher and are not seasonally sensitive. An alternative empirical approach is used for these areas as described below. These average annual rates are apportioned annually and seasonally based on relative rates of soil loss at erosion plots 2 and 3 measured during 1992-1994 and are presented in Table 8.1. These assumptions are assessed further in section 8.5 in the context of the overall sediment budget balance.

Sediment fingerprinting (Chapter 6) indicates that in the Andheri basin, significant sediment production occurs due to the severely-degraded (gullied) lowlands. A supplementary evaluation of this component of sediment production is carried out using an approach similar to that of Reid and Dunne (1984). Using data from the lowland rain-gauge network, an empirical relation has been derived to predict sediment yield (at the Lower Andheri station) from this degraded land in relation to event total rainfall as shown in Figure 8.2. The relation is developed by using the event sediment yield for only lowland events, and knowing that there are few storage opportunities between the gullied lowlands and the Lower Andheri hydrometric station. Only storm events delivering an areal average of at least 7 mm of rainfall are used in the log-transform linear regression (below this value the behaviour is erratic). The two outliers shown on Figure 8.2 were excluded from consideration in calculating the regression relation. The use of rainfall intensity within a multiple regression did not improve the relation. Using this relation, an estimate can be made of the extent to which sediment export from basin and upland rainfall events is derived from the gullied lowlands as summarised in Table 8.2. In calculating these estimates, allowance has been made for sediment production and storage due to non-degraded lands within the gullied area.

Table 8.1 Annual and seasonal rates of normal-regime sediment production (t/ha) from surface erosion determined for *bari*, shrub, forest, and grassland.

Year	P	T	M	Σ
		Percentage of annual erosion within each season (annual percentages refer to the three-year total)		
1992	68.4 ± 13.7	30.7 ± 6.1	1.0 ± 0.2	42.0 ± 8.4
1993	100 ± 0	0 ± 0	0 ± 0	48.9 ± 9.8
1994	97.0 ± 19.4	1.0 ± 0.2	2.0 ± 0.4	9.2 ± 1.8
		Bari - seasonal erosion rates (t/ha)		
1992	15.52 ± 9.67	6.95 ± 4.32	0.23 ± 0.14	22.7 ± 9.6
1993	26.4 ± 11.2	0 ± 0	0 ± 0	26.4 ± 11.2
1994	4.85 ± 3.01	0.05 ± 0.03	0.10 ± 0.062	5.0 ± 2.1
		Shrub - seasonal erosion rates (t/ha)		
1992	7.76 ± 4.84	3.47 ± 2.16	0.12 ± 0.07	11.35 ± 4.8
1993	13.2 ± 5.6	0.0 ± 0.0	0.0 ± 0.0	13.2 ± 5.6
1994	2.43 ± 1.51	0.02 ± 0.015	0.05 ± 0.031	2.50 ± 1.05
		Forest - seasonal erosion rates (t/ha)		
1992	1.55 ± 0.97	0.70 ± 0.43	0.023 ± 0.014	2.27 ± 0.96
1993	2.64 ± 1.12	0.0 ± 0.0	0.0 ± 0.0	2.64 ± 1.12
1994	0.49 ± 0.301	0.005 ± 0.003	0.010 ± 0.0062	0.50 ± 0.21
		Grassland - seasonal erosion rates		
All	0	0	0	0

P - pre-monsoon season; T - transition season; M - monsoon season; Σ - entire rainy season

Table 8.2 stratifies the production totals by type of rainfall event - lowland, upland, and basin. Of the total 2120 tonnes of sediment produced by the gullied areas during 1992-1994, 25% derives from lowland events while 66% is generated from basin events; only 8% is produced during upland events. Due to the sensitivity of the relation shown in Figure 8.2, these totals and percentages can be considered only as rough estimates of actual production.

Yield

Seasonal and annual sediment yields for each spatial scale are calculated for each year of the

Figure 8.2 Sediment yield at Lower Andheri in relation to average rainfall for lowland events and corrected for included production and storage from non-degraded land.

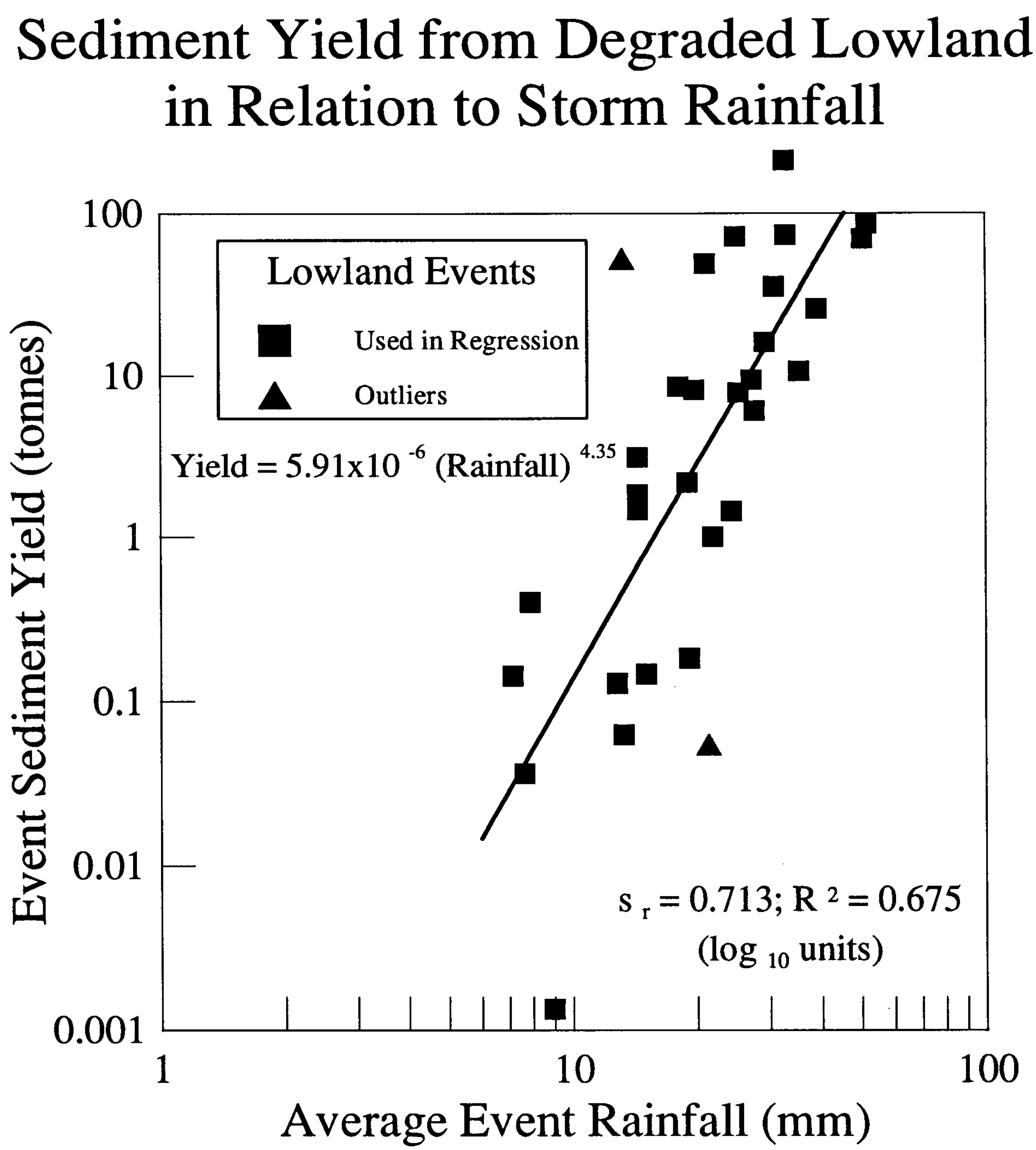


Table 8.2 Sediment production by surface erosion from gullied lowlands (tonnes) calculated using an empirical relation derived from lowland rainfall events (limits represent 95% confidence).

Year	P	T	M	Σ
		Total for all types of events		
1992	40 ± 300 (6)	158 ± 1800 (3)	686 ± 4491 (21)	888 ± 4847 (30)
1993	48 ± 352 (19)	32 ± 352 (4)	591* ± 4754 (20)	671 ± 4778 (43)
1994	170 ± 1318 (18)	45 ± 409 (6)	352 ± 1639 (14)	567 ± 2142 (38)
		Lowland events		
1992	12 ± 151 (2)	1 ± 9 (1)	354 ± 3118 (11)	367 ± 3122 (14)
1993	35 ± 341 (4)	0 ± 1 (2)	40 ± 332 (9)	74 ± 476 (15)
1994	59 ± 481 (8)	0 ± 0 (0)	66 ± 717 (3)	125 ± 863 (11)
		Upland events		
1992	14 ± 184 (1)	133 ± 1770 (1)	12 ± 151 (3)	159 ± 1786 (5)
1993	2 ± 26 (5)	0 ± 0 (0)	0 ± 0 (1)	2 ± 26(6)
1994	0 ± 2 (1)	0 ± 0 (1)	0 ± 0 (0)	0 ± 2 (2)
		Basin events		
1992	14 ± 184 (3)	24 ± 323 (1)	320 ± 3228 (7)	358 ± 3249 (11)
1993	11 ± 83 (10)	32 ± 352 (2)	552* ± 4742 (10)	595 ± 4756 (22)
1994	111 ± 1227 (9)	45 ± 409 (5)	286 ± 1474 (11)	442 ± 1961 (25)

P - pre-monsoon season; T - transition season; M - monsoon season; Σ - entire rainy season
Bracketed numbers indicate the number of individual events involved.
* represents possible underestimate

study as summarised in Table 8.3. Actual basin sediment-yield determinations are made using the continuous flow record and the sediment rating curves (marginal regressions based on Q - see Table 5.7). Seasonal sediment rating curves (Chapter 5) are used to differentiate event sediment export during each year. As discussed in Section 8.2.2, a log-transform correction of $\exp(\frac{1}{2}\sigma^2)$ is applied to the rating curve predictions to adjust for the preponderance of low flow samples used in defining the curves. For stations 1 and 2, this correction was between 1.10 and 1.12 and at Kukhuri it was 1.61 for the pre-monsoon relation and 1.26 for the monsoon relation. Estimates of suspended sediment concentration for the transition season are generated from linear interpolation between the expected results of the pre-monsoon and monsoon seasons at the discharge of interest.

Error bounds represent 95% confidence and are calculated from an average of the absolute de-transformed positive and negative errors. Uncertainty is highest during the pre-monsoon season, at Kukhuri station, and at high discharge. This can result, in some instances, in an error possibility several times that of the prediction.

In section 6.3, it was shown that although synchronous C-Q behaviour is common - probably dominant - in the study basins, many instances of non-synchronised behaviour, including both counterclockwise and clockwise hysteresis loops occurred during the study period. Hysteresis decouples C-Q behaviour reducing the effectiveness of the assumed C-Q power-law relations. In some cases where single-value behaviour occurs, the C values are consistently above or below their seasonal expectation (in all likelihood due to a within-season exhaustion effect). This departure from the expected C-Q relation is probably confounded with hysteresis type which increases the data requirement if pursuing a correction. Unfortunately, although sediment samples are available for most events, data are insufficient to address the effect of hysteresis on sediment yield computation. Consideration was given to correcting the calculated sediment yield for individual events based on available sediment samples but such a non-systematic approach would bias the results because sediment samples are not gathered randomly.

Storage

Sediment storage within the *khet* fields is determined using data from accumulation pins installed each year in a collection of representative fields. Descriptive statistics summarising these measurements are presented in Table 8.4 (see Chapter 5 for further details). The measurements directly provide the annual rates of accumulation for the basins in which the pins were installed (Kukhuri and Lower Andheri) and these results are extrapolated and summarised by basin in Table 8.5. The relative rates of annual accumulation measured by these pins is supported by the annual

Table 8.3 Annual and seasonal sediment yield at Kukhuri (10), Lower Andheri (2), and Jhikhu (1) hydrometric stations (limits represent 95% confidence).

St Yr	P	T	M	Σ
		Sediment Yield (tonnes)		
10 92	812 ± 1222	620 ± 1630	214 ± 140	1650 ± 2041
10 93	913 ± 1170	0	763 ± 415	1680 ± 1243
10 94	130 ± 260	0	125 ± 75	255 ± 271
10 Σ	1860 ± 1710	620 ± 1630	1100 ± 444	3580 ± 2405
2 92	690 ± 262	16700 ± 7150	1500 ± 568	18800 ± 7181
2 93	2200 ± 532	0	1250 ± 455	3450 ± 700
2 94	774 ± 303	49 ± 28	1520 ± 493	2340 ± 579
2 Σ	3660 ± 666	16700 ± 7150	4260 ± 879	24600 ± 7238
1 92	7720 ± 3930	34300 ± 19700	28200 ± 5870	70200 ± 20948
1 93	29600 ± 7620	1200 ± 569	66400 ± 20100	97200 ± 21494
1 94	61100 ± 18600	31000 ± 11700	104000 ± 23100	196000 ± 31914
1 Σ	98400 ± 20500	66500 ± 23000	198000 ± 31200	363000 ± 43810
		Sediment Yield (% of annual total)		(% of 3-year total)
10 92	49.3 ± 135	37.7 ± 146	13.0 ± 24.6	46.0 ± 88.0
10 93	54.5 ± 137	0	45.5 ± 81.2	46.9 ± 66.2
10 94	51.0 ± 156	0	49.0 ± 81.5	7.1 ± 12.4
2 92	3.7 ± 2.8	88.4 ± 71.7	7.9 ± 6.0	76.5±51.6
2 93	63.8 ± 28.4	0	36.2 ± 20.6	14.0±7.0
2 94	33.1 ± 21.1	2.1 ± 1.7	64.8 ± 37.1	9.5 ± 5.1
1 92	11.0 ± 8.9	48.9 ± 42.7	40.1 ± 20.3	19.3 ± 8.1
1 93	30.4 ± 14.6	1.2 ± 0.8	68.3 ± 35.8	26.8 ± 9.2
1 94	31.2 ± 14.6	15.9 ± 8.6	52.9 ± 20.5	53.9 ± 15.3
1 Σ	27.1 ± 8.9	18.3 ± 8.5	54.6 ± 15.2	100 ± 12.1
2 Σ	14.9 ± 7.1	67.8 ± 49.5	17.3 ± 8.7	100 ± 29.4
10 Σ	51.8 ± 82.7	17.3 ± 57.2	30.8 ± 33.1	100 ± 67.2

P - pre-monsoon season; T - transition season; M - monsoon season; Σ - entire rainy season trends in sediment yield at Lower Andheri and Kukhuri stations maintaining confidence in the measurements.

Sediment storage within the *khet kulo* (canal) and *bari bhaal* (ditch) systems is estimated using data from accumulation pins and from farmer interviews. To estimate deposition within the system of *khet* canals, interviews were combined with detailed mapping of the irrigation system (Nakarmi 1995). Interviews during 1992 and 1993 (see Chapter 7) indicate that an average of 13.8 cm/yr is cleaned out by the farmers and that typically, the canals have a width of 20 cm. The canals are cleaned out an average of 2.0 times/year and the farmers report that about half of the deposition is thrown directly into the adjacent stream while the other half goes into long-term storage either within *khet* fields or upon canal sides. Retention is thus calculated as 50% of the deposition. Mapping and the Geographic Information System indicate that Kukhuri basin contains 2230 m of canals (369 m/ha-*khet*) while the Lower Andheri basin contains 15688 m of canals (483 m/ha-*khet*). For the Jhikhu basin, a density of 483 m/ha-*khet* is used, corresponding to the canal density within the entire Andheri basin - a major tributary of the Jhikhu River. These numbers are used in Table 8.5 to yield annual estimates of sediment put into long-term storage as a result of deposition within the system of *khet* canals.

Pins placed directly in the *bari* ditches measured an average of 4.71 cm of accumulation during a portion of the 1993 rainy season (see Chapter 7). These pins were installed between June 16 and July 7 and removed between July 31 and August 11. Considerable further sedimentation occurred beyond what was measured. A conservative assumption is made that the measured deposition represents one deposition cycle between cleanings. The 4.71 cm amount is only 66% of what the farmers indicate in interviews so this estimate appears to be reasonable. The amount of deposition is then extrapolated to other years in proportion to the average rate of soil loss at the two erosion plots. The *bari* ditches were, on average, 19.7 cm in width and the interviews with farmers revealed that these ditches are cleaned out 1.67 times/yr. *bari*-ditch density was measured in 1993 in 21 fields

Table 8.4 Average annual soil accumulation measured annually (1992-1994) in *khet* fields.

	1992	1993	1994
Accumulation (mm)	10.5 ± 8.5	7.8 ± 2.1	1.4 ± 0.4
s (mm)	21.2	6.1	1.3
N (fields)	25	33	47

Total 1992-1994 accumulation = 19.7 mm

dispersed throughout the rainfed terraced lands since detailed mapping was unavailable. These measurements indicate that the average *bari* is 30 m by 30 m containing three 10 m long terraces. These *bari* typically contains four ditches along the width and one vertical ditch along the length (of the low-elevation end). Only 1 or 2 of the ditches along terraces are actively experiencing sedimentation. Hence, the typical *bari* has a ditch density of 1.5 x 30 m = 45 m-ditch/900 m^2-bari, or equivalently, 500 m-ditch/ha-bari. Using these accumulation and density values, total annual sediment retention within the system of *bari* ditches is calculated and presented in Table 8.5.

The annual sediment storage values shown in Table 8.5 are apportioned seasonally in Table 8.6. For the storage in the *khet* and *khet* canals, this is done in relation to the seasonal rates of sediment yield at the nearest downstream hydrometric station to represent best both the surface erosion and mass wasting components of sediment production available for this form of long-term storage. Annual *bari* ditch retention is apportioned seasonally in Table 8.6 according to the seasonal rates of production by surface erosion at the erosion plots (Table 8.1).

Deposition and scour within the channel system was not measured in this study. Channel slopes range up from 1.9 degrees at Lower Andheri (2) to 6.6 degrees at Kukhuri (10) and beyond 40 degrees above Kukhuri and Upper Andheri and limit the potential for fine-sediment deposition. Above Andheri Mid #2 (station 12) bars were observed very infrequently and most bars were seen to be associated with gully outflow from the degraded lowland. Repeat photography of selected bars taken during July and August 1993 indicate some change in these accumulations between Lower Andheri (2)

Table 8.5 Estimated annual rates of accumulation (cm/yr) and total annual sediment storage by basin (tonnes) in the *khet* fields (ha), *khet* canals (m), and *bari* ditches (m).

Station No.	Station Name	Area or Length	Rates of Retention (cm/yr) 1992	1993	1994	Σ
			khet			
10	Kukhuri	5.9	1.05 ± 0.85	0.78 ± 0.21	0.14 ± 0.04	1.97 ± 0.88
2	Lower Andheri	36.2 (ha)	1.05 ± 0.85	0.78 ± 0.21	0.14 ± 0.04	1.97 ± 0.88
			khet canals			
10	Kukhuri	2230	19.0 ± 38.8	19.4 ± 29.8	2.9 ± 5.5	41.4 ± 5.1
2	Lower Andheri	15688 (m)	31.7 ± 25.3	5.8 ± 3.6	3.9 ± 2.6	41.4 ± 5.1
			bari ditches			
10	Kukhuri	19945	9.9 ± 5.9	11.5 ± 6.8	2.2 ± 1.3	23.6 ± 9.2
2	Lower Andheri	88045 (m)	9.9 ± 5.9	11.5 ± 6.8	2.2 ± 1.3	23.6 ± 9.2

Station No.	Station Name	Area or Length	Total Storage (tonnes) 1992	1993	1994	Σ
			khet			
10	Kukhuri	5.9	991 ± 801	736 ± 200	132 ± 36	1860 ± 826
2	Lower Andheri	36.2 (ha)	6078 ± 4909	4515 ± 1227	810 ± 220	11404 ± 5065
			khet canals			
10	Kukhuri	2230	136 ± 277	139 ± 213	21 ± 39	296 ± 351
2	Lower Andheri	15688 (m)	1590 ± 1270	291 ± 181	197 ± 130	2078 ± 1290
			bari ditches			
10	Kukhuri	19945	623 ± 437	723 ± 508	136 ± 96	1482 ± 677
2	Lower Andheri	88045 (m)	2749 ± 1930	3192 ± 2242	601 ± 422	6542 ± 2988

Density of deposition is assumed to be 1.6 t/m^3 (Brady 1990 - slightly compact).

See text for explanation of how retention rates for *khet* area and canal/ditch length are converted to total annual storage.

Table 8.6 Seasonal storage (tonnes) by basin resulting from sediment deposition within *khet*, *khet* canals, and *bari* ditches.

Station No.	Station Name	Yr	Rates of Retention (cm/yr) P	T	M	Σ
				khet		
10	Kukhuri	92	488 ± 590	374 ± 451	129 ± 156	991 ± 801
		93	401 ± 270	0 ± 0	335 ± 225	736 ± 200
		94	67 ± 45	0 ± 0	65 ± 44	132 ± 36
				khet canals		
10	Kukhuri	92	67 ± 163	51 ± 125	18 ± 43	136 ± 277
		93	76 ± 146	0 ± 0	63 ± 122	139 ± 213
		94	11 ± 24	0 ± 0	10 ± 23	21 ± 39
				bari ditches		
10	Kukhuri	92	426 ± 384	191 ± 172	6 ± 6	623 ± 437
		93	723 ± 508	0 ± 0	0 ± 0	723 ± 508
		94	132 ± 119	1 ± 1	3 ± 2	136 ± 96

				khet		
2	Lower Andheri	92	225 ± 227	5373 ± 5414	480 ± 484	6078 ± 4909
		93	2881 ± 1359	0 ± 0	1634 ± 771	4515 ± 1227
		94	268 ± 127	17 ± 8	525 ± 248	810 ± 220
				khet canals		
2	Lower Andheri	92	59 ± 59	1406 ± 1404	126 ± 126	1590 ± 1270
		93	186 ± 153	0 ± 0	105 ± 87	291 ± 181
		94	65 ± 56	4 ± 40	128 ± 110	197 ± 130
				bari ditches		
2	Lower Andheri	92	1877 ± 1694	844 ± 761	28 ± 25	2749 ± 1930
		93	3192 ± 2242	0 ± 0	0 ± 0	3192 ± 2242
		94	583 ± 526	6 ± 5	12 ± 11	601 ± 422

and Andheri Mid #2 (12) though the changes were small compared to the size of the deposits. It was explained in Chapter 6 that suspended sediments derived from rainfall events over the gullied lowland were overwhelmingly red in colour while those from events over the upland were brown in colour. Mixing was observed to occur during only the rising limb of some upland flood events providing further confidence in the premise that change of bed storage of fine sediment is limited. Such changes are not considered in the budgets presented here though it is identified as an area of further research.

In contrast, the larger Jhikhu River has considerable storage capacity. Large meander bends are present near the Andheri River's confluence with the Jhikhu River. Measurements were not undertaken on this river. It is likely, however, that the annual storage and re-entrainment of sediment hypothesised for the Andheri River also occurs on the Jhikhu River (in conjunction with the meander bends) but on a grander scale: the sharp contrast between transport- and supply-limited conditions encourages storage/re-entrainment where stream gradient allows.

8.4.2 Episodic sediment production

To close the sediment budgets, "episodic-regime" sediment production must be added to the sediment production attributed to "normal-regime" surface erosion. Although the measurements and estimates of storage and yield presented in the previous section include the component due to episodic-regime production, the production estimates consider only that part due to repeated, persistent surface erosion. During the study period, mass wasting (stream bank/bed erosion and terrace failure) and severe rilling and gullying occurred on a number of occasions. These episodes occurred dominantly as a result of "major" storms (see Chapter 4 for definition) though less severe rainfall also caused episodic-regime erosion where antecedent geomorphic conditions were sufficient. During the pre-monsoon season, this type of episodic production took the form exclusively of severe rilling. During the monsoon season when the surface is generally well vegetated, episodic regime production consisted of both mass wasting *and* severe surface erosion. In this section, field observations are presented which identify the cause of the episodic-regime production which occurred during the study period. Estimates of episodic-regime production are developed using the yield and storage components of single events.

To account for this episodic production, surveys were carried out after the major runoff events of 1992. Three such events occurred in 1992, the first of which (July 10, 1992) was, by far, the most devastating to the Andheri basin of the entire study - perhaps a ten-year flood event. This event caused widespread damage to stream banks and terraces and many of the openings remained as sediment production opportunities for the two subsequent heavy events which occurred during the 1992 monsoon season (July 30 and August 3), enhancing their production capability.

An initial overview assessment suggested a stratified approach. The headward areas containing very steep streams and dominated by *bari* showed a wide variety of types of erosion. The Kukhuri basin (72 ha) was chosen for detailed measurements identifying quantity and character of sediment produced and delivered to the fluvial system, and the primary cause of the erosion (see Appendix A6). The other areas of Andheri basin responded very differently to the event of July 10. Overwhelmingly, the dominant erosional mechanism outside of the headward areas was severe damage to the Andheri channel in its lower reaches, initiated by the July 10 event. Conversations with farmers corroborated that this event was particularly harsh and unusual.

Detailed measurements within Kukhuri basin (see Appendix A6) reveal that sediment production within Kukhuri basin resulting from the event of July 10 was dominated (70%) by erosion due to channelised runoff flowing uncontrolled downslope. What can begin as a minor problem of water management can quickly develop into a huge erosional event because of the vulnerability of this steep, terraced terrain. In fact, one severely rilled/gullied location yielded almost 39% of the total surveyed sediment delivery (510 tonnes) of this runoff event. Though *khet* failure was observed to be uncommon, when it occurred it too was a large contributor due to the high proportion of fine-sediment involved: one failure contributed 7% of the total fine-sediment delivery measured. *Khet* fields located within draws or at deposition points at the base of hillslopes also acted as sediment traps in some instances. Of the 70% of net sediment production due to uncontrolled runoff, 9% of this amount resulted from runoff flowing unpredictably due to the road traversing through the upper part of Kukhuri basin. Trails were also problematic. The remaining 30% of total fine-sediment delivery was directly due to streampower - especially bank erosion. Bank failures were observed throughout the basin.

As indicated above, the swollen stream of July 10 destroyed every diversion dam within the Kukhuri-Andheri River system. The two subsequent events made little or no obvious change to the lower reaches which were radically reorganised by the earlier July 10 event. It was not possible to estimate the fine-sediment delivery by the July 10 event within the lower reaches of the Andheri River.

To investigate the extent to which episodic-regime erosion from other major monsoon-season events contributed to the basin sediment budgets, Table 8.7 ranks the ten high-flow events with the highest yield at Kukhuri station along with the upland rainfall characteristics of the associated storms. The yield values have been adjusted by prorated storage and normal-regime production to provide indications of each event's episodic-regime sediment delivery. Of these ten, five occurred during the pre-monsoon season, one during the transition season and four during the monsoon season. Observation following these events indicate that the type of episodic-regime sediment production changes with season. These pre-monsoon events resulted in a severe degree of widespread surface erosion - one not accounted for by the normal-regime rates presented in Table 8.1. In contrast, the monsoon season events caused terrace failures and isolated gullying where runoff structures failed. The event of July 10, 1992 resulted in the highest amount of episodic-regime sediment production with terrace collapse and serious gullies occurring throughout steep areas of the basin. In these headwater basins, episodic-regime sediment production accounted for about half of annual sediment production during the period of study (1992 - 64%; 1993 - 47%; 1994 - 0%).

Table 8.7 The 10 high-flow events at Kukhuri station with the highest sediment yield during 1992-1994.

Flood No.	Event Date	Season	Upland Rainfall		Yield at Kukhuri (tonnes)	Suggested Episodic-Regime Event Delivery (tonnes)
			R_T (mm)	I_{10} (mm/hr)		
18	May 27, 1993	P	65	111	768 ± 1163	468 ± 1262 (21%)
6	Jul 10, 1992	T	104	129	582 ± 1629	828 ± 1696 (28%)
4	Jun 28, 1992	P	40	40	266 ± 828	462 ± 852 (16%)
1	Jun 9, 1992	P	51	137	255 ± 785	36 ± 953 (1%)
2	Jun 22, 1992	P	26	96	209 ± 367	367 ± 399 (13%)
26	Aug 10, 1993	M	100	28	182 ± 284	243 ± 290 (11%)
31	Aug 25, 1993	M	41	95	165 ± 231	220 ± 238 (10%)
30	Aug 22, 1993	M	5*	48	85 ± 119	114 ± 122 (5%)
3	Jun 27, 1992	P	8*	24	83 ± 235	146 ± 243 (5%)
8	Jul 30, 1992	M	83	81	74 ± 120	86 ± 121 (3%)

* based on multiple measurements within the basin - see text for further discussion.

1) Total rainfall determined from rain-gauge network when available, otherwise taken from single rainfall-intensity gauge record.
2) Episodic-regime delivery determined by adjusting the basin yield by prorated storage and normal-regime production.
3) Bracketed values beside the episodic-regime event production indicate the percentage of total annual production caused by episodic-regime production during that event (total sediment production values taken from section 8.5.1).

These events also point to the importance of fast and effective erosion-control response in limiting soil loss from runoff events *subsequent* to a large event. Several of the erosion scars from the July 10 1992 event were repaired before the July 30 and August 3 events that same year. (In fact, some already had crops growing on them.) Field survey showed that gullies and failures that had not been repaired were further eroded by the two subsequent events. Though the farmers are very responsive to such erosion damage, due to labour shortages, they are not able to address all problems as fast as they would like. Any strategy which improves the economics of farming might also enhance labour availability within the terraced areas and should contribute positively to reducing erosion by helping the farmers respond more quickly. Otherwise, successive heavy events can initiate an undesirable spiral of degradation.

Table 8.8 presents analogous adjusted high-yield data at the Lower Andheri station. At this larger scale, the importance of the event of July 10 becomes clear. Its rate of episodic-regime sediment delivery is over an order of magnitude greater than any of the other events of the study period. This amount is due to an extraordinary level of recruitment from the bed and banks of the Andheri stream in its lower reaches, below station 12. In contrast to the events in Kukhuri basin where the event of July 10, 1992 produced sediment comparable to the pre-monsoon events of May 27, 1993 and June 9, 1992, the relative effect in the Lower Andheri of the July 10, 1992 event was much more significant. This July 10 event points to the importance of basin spatial scale (discussed further in section 8.5.3). Consistent with Kukhuri station, episodic-regime sediment production contributes about half of the total annual sediment production at the Lower Andheri station. (1992 - 80% (73% from an unusual event); 1993 - 21%; 1994 - 50%). Events of the pre-monsoon season contributed the larger proportion (excluding the July 10, 1992 event).

It is difficult to compare the relative yields at the two stations given that the rainfall varies between upland and basin events and also varies significantly in its erosivity for a given event. It appears unlikely that the diversion dams between Kukhuri and Lower Andheri stations are effective during these large events - the lack of pattern in yield reduction with scale may support this. It may be the low and medium events which are truncated most effectively by these structures.

In Chapter 4, it was determined that a "major" rainfall event required high total rainfall (>30 mm) and a high rainfall intensity (>50 mm/hr). This definition is consistent with these geomorphic findings. Of the storms of the events listed in Table 8.8, eleven were from major events, two were intermediate, and one was unknown. Given that there were few other major storm events during the study period, it is suggested that major events cause episodic-regime erosion. Beyond the events listed in Table 8.7, there is a rapid drop in sediment yield making the contribution to episodic-regime

Table 8.8 The 14 high-flow events at Andheri station with the highest sediment yield during 1992-1994.

Flood No.	Event Date	Upland Rainfall		Lowland Rainfall		Yield at Lower Andheri (tonnes)	Episodic-Regime Event Production (tonnes)	Yield at Kukhuri (tonnes)
		R_T (mm)	I_{10} (mm/hr)	R_T (mm)	I_{10} (mm/hr)			
8	Jul 10, 1992 (major; upland)	104	129	49	80	16647 ± 7154	21029 ± 9265 (73%)	582 ± 1629
39	May 27, 1993 (major; upland)	65	111	18	16	2034 ± 530	279 ± 2309 (3.3%)	768 ± 1163
14	Jul 30, 1992 (major; upland)	83	81	28	32	983 ± 550	1282 ± 659 (4.4%)	74 ± 120
109	Sep 3, 1994 (major; basin)	37	n/a	46	55	742 ± 441	851 ± 560 (25%)	7 ± 151
59	Aug 10, 1993 (≈interm;basin)	100	28	77	24	581 ± 398	621 ± 4309 7.5%)	182 ± 284
85	Jun 14, 1994 (major; basin)	48	48	45	71	517 ± 298	494 ± 1257 (14%)	69 ± 330
1	Jun 9, 1992 (major;upland)	51	137	31	72	340 ± 180	0 ± 2264 (0%)	255 ± 785
6	Jun 28, 1992 (≈major;basin)	40	40	29	48	329 ± 58	406 ± 224 (1.4%)	266 ± 828
67	Aug 24, 1993 (major;basin)	41	95	39	20	244 ± 64	348 ± 661 (4.2%)	165 ± 231
16	Aug 3, 1992 (major;upland)	38	89	14	24	222 ± 51	288 ± 91 (1.0%)	34 ± 122
60	Aug 11, 1993 (interm;basin)	32	40	31	39	207 ± 67	324 ± 209 (3.9%)	324 ± 209
107	Aug 28, 1994 (major;basin)	37	n/a	40	79	205 ± 74	185 ± 729 (5.4%)	185 ± 729
110	Sep 14, 1994 (?;basin)	29	n/a	32	25	192 ± 72	205 ± 294 (6.0%)	205 ± 294
55	Jul 20, 1993 (≈major;lowland)	33	48	28	55	116 ± 50	165 ± 326 (2.0%)	41 ± 114

1) Abbreviations in brackets beside event date indicate storm class based on scheme presented in Chapter 6 (major; intermediate; minor) and the rainfall area type as outlined in Chapter 4 (upland; lowland; basin).
2) Total rainfall determined from rain-gauge network when available, otherwise taken from single rainfall-intensity gauge record.
3) Episodic delivery determined by adjusting the basin yield by prorated storage and normal-regime production.
4) Bracketed values beside the episodic-regime event production indicate the percentage of total annual production caused by episodic-regime production during that event (total sediment production values taken from section 8.5.1).

sediment production unimportant for those events not listed. The low rainfall values for the events of June 27, 1992 and August 22, 1993 are based on measurements at several locations and as such are accurate in their point indications: these smaller events shown in Table 8.8 all followed other significant events by only one day pointing to the importance of antecedent conditions in helping to shape the geomorphic effectiveness of these otherwise much less important rainfall events.

It is useful to consider the consequences of heavy, widespread rainfall occurring during the pre-monsoon season or during the "late" monsoon season (October) when vegetative cover is once again limited. This did not occur during the study period and occurs infrequently in the Middle Mountains (Shah, personal communication; Figure 2.4b). On the basis of this study, such a rainfall event would trigger widespread surface erosion due to the lack of surface cover *and* cause episodic-regime erosion in accordance with the spatial extent of the rainfall and antecedent surface-moisture conditions. These rainfall events are, presumably, the most threatening to this Middle Mountains agricultural system.

8.5 Sediment budgets in space and time

The spatial and temporal components of the sediment budgets quantified in the previous section are assembled by basin. These compilations are presented to investigate the *relative* proportions of sediment produced by different mechanisms and of total sediment delivery relative to total sediment production. To accomplish these comparisons, the components are compiled in two different ways. In section 8.5.2, the budget components are presented and grouped into one of the three categories - production, storage, or yield. In section 8.5.3, the totals of these budget categories are calculated for discussion of sediment redistribution across spatial and temporal scale.

Confidence limits established in section 8.4 are propagated in all these calculations following Beers (1957). Addition of independent errors is calculated in relation to their variances (*i.e.*, $[A \pm a] + [B \pm b] = [A + B] \pm [a^2 + b^2]^{0.5}$). Multiplication and division of independent errors is propagated in relation to their relative error (*i.e.*, $[A \pm a] \cdot [B \pm b] = [AB] \cdot [1 \pm a/A + b/B]$). Completely correlated errors are accumulated directly.

8.5.1 Detailed basin sediment budgets

For each basin scale, the quantity of production, storage, and yield of fine sediment are given based on the determinations made in the previous section. These compilations are generated using spatial landuse information available in a Geographic Information System. For each production and storage component, the total applicable area (or length for canals and ditches) is provided through GIS queries. These landuse quantities are used to determine sediment-budget estimates using the rates of production given in Table 8.1 and the rates of storage provided in Table 8.5. Production from severely-gullied land is obtained from the relation given in Figure 8.2. Episodic-regime sediment delivery follows Table 8.7 and Table 8.8. Yield values are provided directly from measurements (Table 8.5). The budgets are compiled for both basins and for each year of the study - Tables 8.9 (1992), 8.10 (1993), and 8.11 (1994). Yields are also computed for comparison based on the production and storage estimates.

Typically, over two-thirds of the normal-regime surface-erosion from the *bari* is deposited in the system of *bhaal* before it reaches the fluvial system. Net *bari* retention is lowest in the pre-monsoon season because episodic-regime surface-erosion losses also occur during this season due to major storms occurring before the vegetative cover is complete - overall, between 25% and 50% is retained during the pre-monsoon season. In addition, the *khet* system traps over one-third of sediment entrained in the stream in Kukhuri basin and between 20% and 50% in the Lower Andheri basin, diverting this sediment into potentially-indefinite storage. The *bari* and *khet* provide a considerable level of sediment retention within both basins.

The components of sediment production reveal a seasonal shift from pre-monsoon surface erosion to monsoon-season mass wasting and severe rilling/gullying. In addition, there is a consistent

Table 8.9 Seasonal and annual sediment budget components (production, storage, yield) in tonnes in 1992 for Kukhuri and Lower Andheri basins.

Item	Kukhuri				Lower Andheri			
	P	T	M	Σ	P	T	M	Σ
					Normal-regime Production			
bari	619 ± 386	277 ± 172	9 ± 6	906 ± 383	2733 ± 1703	1224 ± 761	41 ± 25	3997 ± 1691
grassland	0 ± 0	0 ± 0	0 ± 0	0 ± 0	180 ± 112	81 ± 50	2.8 ± 1.6	263 ± 111
shrub	34 ± 21	15 ± 10	0.5 ± 0.3	50 ± 21	457 ± 286	204 ± 127	7.1 ± 4.1	669 ± 283
forest	20 ± 13	9 ± 6	0.3 ± 0.2	29 ± 12	266 ± 166	119 ± 74	4.0 ± 2.4	390 ± 165
degraded	0 ± 0	0 ± 0	0 ± 0	0 ± 0	40 ± 300	158 ± 1800	686 ± 4491	883 ± 4847
					Episodic-regime Production			
non-degraded	1011 ± 1361	828 ± 1700	86 ± 121	1925 ± 2181	406 ± 2275	21029 ± 9265	1570 ± 665	22600 ± 9289
Total	1684 ± 1415	1129 ± 1709	96 ± 121	2910 ± 2215	4082 ± 2879	22815 ± 1960	2311 ± 4540	28802 ± 10620
					Storage			
khet	488 ± 590	374 ± 451	129 ± 156	991 ± 801	225 ± 227	5373 ± 5414	480 ± 484	6078 ± 4909
khet canal	67 ± 163	51 ± 125	18 ± 43	136 ± 277	59 ± 59	1406 ± 1404	126 ± 126	1590 ± 1270
bari ditch	426 ± 384	191 ± 172	6 ± 6	623 ± 437	1877 ± 1694	844 ± 761	28 ± 25	2749 ± 1930
Total	981 ± 723	616 ± 499	153 ± 162	1750 ± 954	2161 ± 1710	7623 ± 5645	634 ± 501	10420 ± 5426
					Yield			
measured	812 ± 1222	620 ± 1630	214 ± 140	1646 ± 2041	690 ± 262	16660 ± 7154	1492 ± 568	18843 ± 7181
from budget	703 ± 1589	513 ± 1780	-57 ± 202	1160 ± 2412	1921 ± 3348	15192 ± 5976	1677 ± 4575	18382 ± 11930

decline in total sediment production and basin sediment yield through the rainy season for both Kukhuri and Lower Andheri basins. These findings indicate strongly that reducing surface erosion during the pre-monsoon season can provide a greater return in reducing basin sediment yield than modifying agricultural practices during the monsoon season.

Though degraded land produced about 5% of all sediment during 1992-1994, it contributed about 9% to basin sediment yield due to the lack of storage opportunities for this sediment. Because the degraded areas are responsive to rainfall amount during any season, they produce sediment in an opposite pattern to normal-regime erosion from *bari*. Sediment production from the degraded areas is equivalent to 22% of ***total*** normal-regime production and 71% of the ***net*** normal-regime production from all *bari* in Lower Andheri basin.

Uncertainty in these budgeted quantities originate from three main sources - erosion from the

Table 8.10 Seasonal and annual sediment budget components (production, storage, yield) in tonnes in 1993 for Kukhuri and Lower Andheri basins.

Item	Kukhuri				Lower Andheri			
	P	T	M	Σ	P	T	M	Σ
				Normal-regime Production				
bari	1053 ± 447	0 ± 0	0 ± 0	1053 ± 447	4649 ± 1972	0 ± 0	0 ± 0	4649 ± 1972
grassland	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
shrub	58 ± 25	0 ± 0	0 ± 0	58 ± 25	777 ± 330	0 ± 0	0 ± 0	777 ± 330
forest	34 ± 14	0 ± 0	0 ± 0	34 ± 14	454 ± 192	0 ± 0	0 ± 0	454 ± 192
degraded	0 ± 0	0 ± 0	0 ± 0	0 ± 0	48 ± 352	32 ± 352	591 ± 4754	671 ± 4780
				Episodic-regime Production				
non-degraded	468 ± 1262	0 ± 1	577 ± 394	1045 ± 1322	279 ± 2309	0 ± 0	1458 ± 4377	1737 ± 4949
Total	1613 ± 1339	0 ± 0	577 ± 394	2190 ± 1396	6209 ± 3080	32 ± 352	2049 ± 6462	8288 ± 7170
				Storage				
khet	401 ± 270	0 ± 0	335 ± 225	736 ± 200	2881 ± 1359	0 ± 0	1634 ± 771	4515 ± 1227
khet canal	76 ± 146	0 ± 0	63 ± 122	139 ± 213	186 ± 153	0 ± 0	105 ± 87	291 ± 181
bari ditch	723 ± 508	0 ± 0	0 ± 0	723 ± 508	3192 ± 2242	0 ± 0	0 ± 0	3192 ± 2242
Total	1200 ± 594	0 ± 0	398 ± 256	1598 ± 586	6259 ± 2626	0 ± 0	1739 ± 776	7998 ± 2562
				Yield				
measured	913 ± 1171	0 ± 0	763 ± 415	1676 ± 1243	2199 ± 532	0 ± 0	1249 ± 455	3448 ± 700
from budget	413 ± 1465	0 ± 0	179 ± 470	592 ± 1514	-50 ± 4048	32 ± 352	310 ± 6508	290 ± 7610

degraded lands, surface erosion from *bari,* and uncertainty in the C-Q relation during high-flow events in the pre-monsoon season. These uncertainties, and in particular the variance due to the relation for degraded-land production (illustrated in Figure 8.2), propagate throughout the budgets resulting in computed yields which have error margins typically more than double the predicted value. Fortunately, the measured yield values provide a check on the computed yield values and generally show good agreement. In only one case (Kukhuri monsoon season) do the two results not overlap.

8.5.2 Basin sediment production and delivery across temporal scales

Table 8.12 contrasts production and yield components for seasonal and annual periods within the Kukhuri basin sediment budget. During the 1992-1994 study period, an average of 1770 tonnes/year of sediment was produced within the basin, equivalent to 25 $t \cdot ha^{-1} \cdot yr^{-1}$ tonnes/ha/yr. Of

Table 8.11 Seasonal and annual sediment budget components (production, storage, yield) in tonnes in 1994 for Kukhuri and Lower Andheri basins.

Item	Kukhuri				Lower Andheri			
	P	T	M	Σ	P	T	M	Σ
				Normal-regime Production				
bari	194 ± 120	2 ± 1.2	4 ± 2.5	200 ± 84	854 ± 530	8.8 ± 5.3	18 ± 11	881 ± 370
grassland	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
shrub	11 ± 6.6	0.1 ± 0.1	0.2 ± 0.1	11 ± 4.6	143 ± 89	1.1 ± 0.9	2.9 ± 1.8	147 ± 62
forest	6.3 ± 3.9	0.1 ± 0.1	0.1 ± 0.1	6.5 ± 2.7	83 ± 52	0.9 ± 0.5	1.7 ± 1.1	86 ± 36
degraded	0 ± 0	0 ± 0	0 ± 0	0 ± 0	170 ± 1318	45 ± 409	352 ± 1639	567 ± 2142
				Episodic-regime Production				
all non-degraded	0 ± 0	0 ± 0	0 ± 0	0 ± 0	494 ± 1257	0 ± 0	1241 ± 965	1735 ± 1584
Total	211 ± 120	2.2 ± 1.2	4.3 ± 2.5	218 ± 84	1744 ± 1899	56 ± 409	1616 ± 1902	3416 ± 2691
				Storage				
khet	67 ± 45	0 ± 0	65 ± 44	132 ± 36	268 ± 127	17 ± 8	525 ± 248	810 ± 220
khet canal	11 ± 24	0 ± 0	10 ± 23	21 ± 39	65 ± 56	4 ± 4	128 ± 110	197 ± 130
bari ditch	132 ± 119	1 ± 1	3 ± 2	136 ± 96	583 ± 526	6 ± 5	12 ± 11	601 ± 422
channel bed								
Total	210 ± 129	1 ± 1	78 ± 50	289 ± 110	916 ± 544	27 ± 10	665 ± 272	1608 ± 493
				Yield				
measured	130 ± 260	0 ± 0	125 ± 75	255 ± 271	774 ± 303	49 ± 28	1517 ± 493	2340 ± 579
from budget	1 ± 176	1.2 ± 1.6	-74 ± 50	-71 ± 138	828 ± 1976	29 ± 409	1001 ± 1921	1808 ± 2736

this total, 64% was produced during the pre-monsoon season. An average of 1200 tonnes/year was exported from the basin for an overall basin sediment delivery ratio (SDR) of 68% - that is, 32% of all sediment produced within this 72-ha headwater catchment was recaptured before it left the basin. During the pre-monsoon and transition seasons, the rate of recapture was higher with 47% of all sediment produced being retained within the basin. The total average annual basin yield was 17 $t \cdot ha^{-1} \cdot yr^{-1}$ with 8.6 $t \cdot ha^{-1} \cdot yr^{-1}$ of this derived during the pre-monsoon season.

Table 8.13 presents the analogous results for the Lower Andheri basin. Specifically, an annual average of 13 500 tonnes of sediment (25 $t \cdot ha^{-1} \cdot yr^{-1}$) was produced during the three-year study period. Thirty percent of this amount was produced during the pre-monsoon season and a further 56% was produced during the transition season, mostly coming from the one event on July 10, 1992. Only

Table 8.12 Seasonal and annual sediment production, yield, and overall percentage delivery for the Kukhuri basin (1992-1994).

	P	T	M	Σ
		Total Production (tonnes)		
1992	1680 ± 1420	1130 ± 1710	96 ± 121	2910 ± 2220
1993	1610 ± 1340	0 ± 0	577 ± 394	2190 ± 1400
1994	211 ± 120	2.2 ± 1.2	4.3 ± 2.5	218 ± 84
Σ	3501 ± 1960	1132 ± 1910	677 ± 412	5318 ± 2630
Avg	1170 ± 650	377 ± 640	226 ± 137	1770 ± 880
		Specific Production (tonnes/hectare)		
1992	23 ± 20	16 ± 24	1.3 ± 1.7	40 ± 31
1993	22 ± 19	0 ± 0	8.0 ± 5.5	30 ± 19
1994	2.9 ± 1.7	0.03 ± 0.02	0.06 ± 0.03	3.0 ± 1.2
Total	30 ± 27	16 ± 24	9.4 ± 5.7	74 ± 37
Avg	16 ± 9	5.2 ± 8	3.1 ± 1.9	25 ± 12
% of annual	64%	21%	12%	100%
		Total Yield (tonnes)		
1992	812 ± 1220	620 ± 1630	214 ± 140	1650 ± 2040
1993	913 ± 1170	0 ± 0	763 ± 415	1680 ± 1240
1994	130 ± 260	0 ± 0	125 ± 75	255 ± 271
Σ	1855 ± 1710	620 ± 1630	1102 ± 444	3585 ± 2400
Avg	618 ± 570	207 ± 540	367 ± 148	1200 ± 800
		Specific Yield (tonnes/hectare)		
1992	11 ± 17	8.6 ± 23	3.0 ± 1.9	23 ± 28
1993	13 ± 16	0 ± 0	11 ± 5.8	23 ± 17
1994	1.8 ± 3.6	0 ± 0	1.7 ± 1.0	3.5 ± 3.8
Σ	26 ± 24	8.6 ± 23	15 ± 6	50 ± 33
Avg	8.6 ± 8	2.9 ± 7.7	5.1 ± 2.0	17 ± 11
% of annual	52%	17%	31%	100%

Note: The confidence limits shown do not consider error due to hysteresis.

Table 8.13 Seasonal and annual sediment production, yield, and overall percentage delivery for the Lower Andheri basin (1992-1994).

	P	T	M	Σ
		Total Production (tonnes)		
1992	4080 ± 2880	22800 ± 2000	2310 ± 4540	28800 ± 10600
1993	6210 ± 3080	32 ± 352	2050 ± 6460	8290 ± 7170
1994	1740 ± 1900	56 ± 409	1620 ± 1900	3420 ± 2690
Σ	12030 ± 4630	22888 ± 2070	5980 ± 8120	40510 ± 13100
Avg	4010 ± 1540	7630 ± 690	1990 ± 2710	13500 ± 4370
		Specific Production (tonnes/hectare)		
1992	7.7 ± 5.4	43 ± 4	4.3 ± 8.5	54 ± 20
1993	11 ± 6	0.06 ± 0.66	3.9 ± 12	16 ± 13
1994	3.3 ± 3.6	0.11 ± 0.77	3.0 ± 3.6	0.64 ± 5.1
Σ	23 ± 8	43 ± 4	11 ± 15	76 ± 25
Avg	7.5 ± 2.7	14 ± 1.4	3.7 ± 5.0	25 ± 8.1
% of annual	30%	56%	15%	100%
		Total Yield (tonnes)		
1992	690 ± 262	16700 ± 7200	1490 ± 570	18800 ± 7200
1993	2200 ± 530	0 ± 0	1250 ± 460	3450 ± 700
1994	774 ± 303	49 ± 28	1520 ± 490	2340 ± 580
Σ	3664 ± 660	16749 ± 7200	4260 ± 880	24590 ± 7260
Avg	1220 ± 220	5580 ± 2400	1420 ± 290	8200 ± 2400
		Specific Yield (tonnes/hectare)		
1992	1.3 ± 0.5	31 ± 14	2.8 ± 1.1	35 ± 14
1993	4.1 ± 1.0	0 ± 0	2.3 ± 0.9	6.5 ± 1.3
1994	1.5 ± 0.6	0.09 ± 0.05	2.9 ± 0.9	4.4 ± 1.1
Σ	0.7 ± 1.2	31 ± 14	8.0 ± 1.7	46 ± 14
Avg	2.3 ± 0.4	10 ± 4.7	2.7 ± 0.6	15 ± 5
% of annual	15%	67%	18%	100%

Note: The confidence limits shown do not consider error due to hysteresis.

8200 tonnes/year were exported from the basin for an overall SDR of 61%. The pre-monsoon season demonstrated a greater ability to retain sediment at this scale than at the Kukhuri scale - only 30% of pre-monsoon production was exported from the basin. The total average annual basin yield was 15 $t \cdot ha^{-1} \cdot yr^{-1}$ with 10 $t \cdot ha^{-1} \cdot yr^{-1}$ of this due to the event of July 10, 1992.

Surface hydrological response at the rainfall-runoff interface is an important control in determining the percentage basin sediment yield. In Chapter 5, it was shown that rainfall events of the pre-monsoon season yield a lower percentage of their water input at the Lower Andheri station than events of the monsoon season. The *khet* system is more able to hold water during the pre-monsoon contributing to this differential in basin water yield. Also, the hydrological response of the surface changes seasonally. As the surface becomes saturated during the monsoon season, rainfall input is more prone to rapidly running off into the stream rather than infiltrating into the upper soil horizons.

Landuse is also an important factor affecting runoff behaviour. Infiltration measurements carried out during 1992 indicate that the long-term steady-state infiltration rate of grassland, forest, shrub, and degraded lands is typically between 1 and 7 cm/hr. In contrast, *bari* exhibits rates typically varying between 10 and 50 cm/hr, chiefly depending on the coarse-fragment content of the surface soil horizons. In the sample of 20 infiltration tests, the two undertaken on south-facing *bari* (hotter - see Chapter 2) had the highest infiltration rates, resulting from the coarse B and C horizons being close to the surface at these hot sites (they lacked a significant A horizon). Indirectly, by "mining" the soil on these exposed sites, surface runoff may have dropped thereby reducing the downslope erosion hazard. Conversely, the system of *bari* ditches, contributes to a faster surface response and an aggravated downstream erosion hazard by providing a vast, anthropogenic extension to the natural fluvial system.

Table 8.14 presents the average annual sediment yield from the Jhikhu basin during 1992-1994. An average of 120 000 tonnes/year was exported from the basin, or a basin average of 11 tonnes/ha. Due to the measurement limitation identified and discussed in Chapter 6, the actual yield is

Table 8.14 Seasonal and annual sediment yield from the Jhikhu basin (1992-1994).

	P	T	M	Σ
		Total (tonnes)		
1992	7720 ± 3930	34300 ± 19700	28200 ± 5870	70200 ± 20900
1993	29600 ± 7620	1200 ± 569	66400 ± 20100	97200 ± 21500
1994	61100 ± 18600	31000 ± 11700	104000 ± 23100	196000 ± 31900
Σ	98400 ± 20500	66500 ± 22900	199000 ± 31200	363000 ± 43800
Avg	32800 ± 6830	22200 ± 7630	66200 ± 10400	121000 ± 14600
		Specific (tonnes/hectare)		
1992	0.69 ± 0.35	3.1 ± 1.8	2.5 ± 0.5	6.3 ± 1.9
1993	2.7 ± 0.7	0.11 ± 0.05	6.0 ± 1.8	8.7 ± 1.9
1994	5.5 ± 1.7	2.8 ± 1.1	9.3 ± 2.1	18 ± 3
Σ	8.8 ± 1.8	6.0 ± 2.1	18 ± 3	33 ± 4
Avg	2.9 ± 0.6	2.0 ± 0.7	5.9 ± 1.0	11 ± 1.3
% of annual	26%	18%	54%	100%

Note: The confidence limits shown do not consider error due to hysteresis.

larger due to higher sand transport. The annual trend during 1992-1994 at the Jhikhu station is inconsistent with the trends exhibited by the other nested basins. This decoupling of basin behaviour between the 10- and 100-km^2 scales illustrates where variability in these basins is of greatest concern to monitoring. At the Lower Andheri station, most of the rainfall-runoff activity within the basin had a signature at the basin outlet - *i.e.*, local events in the headwaters or over the lowlands were well "tracked" at the outlet. The behaviour of this tributary system, however, is decoupled with respect to the larger Jhikhu system through the combined mechanism of rainfall spatial extent and runoff behaviour. Few rainfall events cover the entire Jhikhu basin hence a given tributary may or may not have behaviour coinciding with what is recorded at the Jhikhu station once a convective system has passed through the basin. Also, the possibilities for storage within the larger, lower-gradient Jhikhu basin are considerably increased. As basin scale increases, these scale-related changes bring about a decoupling of the tributary-basin sediment regimes. Presumably, this decoupling occurs between 10 and 100 km^2 though it also depends on the specific character (especially slope) of the basin and sub-basins of concern.

The behaviour of south-facing tributaries may add further to the variable complexity. Observations suggest that surface soils and management practices differ between the south-facing and north-facing tributary basins within the Jhikhu valley cross-section through Baluwa. Extrapolation of behaviours identified within the steep north-facing basin to south-facing basins may be inappropriate.

While the basin-tributary regimes are decoupled except under exceptional circumstances (of widespread rainfall), sub-basins of a tributary are frequently further decoupled from the tributary behaviour due to rainfall spatial variability and landuse heterogeneity. In Chapter 4, it was revealed how only 43% of combined "intermediate" and "major" rainfall events were basin-wide events. The remainder was local in nature being centred over only the upland or over only the lowland. These facts, combined with the seasonal variability in erosivity of the surface soil due to management, suggest further significant decoupling of the sediment regimes of sub-basins within the tributary systems.

Table 8.15 provides evidence of this decoupling by contrasting, according to scale, the extent to which individual (and several) events cause a high percentage of the seasonal and annual sediment yield at a station. As scale decreases, the vulnerability of the basin/plot to individual events increases. This trend is particularly acute during the pre-monsoon season. At small scales, pre-monsoon yields are the highest individual contributors to total annual yields. As the spatial scale increases, the transition season and monsoon-season events increase in their effect.

8.5.3 Three-year, sediment production and yield across spatial scales

Seasonal and annual comparisons

Table 8.16 assembles the average sediment yield for each spatial scale under study. Specific

Table 8.15 Seasonal and annual sediment yield as percentage of seasonal and annual totals respectively for individual and selected groups of events for all spatial scales.

Area	1992				1993				1994			
(km^2)	P	T	M	Yr	P	T	M	Yr	P	T	M	Yr
0.0001					**Erosion Plot**							
a)	0.21	0.094	0.003	0.31	0.36	0	0	0.36	0.065	0.0007	0.0014	0.067
b)	93	69	57	63	62	-	-	62	75	69	30	68
c)	2	2	3	3	3	-	-	3	3	2	2	3
d)	99	100	92	94	97	-	-	97	96	100	41	93
0.72					**Kukhuri Basin**							
a)	812	620	214	1 650	913	0	763	1 680	130	0	125	255
b)	33	94	35	35	84	-	24	46	53	-	33	27
c)	3	3	2	4	2	-	3	4	2	-	3	3
d)	90	100	62	80	91	-	57	71	89	-	57	62
5.3					**Lower Andheri Basin**							
a)	690	16 700	1 490	18 800	2 200	0	1 250	3 450	774	49	1 520	2 340
b)	49	99.7	66	89	92	-	46	59	67	100	49	32
c)	2	2	2	5	2	-	4	5	2	-	3	5
d)	97	100	81	99	95	-	92	92	75	-	75	75
111					**Jhikhu Basin**							
a)	7 720	34 300	28 200	70 200	29600	1 200	66 400	97 200	61 100	31 000	104 000	196 000
b)	60	80	30	39	27	100	45	31	34	53	33	17
c)	3	3	4	4	3	-	3	4	3	2	4	5
d)	85	97	70	65	65	-	73	58	74	81	62	52

Underlined values refer to the season in which the highest-yield event occurred.

Letters in left margin are defined according to:
a) total seasonal (or annual) fine-sediment yield (tonnes).
b) percentage of total yielded in single largest event;
c) number of events, n, used to determine the percentage in d); and
d) percentage of total yielded in n events (from c).

Table 8.16 Average seasonal sediment budgets across all spatial scales.

a) total average fine-sediment yield (tonnes)				
Area	P	T	M	Yr
0.72 km^2	618 ± 987	207 ± 941	367 ± 257	1200 ± 1390
5.3 km^2	1220 ± 380	5580 ± 4160	1420 ± 510	8200 ± 4200
111 km^2	32 800 ± 11 800	22 200 ± 13 200	66 200 ± 18 000	121 000 ± 25 300
b) specific average fine-sediment yield (tonnes/ha)				
Area	P	T	M	Yr
0.0001* km^2	27.9 ± 16.3	2.3 ± 1.4	0.1 ± 0.06	30 ± 16 (60%)
0.72 km^2	8.6 ± 14	2.9 ± 13.1	5.1 ± 3.6	17 ± 19 (68%)
5.3 km^2	2.3 ± 0.7	10 ± 8	2.7 ± 1.0	15 ± 8 (50%)
111 km^2	2.9 ± 1.1	2.0 ± 1.2	5.9 ± 1.7	11 ± 2.3 (30-40%+)

Bracketed quantities refer to overall fine-sediment delivery ratios.

* Results are for *bari* and include episodic-regime production of only the pre-monsoon season (based on behaviour of *bari* within the Kukhuri basin); if episodic-regime production during the transition and monsoon seasons were included, sediment delivery ratio would rise above 60%.

+ See text for explanation.

average yield shows the effect of scale on sediment yield. As scale increases, the specific yield decreases from 30 to 11 t/ha. Though specific production shows little overall change from Kukhuri to Lower Andheri (*c.f.* Tables 8.12 and 8.13) this drop in specific yield is largely a result of an increase in deposition and recapture *within* the basins. The estimated total production from *bari* does not include the episodic-regime component attributed to terrace collapse. Due to its high delivery rate, inclusion of this source should increase the sediment-delivery ratio above 60%.

As scale increases, there is also a shift from yield during the pre-monsoon season to yield during the monsoon season. High losses on individual fields during the pre-monsoon season are moderated as scale increases. Conversely, as scale increases beyond the plot, the possibility for erosion damage from saturation and channelised runoff increases and hence the increase in specific soil loss with scale during the monsoon season. In fact, the overall rate during the pre-monsoon and monsoon seasons is equal at the 1-km^2 scale. The 10-t/ha result for the 5.3-km^2 basin is anomalous due to the widespread extent of the rainfall associated with the July 10, 1992 event over the Lower Andheri basin.

The importance of individual events is highlighted by considering the relative lengths of the pre-monsoon and monsoon seasons. As scale increases, the relative number of high-flow events in the monsoon season as compared to the pre-monsoon season increases. For instance, at 0.72 km^2, there were twice as many events, on average, during the monsoon season in comparison with the pre-monsoon season. At 5.3 km^2, the ratio grows to 1:3 and at 111 km^2, it is about 1:4. At the larger scales, the erosive pre-monsoon events are diluted by a much larger number of monsoon events so that the pre-monsoon component of sediment yield declines in relative importance.

What is the SDR at the Jhikhu scale? Measurements of sediment production are unavailable at this 111-km^2 scale hence the SDR cannot be calculated. Figure 8.3 presents the annual specific yields in relation to scale. The morphology of the meandering Jhikhu River and its floodplain both suggest that its storage capacity is far greater than that of the tributary streams (like the Andheri). Further, there are several large diversion systems on the Jhikhu River which serve extensive systems of valley-bottom khet. The extent of *khet* fields is 2.5 times as great in relative area in the Jhikhu basin as in the Andheri basin. These differences between the studied tributary system and the Jhikhu basin point to a strong *drop* in SDR between the 5.3- and 111-km^2 basins. This drop is consistent with the decoupling of the basins' sediment regimes discussed earlier. A SDR ratio of 30% to 40% appears reasonable. The actual value may be lower but it appears unlikely to be higher.

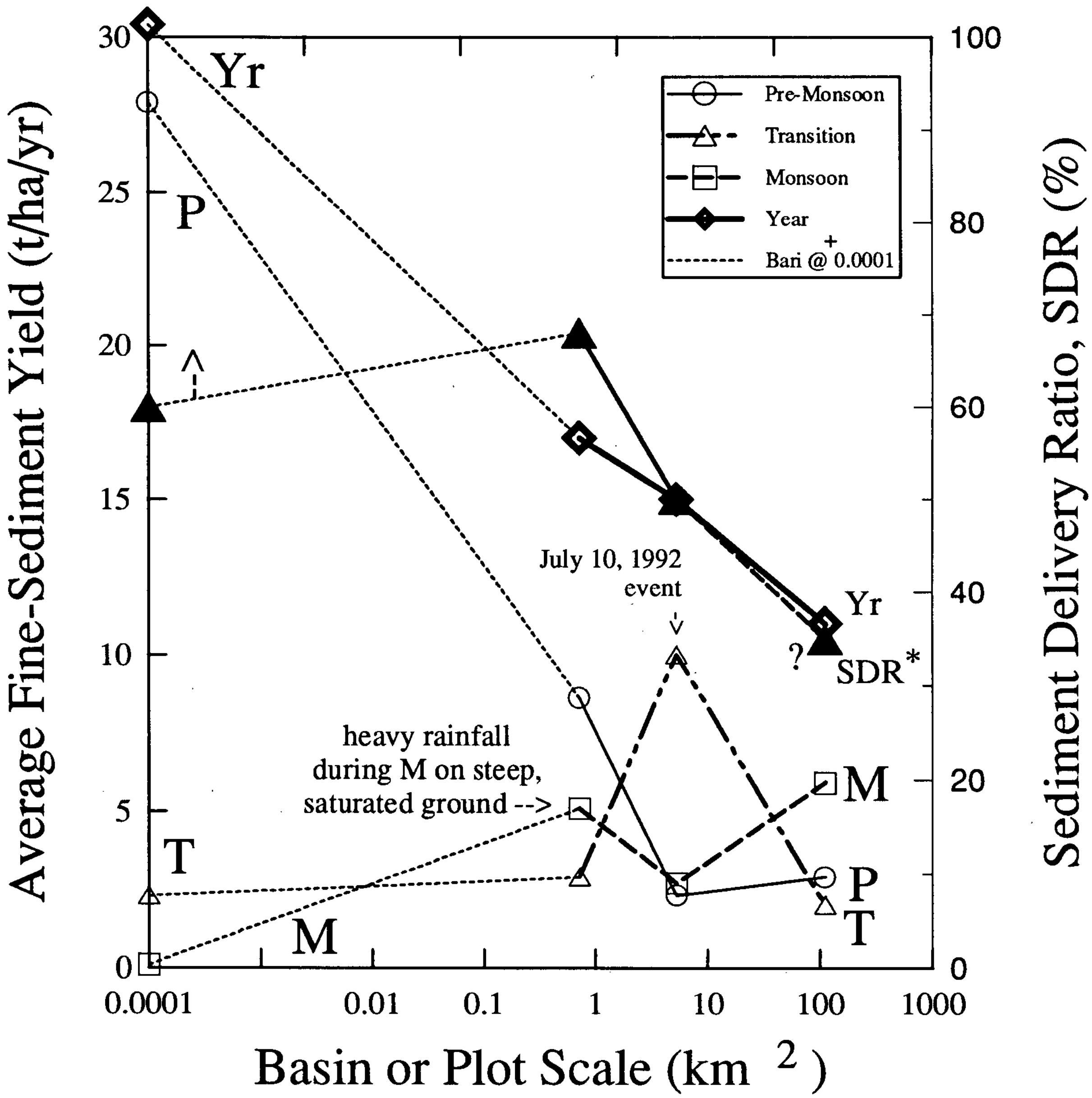
In Figure 8.3, the data illustrated for the smallest scale (100 m^2) are for normal-regime *bari* erosion. At this scale, landuse is resolved and the sediment regimes are therefore landuse specific. *Bari* is used because it is dominant in the headwater basins. In particular, the rates are determined based on the behaviour of *bari* within Kukhuri basin.

Figure 8.3 Annual fine-sediment yield and fine-sediment delivery ratio in relation to scale during 1992-1994.

Notes:

*SDR for Jhikhu (111 km^2) is indicated by "?" because it is not based on calculation due to the absence of measurements of sediment production within this basin.

+Yield at the 0.0001 km^2 scale is shown for (Kukhuri) bari because this landuse dominates in this and other headwater basins.



Single events

The annual and seasonal patterns identified above are also evident for single events. Table 8.17 contrasts measured sediment yield at the nested hydrometric stations for the major fine-sediment transport events during 1992-1994. Of the seven pre-monsoon events shown, five show a decrease in specific yield in relation to basin size. Trends during the monsoon season show greater variability: almost half show a decrease while the other events either are mixed or increase. With the exception of the July 10, 1992 event, increases in specific yield are due to rainfall spatial variability - significant rainfall during these events did not fall on Kukhuri basin (and sometimes also did not fall on Andheri basin). The rate of decrease for monsoon-season events is less than that of the pre-monsoon events, consistent with the annual and seasonal results discussed above.

8.6 Implications for nutrient loss

The trends in soil loss hold implications for nutrient loss and redistribution. The high level of redistribution within these basins (suggested by the low SDR) indicates that erosion causes not only basin loss. In the small headward sub-basin of 72 ha, 40% of eroded soil is recaptured before it leaves the basin. One farmer's loss is another farmer's gain.

In Chapter 6, it was determined that the nutrient content of suspended sediment in the pre-monsoon can be up to an order of magnitude higher than that of the monsoon season (Figures 6.25b, 6.26b, 6.27b, 6.31b, and 6.34b). Since 26-87% of total average annual soil loss occurs typically during the pre-monsoon season at all scales, this suggests that over 75% of annual nutrient yield through sediment export may occur during the pre-monsoon in intensively managed basins. At some scales this number may be over 95%. These nutrients originate in upland *bari* and are dominantly in the clay and silt fractions and are in addition to the nutrients lost in the organic matter which is lost during pre-monsoon floods. Severely-degraded areas, though providing an important contribution to basin sediment yield (up to 24%), do not contribute significantly to basin nutrient yield.

Table 8.17 Sediment yield at nested hydrometric stations for single events.

Event Date	Total Yield (t)			Specific Yield (t/ha)		
	Station Number					
	10	2	1	10	2	1
			Pre-Monsoon Season			
Jun 9, 1992	255 ± 785	340 ± 180	632 ± 463	3.5 ± 10.9	0.64 ± 0.34	0.057 ± 0.042
Jun 22, 1992	209 ± 367	0 ± 0	0 ± 0	2.9 ± 5.1	0 ± 0	0 ± 0
Jun 27, 1992	83 ± 235	4.0 ± 1.8	0 ± 0	1.2 ± 3.3	0.008 ± 0.003	0 ± 0
Jun 28, 1992	266 ± 828	329 ± 191	1289 ± 1049	3.7 ± 11.5	0.62 ± 0.36	0.12 ± 0.09
May 27, 1993	768 ± 1163	2034 ± 530	5453 ± 2978	10.7 ± 16.2	3.8 ± 1.0	0.49 ± 0.27
Jun 14, 1994	69 ± 229	517 ± 298	15130 ± 9780	0.9 ± 3.2	0.97 ± 0.56	1.4 ± 0.9
Jun 16, 1994	0 ± 0	7.3 ± 3.8	20530 ± 13840	0 ± 0	0.013 ± 0.007	1.8 ± 1.2
			Transition Season			
Jul 10, 1992	582 ± 1629	16650± 7150	27460 ± 19630	8.1 ± 22.6	31.3 ± 13.4	2.5 ± 1.8
Jul 9, 1994	0 ± 0	0.03 ± 0.01	8760 ± 5430	0 ± 0	0.00 ± 0.00	0.79 ± 0.49
Jul 9, 1994	0 ± 0	0 ± 0	16460 ± 9820	0 ± 0	0 ± 0	1.5 ± 0.9
			Monsoon Season			
Jul 30, 1992	74 ± 120	983 ± 550	2200 ± 1090	1.0 ± 1.7	1.8 ± 1.0	0.20 ± 0.10
Aug 3, 1992	34 ± 41	222 ± 114	137 ± 197	0.47 ± 0.56	0.42 ± 0.21	0.012 ± 0.009
Jul 20, 1993	41 ± 47	116 ± 58	2360 ± 1380	0.57 ± 0.65	0.22 ± 0.11	0.21 ± 0.12
Aug 10, 1993	182 ± 284	581 ± 398	29900 ± 17900	2.5 ± 3.9	1.1 ± 0.8	2.7 ± 1.6
Aug 11, 1993	38 ± 51	207 ± 139	3810 ± 2450	0.53 ± 0.71	0.39 ± 0.26	0.34 ± 0.22
Aug 14, 1993	0 ± 0	0.1 ± 0.1	9690 ± 6150	0 ± 0	0 ± 0	0.87 ± 0.55
Aug 22, 1993	85 ± 119	0 ± 0	0 ± 0	1.2 ± 1.7	0 ± 0	0 ± 0
Aug 24, 1993	165 ± 231	244 ± 157	8950 ± 5600	2.3 ± 3.2	0.46 ± 0.30	0.80 ± 0.50
Aug 8, 1994	13 ± 20	74 ± 51	34200 ± 19400	0.18 ± 0.28	0.14 ± 0.10	3.1 ± 1.7
Aug 28, 1994	41 ± 61	205 ± 151	3040 ± 1780	0.57 ± 0.85	0.39 ± 0.28	0.27 ± 0.16
Sep 3, 1994	7.3 ± 11	742 ± 441	14830 ± 9360	0.10 ± 0.15	1.4 ± 0.8	1.3 ± 0.8
Sep 12, 1994	0 ± 0	0 ± 0	7200 ± 3450	0 ± 0	0 ± 0	0.65 ± 0.31

8.7 Conclusions and Recommendations

Conclusions focus on both the relative contributions to the sediment budget by landuse and mechanism as a function of scale and on patterns of behaviour which shape these component quantities. These results have implications for the farming system and for further research and monitoring in these environments.

8.7.1 Conclusions

Sediment behaviour

Sediment production and yield varies with season, scale, and landuse. Pre-monsoon production dominates annual production at the smaller basin scales and results from moderate to severe sheet and rill erosion especially during high-intensity rainfall events (I_{10} > 50 mm/h). As scale increases, erosional mechanisms characteristic of significant monsoon-season events (stream bank and bed erosion and terrace failure) dominate annual sediment production. The system of *bari* ditches captures about one third of sediment production within this landuse class and the khet system captures between 30 and 60% of total sediment production. While storage mechanisms are dominated by these management activities within the 10-km^2 scale, alluvial storage may dominate between the 10- and 100-km^2 scales. About half of all sediment production is returned to long-term storage before it can leave the basin indicating a high degree of soil redistribution within these headwater systems.

The average annual yield rates of 10 to 20 t/ha for all basins are consistent with high values reported in the literature for basins of 1 to 10 ha (see section 5.2.1) but are an order of magnitude less than extreme values (100-200 t/ha) often associated with loess and other highly erodible soils. In Galay's (1997) assembly of regional denudation rates based largely on monitoring programs in larger rivers, the results for Jhikhu basin are some of the lower values presented for Nepal.

Landuse

Landuse plays a pivotal role in shaping the timing and quality of sediment yield. The incomplete vegetative cover of the pre-monsoon season (especially during the early part of this season) results locally in predictable damaging rates of sediment production during high-intensity rainfall. This soil loss is dominated by erosion of nutrient-rich clays and silts and represent the large majority of agriculturally important nutrients lost in sediment during the entire rainy season. Rainfall events of the monsoon season are most damaging delivering high-intensity, high-volume rain over steep slopes. All landuse types are affected but inadequate water management resulting in water flowing uncontrolled downslope is the largest contributor to episodic soil loss from cultivated areas during this season. Sudden and untested changes to hillslope hydrology (perhaps due to a new road) may present problems to present indigenous approaches which rely on the empirical testing of runoff control design. If these "major" storms are also sufficiently widespread, the swollen streams cause massive channel degradation and bank failure as evidenced by the July 10, 1992 event - the most geomorphically significant event of the three-year study period. Degraded land without a seasonal change in surface cover produces sediment throughout the rainy season in proportion to storm rainfall. Because degraded land is typically of low nutrient content (especially that within the study area), it is important for downstream sedimentation but of limited importance to nutrient loss from the headwater agricultural system.

Episodicity

Sediment and nutrient production and yield are highly episodic and are a function of both season and scale. The effect of individual events is greatest during the pre-monsoon and declines through the rainy season. As scale increases, the importance of individual events also declines. Individual events typically yield over half of the respective seasonal yield within the 10-km^2 scale and often yield 90 to 100% of the seasonal total. In addition, individual events commonly yield between 30 and 50% of the annual total yield at all scales. The dominant yield event tends to occur during the pre-monsoon season at smaller scales and during the monsoon season at larger scales.

These results suggest that total sediment production during normal-regime and episodic-regime events are roughly equivalent within the annual budget - *i.e.*, each contributes about half of annual production. It is the character of the sediment in these two production components which is contrasting and is strongly seasonal.

Rainfall

The storm classification system developed in Chapter 4 presents a useful framework for evaluating the importance of storm rainfall to the sediment budget. "Major" events provide the greatest potential for episodic-regime sediment production; intermediate and (significant) minor events can result in episodic-regime production though favourable antecedent conditions appear to be necessary.

Given the prevailing management within the Middle Mountains, *high-intensity* rainfall poses the greatest practical threat for sediment production during the pre-monsoon season whereas *high-volume* rainfall is the greatest ongoing concern during the monsoon season. In addition, if high-volume rainfall during the monsoon season is also sufficiently widespread, massive sediment production and channel reorganisation is possible - this is of great concern to farmers because ubiquitous irrigation structures built and maintained *within* channels are a vital component of the agricultural system. High-volume rainfall arriving during the pre-monsoon season poses the greatest physical threat to this agricultural system. Such an event last was recorded in Kathmandu in June, 1971 and within the Jhikhu basin in June 1978 but did not occur in the study area during 1992-1994.

8.7.2 Recommendations

Monitoring and further research

The conclusions of the present study suggest the effect of management regime in general and indicate broadly applicable prescriptions. However, many site-specific situations cannot be addressed by this study due to the lack of detailed evaluation of field-scale erosion mechanisms. For instance, which *bari* ditch design is most effective and feasible in recapturing eroded soil under a specific range of conditions? In addition, improving the confidence of storage estimates would significantly strengthen conclusions reached from the sediment budgets.

Erosion rates in relation to surface condition (landuse) need further investigation (*bari*, forest, shrub). Beyond surface cover, which of the controlling variables is most influential in shaping surface erosion rates in *bari*? How important is terrace slope as opposed to hill slope? Rates of surface erosion from non-cultivated landuse classes should be measured. Measurements of soil loss from gullied land would greatly reduce error margins of budget estimates and provide a stronger basis for choosing between investment in the rehabilitation of degraded land versus improved management strategies within intensively-managed *bari*.

Strict attention should be paid to scale variability with respect to rainfall input and surface response. Tributary sediment-regime behaviour is variably complex between the 10 and 100 km^2 scales. Sub-basin (1-km^2 scale) sediment-regime behaviour can be decoupled from tributary basin behaviour (10-km^2 scale) for some events due to landuse heterogeneity and rainfall spatial variability. These complexities should be built in to the sampling design at the earliest stage possible.

Management

Reducing surface erosion during the pre-monsoon season provides a greater return in reducing basin sediment yield than modifying agricultural practices during the monsoon season. This strategy also provides the most direct approach for reducing nutrient losses from the agricultural system.

Development strategies which improve labour availability to the upland farmers should improve the erosion-control effectiveness of current indigenous management techniques.

The greatest potential for erosion in the terraced uplands is a heavy *pre-monsoon* rainfall event with required threshold rainfall total and intensity and extent sufficiently widespread to cause extensive channel erosion downstream. The combination would devastate the upland *bari* and destroy the productivity of the *khet* system downstream by damaging the diversion dams, canal system, and potentially also the *khet* themselves. Such an event did not occur during the study period. The vulnerability of this agricultural system to rainfall of different character indicates the precarious balance present.

Due to the lack of a control, the findings do not allow comment on the relative sediment regimes of agriculturally-managed versus natural basins. However, within these highly-managed basins, the chapter has illustrated the significance of the human role to the basin's sediment budget and has identified the extent to which the sediment regimes of these managed, headwater Middle Mountain basins are systems of soil redistribution rather than systems of sediment export.

9. Conclusions, General Discussion, and Recommendations

Erosion and sediment transport in headwater, agricultural basins of the Middle Mountains have been studied using intensive monitoring during 1992-1994 within nested basins ranging in size from 72 to 11 141 ha. Variation of storm-period variables in time and space was assessed using five recording rain gauges and a network of up to fifty 24-hour gauges. Surface erosion was measured from five erosion plots on steep, cultivated *bari*. Patterns of suspended sediment behaviour were examined using detailed event sampling at seven hydrometric stations. Basin sediment yield was determined for three of these nested basins. Sediment storage was assessed using accumulation pins in *khet* fields, *khet* canals, and *bari* ditches and through erosion and channel surveys. Findings have been assembled into sediment budgets over contrasting spatial and temporal scales.

Detailed laboratory and hydrological analyses of stream suspended sediments (2287 high-flow samples) have been presented. Hysteresis in sediment transport was assessed using data from 141 high-flow events. Sediment colour (1649 samples) and phosphorus content (598 samples) have been used as fingerprints to investigate how the controls on suspended sediment shape its behaviour. Sediment texture was determined for 341 sediment samples and these data were used to further explore suspended sediment behaviour and examine additional connections between landuse and soil loss through time and space.

9.1 Conclusions

The main findings from the study are as follows:

Rainfall dynamics

An annual average of 77 storms was identified over the three-year period. Using I_{10} (peak 10-minute storm rainfall intensity) and R_T (total storm rainfall) in a matrix storm classification, 3.5% were classified as major storms ($R_T > 30$ mm *and* $I_{10} > 50$ mm/h), 76.8% as minor storms ($R_T <$ 10 mm *and* 3 mm $< I_{10} <$ 10 mm), and the remainder (19.7%) as intermediate storms. About 1/3 of all storms occurred during the pre-monsoon season.

In over 50% of all storms, I_{10} and I_{60} began in the first 15 min of the storm and in 25% of all storms, I_{10} exceeded 30 mm/h. There were no significant differences between the distribution of monsoon and pre-monsoon storms by aspect nor elevation though some storm period variables did show differences. In comparison with monsoon storms, pre-monsoon storms delivered less total rainfall, were shorter in duration, occurred after longer periods without rain, and showed a delayed occurrence of I_{60}.

Regionally, over the 111-km^2 study basin, wet-season rainfall increased with elevation. though a positive trend with elevation was also discernible on the 5-km^2 hillslope scale, local topographic and synoptic interactions resulted in marked exceptions. Variation in monthly hillslope rainfall exceeded 50% and elevational trends seasonally reversed. The majority of tributary basin delivery was local in nature with significantly different amounts of rain falling over contrasting upland and lowland 1-km^2 areas. Given the measured variability, several rain gauges are needed (within the 5-km^2 basin) to limit error to within 50%.

Soil erosion and dynamics

Annual soil losses of up to 40 t/ha were measured from rainfed upland cultivated fields. Pre-monsoon losses were over an order of magnitude greater than the monsoon losses and were attributed to a lack of vegetative cover during the pre-monsoon season. The highest annual rates of soil loss resulted from unfortunate timing of pre-monsoon storms with respect to the development of the surface cover. Below a threshold of I_{10} = 30 mm/h, little erosion was observed due to surface erosion from *bari*. Degraded land with a year-round lack of surface cover (and often gullied), experienced an accelerated rate of erosion from rains in every season.

Vegetative cover was the strongest observed management control on sediment regimes. In addition, the irrigation system captured a major proportion of surface run-off through diversion. However, indigenous management showed a reduced effectiveness at the highest measured flows.

Sediment properties and behaviour

Seasonal shifts in sediment rating curves resulted from a change in clay and silt recruitment from *bari*. Silt and clay dominated sediment yield during the pre-monsoon season whereas silt and fine sand dominated during the monsoon season. Sand output was controlled hydraulically over all scales and the slope of the sand C-Q relation was proportional to basin steepness with a minimum threshold discharge required. Although C-Q relations commonly lacked hysteresis (SV behaviour was observed most frequently) hysteretic relations were also common. In particular, clockwise hysteresis indicating a degree of sediment exhaustion was observed frequently during the monsoon season.

High-phosphorus sediment derived almost uniformly from the intensively-cultivated uplands, especially during the pre-monsoon season, and dominated the high-flow samples. Most low-phosphorus stream sediment originated from areas of gullied red soil. Sediment colour paralleled closely its nutrient condition. Phosphorus content, colour, and texture of soil and sediment were found to be effective sediment fingerprints (tracers) especially when conclusions based on their behaviour were supported by hydrological data relevant to their interaction.

Indigenous management

The farmers alter profoundly the sediment regimes of these headwater basins and in general most of their management activities are designed to minimise net soil loss from a basin. Farmers were observed to practise techniques well adapted to this mountain environment and to be very receptive to innovation. Indigenous knowledge is in keeping with scientific calibration though it is inconsistent across the farming population. It was suggested that any attempt to introduce new erosion-control measures would require, in order to successful, a good understanding of the measure's interactions with the larger complex farming system and the importance of labour which is generally in short supply.

Sediment budgets

Sediment yield was determined to be highly dependent on season, scale, and landuse. Pre-monsoon sediment production dominated annual production in the headwater basins with rill and sheet erosion being the dominant process. Streambank erosion and terrace failure were the dominant processes during the monsoon season. Of the total sediment production, 30 to 60% was recaptured into the *bari* and *khet* at the 10-km^2 basin scale. At larger scales, up to 60 to 70% of sediment production was put into long-term storage within the basin. Average annual sediment yield was found to be 10 to 20 t/ha for all three basin scales examined in this study with a decreasing trend from the smallest to the largest basins. Degraded lands produced sediment in direct proportion to total event rainfall, independent of season and spatial scale.

Individual events were most damaging at small spatial scales (over 60% of total annual soil loss at 100 m^2) declining in importance as scale increased (15% to 20% of total annual soil loss at 100 km^2). Episodic-regime losses are the most damaging during the pre-monsoon when fields are prepared for production. The results suggest that total sediment production during normal-regime and sediment-regime events are roughly equivalent within the annual budget. *Major* rainfall events provided the greatest potential for episodic-regime sediment production; *intermediate* and significant *minor* events resulted in episodic-regime production though favourable conditions were necessary.

This study supports the hypothesis put forth at its outset. Management practices pursued by the Middle Mountain farmers are effective at restricting soil erosion and at limiting soil loss from headwater basins. In addition, measured rates of soil erosion and the high degree of sediment recapture do not in themselves indicate a deterioration of the health of this agricultural system. The sediment dynamics, however, do suggest vulnerability especially given the likelihood in the future of increased population and reduced soil fertility.

9.2 General discussion

The findings from this study provide an erosional diagnosis and have important implications for soil-erosion monitoring schemes especially those implemented to guide development activities.

The source of suspended sediment in these low-order streams varies with catchment scale and with the advance of the rainy season. Erosion from dryland cultivated fields (*bari*) is of greatest concern to farmers and has been observed to be strongly seasonal. Perhaps the most important finding of this study is the damaging rates of soil erosion which occur during the pre-monsoon season when infrequent, high-intensity rain falls on bare, cultivated soils. During May and June, the farmers begin to cultivate their soils in anticipation of the rain and the vegetative cover increases rapidly as the rainy season progresses. By mid-July, this mechanism of persistent sediment production and nutrient loss from the upland areas becomes of little concern. Farmers are aware of the importance of surface cover and have adjusted their techniques to reduce soil loss during the rainy season but further attention is needed during the pre-monsoon period. Modifications to the farming system which address vegetative cover during the pre-monsoon season will result in immediate reduction of soil losses from steep *bari*. Farmers who cultivate steep marginal slopes are some of the poorest living within these headwater areas and will benefit most from the implementation of practices of enhanced soil conservation during the pre-monsoon season. Unfortunately, the timing of high-intensity rainfall with respect to the timing of cultivation is difficult to predict and remains a major problem in pursuing upland soil conservation.

Sediment export from these basins declines substantially with the arrival of the monsoon season but new concerns arise. Though peak rainfall intensity is comparable between the pre-monsoon and the monsoon seasons, the total amount of rainfall during monsoon storms is higher which stresses the farming system in two important ways. The vast system of ditches throughout the *bari* serves to evacuate runoff efficiently to preserve the stability of steep slopes. However, it is a precarious balance and any part of the system which is not diligently maintained or has been changed recently without proper design, can result in large losses episodically due to severe rilling or gullying or due to the complete failure of a terrace or system of terraces. Second, synchronised tributary inflow or widespread heavy rainfall, or both, can yield discharge rates which, even if only brief, are damaging to riparian areas and to structures or both. The high-value summer rice crop is vulnerable to large flood events that destroy dams constructed within the streams for irrigation. These losses are harder to prevent due to their episodic nature and variation with rainfall. In general, hillslope losses can be mitigated by improving the economic viability of the agricultural system so that sufficient labour is available for its intensive maintenance.

The effect of spatial and temporal differences in rainfall on the sediment regimes is not as important as the effect of vegetative cover. The character of pre-monsoon and monsoon season storms is not significantly different in rainfall intensity. Total rainfall, as mentioned above, can be greater during monsoon storms causing problems downstream. Long-term rainfall records suggest that, historically, the highest monthly and 24-hour rainfall amounts come in June - these storms pose the greatest episodic threat by rainfall to the farming system. Simultaneous damage would result from high-volume runoff in streams *and* high-intensity rainfall on bare cultivated ground. It is due, in particular, to the unpredictability of these types of events that a broader prescription for land management cannot be developed from this study.

Different problems arise from severe land degradation. These areas do not typically enjoy an improved vegetative cover in any season and hence are chronic sediment producers. Degraded areas examined in this study area are on relatively gentle slopes thereby restricting mechanisms of sediment production on these lands to surface erosion (notably gully erosion). Presumably, severely-degraded areas on steep hillslopes (*e.g.*, neglected *bari* gone out of production) would erode at a greater rate due to the additional mass wasting component. The soil loss from degraded land has little direct economic importance to farmers due to its low nutrient content. However, the loss of this land from production means greater pressure on the remaining land to support the population. In addition, in a country with considerable hydropower potential, there is a direct cost associated with reservoir sedimentation due to sediment production from these areas. It may be cost effective for proponents of these capital-intensive projects to include targeted off-site land rehabilitation in their development proposals to increase the lifetime of reservoirs. Measures taken to prevent additional degradation may also be cost effective on this basis.

By design, a large proportion of these headwater soil losses is recaptured before leaving these basins. Although at larger basin scales (100 km^2), alluvial storage may be an important mechanism (especially for sands), it is the intentional and incidental recapture and storage due to manipulation by the indigenous farmers that is important in the headwater basins. The indigenous methods are both effective and vulnerable. On July 10, 1992, a flood resulting from rainfall widespread over a 5-km^2 study basin destroyed every irrigation dam within the stream. Working with the farmers to develop techniques to improve their ability to recapture previously-eroded soil is a useful area of applied research.

The high rates of sediment recapture with scale determined in this study are consistent with other agricultural basins around the world (Church *et al.* 1989) and help to put in perspective the measurements summarised earlier in Tables 5.1 and 5.2. Despite detailed research, it will remain a challenge to integrate findings like these into models of larger systems in Nepal especially those which cross physiographic regions due to the heterogeneous nature of sediment production, storage, and transport.

Rainfall and land-surface variabilities challenge the ability of conventional measurements to reach definitive conclusions. Rainfall can be highly "cellular" restricting the usefulness of individual rain gauges to providing broad regional indications of monthly rainfall expectation. Preferred topographic pathways and exhaustion and enhancement due to elevation are additional effects which limit the usefulness of a single gauge, even when it is *within* the basin of interest. Surface hydrological response varies seasonally due to vegetative cover and spatially due to management and topography over scales too small to be considered by most development-related monitoring programs in these environments.

How best to respond to these monitoring limitations? Placing tight limits on research goals would help to restrict data requirements and limit expectations of the monitoring. Pilot-scale monitoring may help to expose site-specific variability important to the project under consideration. A high degree of uncertainty should be anticipated.

If soil and sediment dynamics are to be understood cost effectively, it is necessary to be creative in exploiting site-specific opportunities for investigation. For instance, sediment texture and other sediment-quality parameters may be able to provide a quick assessment of the origin of suspended sediment. Repeat measurements should be taken to partition variance. Incorporating the recommendations from research into sediment budget techniques should also be a priority (*e.g.*, Dunne 1984). Above all, distinguishing between development to support the farming system and development to reduce downstream sedimentation should help to focus monitoring. If the inherent variability in these headwater basins is ignored and findings are inaccurate or inconclusive, development monies may be poorly or mistakenly applied.

What can this study conclude about the health of this agricultural system with respect to soil erosion? The indigenous management techniques are very capable at restricting basin soil loss despite the low level of capital available and the physical difficulties that this environment imposes. The challenging physical environment and the duration of agriculture on these hillslopes imply that, historically, net soil losses may have been equivalent to soil development. However, the system is vulnerable to rapid change because of the difficulties for indigenous management to adapt quickly enough to additional constraints. In particular, any economic changes which reduce the viability of labour-intensive management could diminish the ability of the system as a whole to maintain soil loss at the current relative levels. However, the high degree of skill and adaptability of the farmers within this environment suggests that carefully designed interventions (see section 9.2.1) which target aspects of the agricultural system most in need of support while not undermining the present methods have a reasonable likelihood for success.

There is an implication that Middle Mountain farmers have not been involved in an alleged spiral of cause and effect bringing devastating floods to the Indo-Gangetic Plain. Present management is effective in limiting net basin sediment loss if only for the farmers' own self interest. Basin export is not extreme by worldwide standards (section 5.2.1) nor is it high within Nepal in comparison to rates determined at stations on the major rivers (Galay 1997).

If the documented decline in soil fertility (Schreier *et al.* 1994) continues, it may undermine the viability of the present system in containing soil losses to their current levels. As such, changes in soil fertility warrant further attention including nutrient budgets which parallel the sediment budgets presented in this study. To plan for effective intervention, a closer quantitative examination of indigenous methods is also justified.

Is the farming system sustainable given observed current soil dynamics? Though they may be sustainable today, it is unlikely that they can remain sustainable in the future under the increased landuse intensification that may be necessary with projected population increases unless support is provided strategically from outside sources. As the vulnerability of the agricultural system increases, it will take increasingly longer for it to recover from damaging, infrequent events. Meanwhile, it is just a matter of time before a large pre-monsoon storm occurs which decimates both the hillslopes and the channels. Who will pay the price for a delayed recovery?

9.3 Recommendations

The above conclusions and discussion suggest the following recommendations:

9.3.1 Farming system

- New approaches should be pursued which bring a vegetative cover to bare soil in the pre-monsoon season (*e.g.*, mulches, relay crops, drought-resistant cover crops through intercropping, plastic film technology, or other physical barriers). Benefits from such changes will be felt primarily on-site by the upland farmer in terms of higher productivity.

- New approaches should be pursued to decrease the erodibility of upland cultivated soils. One possibility is to increase the organic matter content of the plough layer though this is also perhaps the most difficult given the severe constraints on organic matter inputs present in this agricultural system.
- Selective structural enhancements to the water-management system should be made to minimise failures during the rainy season and to reduce water losses during the dry season.
- Severely-degraded land should be put back into production, particularly gullied areas and areas with poor surface cover: recommended approaches include stabilising gullies and other bare surfaces through structural and vegetative techniques; initiating and supporting community efforts to bring seriously degraded lands back into production, paying particular attention to solutions which do not require indefinite input from the outside (*e.g.*, Upadyha 1994); and taking action to prevent moderately-degraded land from becoming seriously degraded. Though these steps can also take pressure off the limited land base, their most significant effect will be to reduce downstream sedimentation.
- It may be beneficial to maintain production on marginal lands with stony surface soils because the high infiltration rates promote reduced runoff. Yields will be low but they may be stable overall especially in contrast with strategies which focus on developing high-yield steeplands. The biggest hurdle in maintaining production on stony fields will be in overcoming the moisture deficit during the growing season.
- The current indigenous management system practised in the Middle Mountains should be supported by policies promoted by government and development organisations.
- Development strategies should be implemented to improve labour availability for the upland farmers to help improve the erosion-control effectiveness of current indigenous management techniques.

9.3.2 Monitoring

- When pursuing rainfall monitoring for erosion studies in the Middle Mountains, a minimum resolution of 0.25 mm and a sampling interval not exceeding 2 min should be used. A storm definition based on a two-hour period-without-rain respects inherent characteristics of rainfall in the Middle Mountains.
- A stage-stratified rating curve can be used for small basins (1 km^2); in larger basins (above 5 km^2), further supplementary data are needed to address the complexity of interacting processes.
- Particle-size measurements of suspended sediment and other sediment properties can provide useful clues with respect to dominant sediment supplies; mineralogy holds great potential in landscapes with such diverse soils and erosional processes. Treating sediment as a single, bulk quantity severely limits insights gained into the system under study and drastically restricts the ability to have confidence in predictive relations.
- Study design should include both a nested and a non-nested set of basins and sub-basins to provide maximum information. Nested basins assist in examining the role of controls while non-nested basins can remove confounding associated with scale and steepness.
- Deterministic behaviour within the erosion and sediment-transport system should be identified and exploited to decrease monitoring requirements.
- Measurements should be carried out in all seasons, particularly when examining dynamics over small spatial scales (within 1 km^2).
- Before beginning any monitoring program, a careful examination of research goals is needed and two questions should be asked:
    - Can temporal and spatial variabilities be disguised at the intensity of the planned monitoring?
    - Could these scale effects be important to the goals of the research?

  If the answer to both of these questions is yes, greater monitoring resolution is needed or the research goals should be modified to accommodate a smaller study area.

9.3.3 Further Research

This study has identified several areas in need of further research for studies of erosion and sediment budgets in the Middle Mountains:

Sediment Sources

- Map all sediment sources within channels and on land surfaces.
- Measure rates of surface erosion from degraded grassland, shrub, and forest land.
- Improve the quantitative understanding of rates of surface erosion from *bari* by examining soil properties - *e.g.*, soil infiltrability, degraded/cumulic profile description, and the relative importance of aggregate stability.

Sediment Storage

- Carry out water and sediment mass balances of the irrigation system. Determine the efficiency of the diversion dams.
- Improve the measurements of deposition in *bari* and *khet* canals. Carry out detailed mapping of *bari* ditches.

Modelling

- Investigate the usefulness of a "floating" rating curve especially for subseasonal periods during which the sediment regime substantially departs from the seasonal average - for instance, during May in the early part of the pre-monsoon season. A floating rating curve ratchets down gradually within a season (perhaps daily) rather than discontinuously at seasonal limits.

Indigenous Management

- Carry out further investigation to document and calibrate indigenous methods influential to the sediment regime.

Scale

- Resolve the scale between the plot (0.01 ha) and the sub-basin (72 ha). Measure total event runoff and soil loss from 0.1-ha *bari* plots using sampling installations within natural draws.
- Plan ahead to deal with measurement limitations. If interested in sand export from these basins, implement a reliable sampling strategy. Consider nutrient calculations which require only clay and silt yield.

Nutrients

- Develop nutrient budgets within headwater basins. Identify areas of vulnerability in total nutrient loss.

9.4 Postscript

A common western view of these steepland farmers sees them as an enemy of the land, practising agriculture where they should not. This study suggests a different view, one that sees the farmers managing in a way that is well tuned and adapted to their environment, and open to improvements which creatively build upon their existing knowledge rather than cast it aside.

This research also suggests that there remains a useful place for Science in international development in Nepal. Many scientific questions need to be addressed to improve the effectiveness of development activities. This perspective is somewhat contrary to the idea of trans-science as put forth by Thompson and Warburton (1985). If appropriate and carefully-constructed questions are asked, results from scientific investigations can be useful. While such findings may bear directly on an evaluation of the Theory of Himalayan Environmental Degradation, more importantly the improved understanding can make development more able to enhance the lives of upland farmers.

Appendices

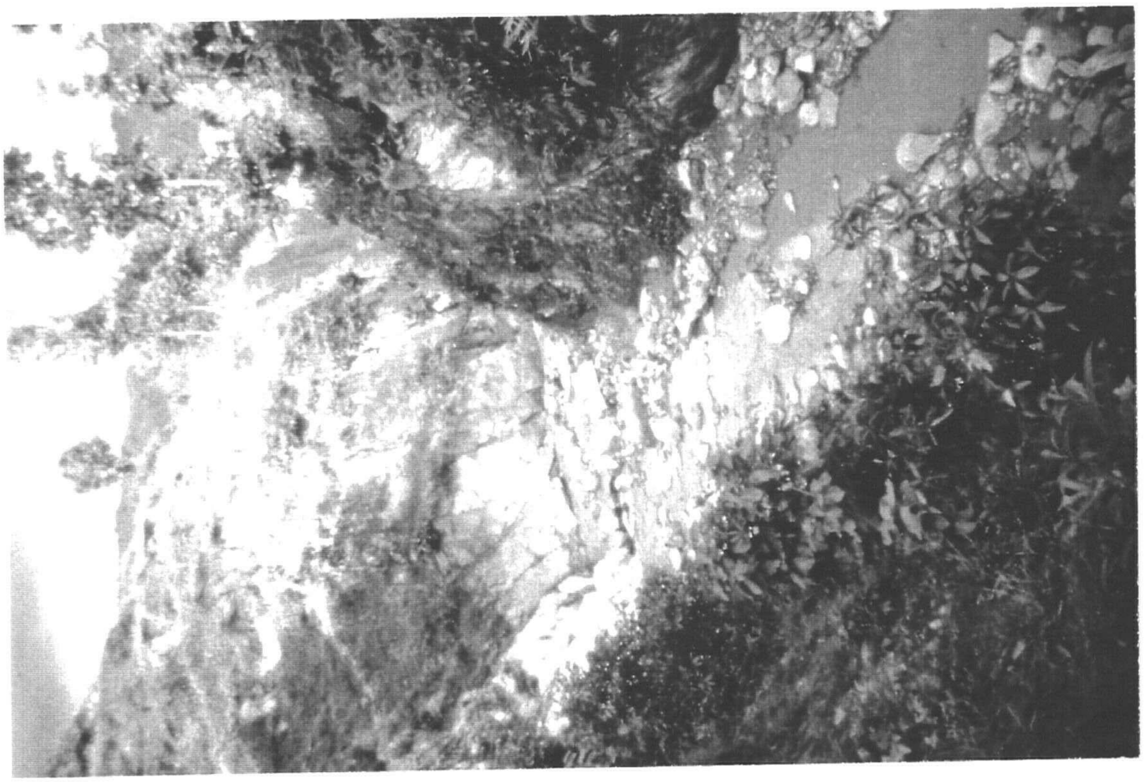
Appendix A1 Photographs of the Study Area

Figure A1.1 Terraced agriculture in the study area: (a) rainfed (*bari*) and (b) irrigated (*khet*).

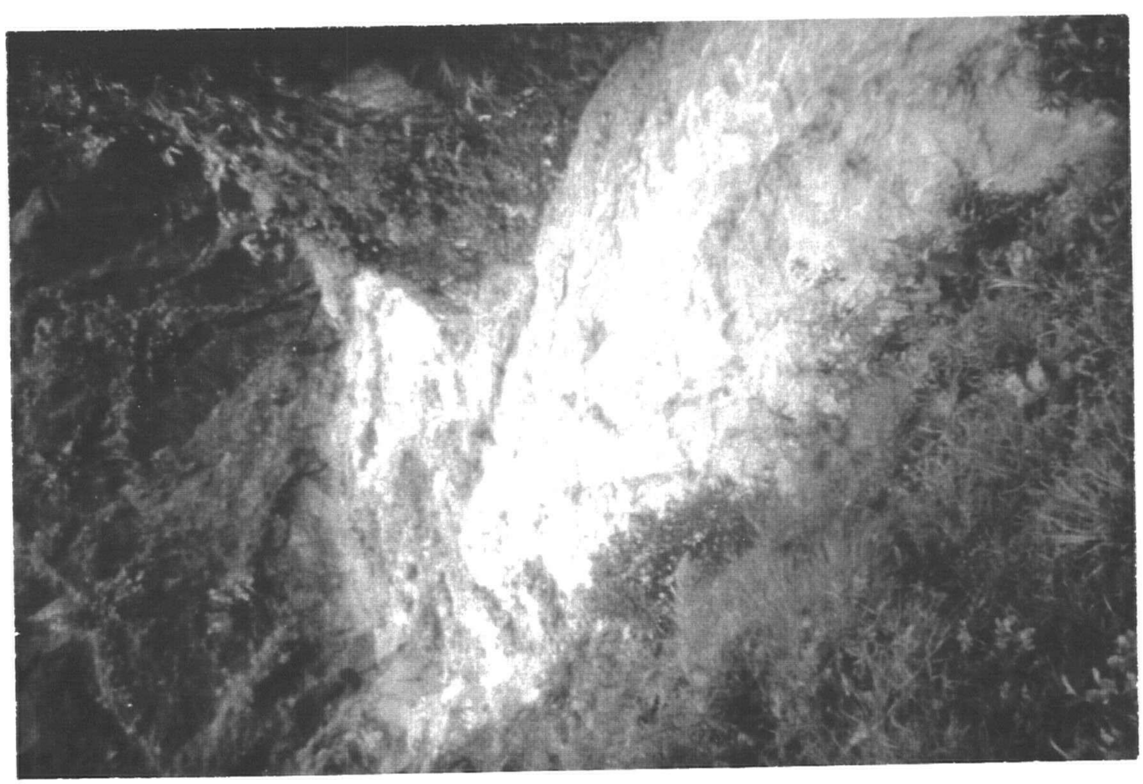
(a)

(b)

Figure A1.2 Reach of the Lower Andheri River during mid-monsoon at (a) high flow and (b) low flow.



(b)



(a)

Appendix A2 Descriptive Rainfall Statistics of Study Area

Table A2.1 Average monthly, maximum monthly, minimum monthly, and maximum 24-hour rainfall (mm) at Baluwa, 900 m (1992-1994, averages based on 1993-1994).

Period	Average Monthly	Maximum Monthly	Minimum Monthly	Maximum 24-hour
January	29.1	41.2	17.0	20.7
February	15.0	18.4	11.6	15.9
March	24.0	40.2	7.8	22.2
April	45.1	80.9	9.2	19.5
May	80.5	83.3	76.0	39.5
June	234.3	314.0	154.6	84.1
July	226.2	480.0	203.7	75.2
August	324.4	338.8	213.0	71.9
September	163.3	215.4	111.1	58.0
October	4.7	32.6	0.0	13.8
November	6.2	12.3	0.0	12.3
December	0.0	3.9	0.0	3.9
Year	1152.6	1254.6	1051.0	84.1

Table A2.2 Average monthly, maximum monthly, minimum monthly, and maximum 24-hour rainfall (mm) at Kathmandu Airport, 1336 m (1968-1986).

Period	Average Monthly	Maximum Monthly	Minimum Monthly	Maximum 24-Hour
January	12.8	47.4	0.0	31.3
February	19.4	45.3	0.0	25.8
March	32.9	80.4	0.0	39.0
April	57.6	180.8	4.0	38.0
May	114.1	305.7	37.0	73.2
June	240.7	608.1	74.8	100.0
July	363.1	500.0	204.6	86.5
August	285.3	434.0	86.9	76.0
September	198.1	376.0	36.4	69.0
October	62.3	167.0	0.0	124.4
November	6.1	42.0	0.0	18.0
December	15.6	78.9	0.0	51.0
Year	1408.2	1799.8	1132.0	124.4

Table A2.3 Average monthly, maximum monthly, minimum monthly, and maximum 24-hour rainfall (mm) at Bela, 1211 m (1990-1994).

Period	Average Monthly	Maximum Monthly	Minimum Monthly	Maximum 24-Hour
January	25.9	64.4	0.0	42.4
February	25.7	53.7	13.0	18.7
March	32.7	66.5	0.0	28.8
April	47.3	88.6	16.6	26.9
May	155.9	208.2	99.1	56.5
June	190.6	250.3	140.3	56.5
July	352.7	400.8	279.4	115.6
August	308.9	384.0	217.6	101.4
September	181.8	230.0	126.0	75.0
October	19.2	44.3	0.0	21.4
November	6.6	19.9	0.0	19.9
December	5.6	17.2	0.0	11.8
Year	1352.9	1617.2	1179.0	115.6

Table A2.4 Average monthly, maximum monthly, minimum monthly, and maximum 24-hour rainfall (mm) at Dhulikhel, 1500 m (1990-1994).

Period	Average Monthly	Maximum Monthly	Minimum Monthly	Maximum 24-Hour
January	19.5	40.4	0.0	19.9
February	28.6	46.2	16.2	19.9
March	36.0	63.5	0.0	24.5
April	45.9	76.3	12.8	43.3
May	127.0	226.8	12.8	60.8
June	280.4	444.5	202.5	76.6
July	430.0	552.9	299.0	82.4
August	426.7	558.4	364.4	92.7
September	249.2	352.0	159.4	84.5
October	32.4	79.3	0.0	22.8
November	9.3	26.6	0.0	20.1
December	4.0	19.8	0.0	12.7
Year	1689.0	1974.7	1297.0	92.7

Table A2.5 Average monthly, maximum monthly, minimum monthly, and maximum 24-hour rainfall at Panchkhal, 865 m (1978-1994, averages based on 1978-1985 and 1988-1994).

Period	Average Monthly	Maximum Monthly	Minimum Monthly	Maximum 24-Hour
January	13.2	54.0	0.0	43.2
February	16.8	37.4	1.0	21.0
March	25.4	98.6	0.0	41.6
April	46.0	123.5	2.7	90.0
May	103.1	176.0	33.0	121.0
June	186.6	489.0	36.0	133.0
July	300.4	428.0	192.4	116.0
August	292.0	390.0	201.0	99.0
September	190.8	373.0	87.2	75.1
October	38.8	218.0	0.0	67.0
November	7.4	29.0	0.0	17.3
December	19.0	83.0	0.0	67.0
Year	1227.4	1692.0	1023.0	133.0

A3. Location and Performance Information of Rain Gauges

A3.1 Location

Table A3.1 Rain-gauge summary information including gauge number, elevation, and location.

Gauge	Elevation (m)	Location
1	865	Baluwa (by tipping bucket, Gauge 80)
2	835	Kharel Tol
3	850	Khampur
4	880	Bakultar
5	930	Luitelgaun (lower)
6	975	Luitelgaun (upper)
7	915	Dhaireni Danda
8	880	Sitraulagaun
9	900	Ojhetar
10	898	Station 2
11	1240	Erosion Plot 2/3 (by tipping bucket, Gauge 84)
12	1215	Chiurebot
13	1315	Aitabari Bari
14	1420	Dahaldanda
15	1485	Thapagairi
16	1400	Salgadekothumka
17	1311	Dandaghar
18	1220	Dandapari
19	1182	Lalgiri
20	1280	Bela (by HMG standard, Gauge 92)
21	1215	Thumka
22	1105	Chhap
23	1390	Dandagaun
24	1314	Dandagaun (lower)
25	1240	Erosion Plot 1 (by tipping bucket, Gauge 83)
26	853	Baluwa school
27	962	Dhurapura
28	1124	Saurachaurdanda

Table A3.1 (continued).

Gauge	Elevation (m)	Location
31	895	Bhimsenthan (by tipping bucket, Gauge 82)
32	900	Simle
33	875	Aapgari
34	865	Bhimsenthan (lower)
35	910	Thulogaun (upper)
36	870	Thulogaun (low
37	860	Tinghare
38	855	Bikramtar
39	1000	Ramche
40	945	Gothgaun
41	1305	Erosion Plot 4 (by tipping bucket, Gauge 81 and by HMG standard, Gauge 97)
42	1260	Erosion Plot 5
43	1165	Sarkithok
44	1325	Dandathok
45	1310	Thuligaun
46	1405	Palanchok Bhagawatisthan
47	1120	Jogi Thok
48	1260	Khoria (upper)
49	985	Pandali
50	1325	Palanchok Bhagawatisthan (lower)
51	1225	below Khoria
52	1145	Saline
53	980	Thulipipal
60	870	Tamaghat
61	810	Station 1
62	825	Sri Ram Pati
63	890	MRM Nursery
65	1061	Khukuriko Rumto (station 10)

Table A3.1 (continued).

Gauge	Elevation (m)	Location
66	940	Above station 2
67	1310	San Danda (near Gauge 17)
68	1545	Dhulikhel (by HMG standard, Gauge 93)
69	938	Bela Pakha (between stations 11 & 12)
70	928	Dhaireni Bagmahal
80	865	Baluwa (tipping bucket at Gauge 1)
81	1300	Bhetwalthok (tipping bucket at Gauge 41)
82	890	Bhimsenthan (tipping bucket at Gauge 31)
83	1240	Kamidanda (tipping bucket at Gauge 25)
84	1240	Bela (tipping bucket at Gauge 11)
92	1254	Bela - HMG standard (at Gauge 20)
93	1545	Dhulikhel - HMG standard (at Gauge 68)
94	865	Panchkhal - HMG station (no replicate; government maintained)
97	1300	Bhetwalthok - HMG standard (at Gauges 41 & 81)

A3.2 Performance characteristics

Three different types of rain gauges are compared here:

1) recording rain gauge ("tipping bucket")

2) standard gauge of Nepal government ("HMG")

3) gauge custom made for this study ("Custom")

There are eight comparisons. In five instances, the tipping bucket is compared to the custom gauge; in three instances, the government standard (HMG) is compared to the custom gauge.

Figure A3.1 Catch ratios (Custom/Tipping-bucket) at Sites 1, 2, 3, and 4.

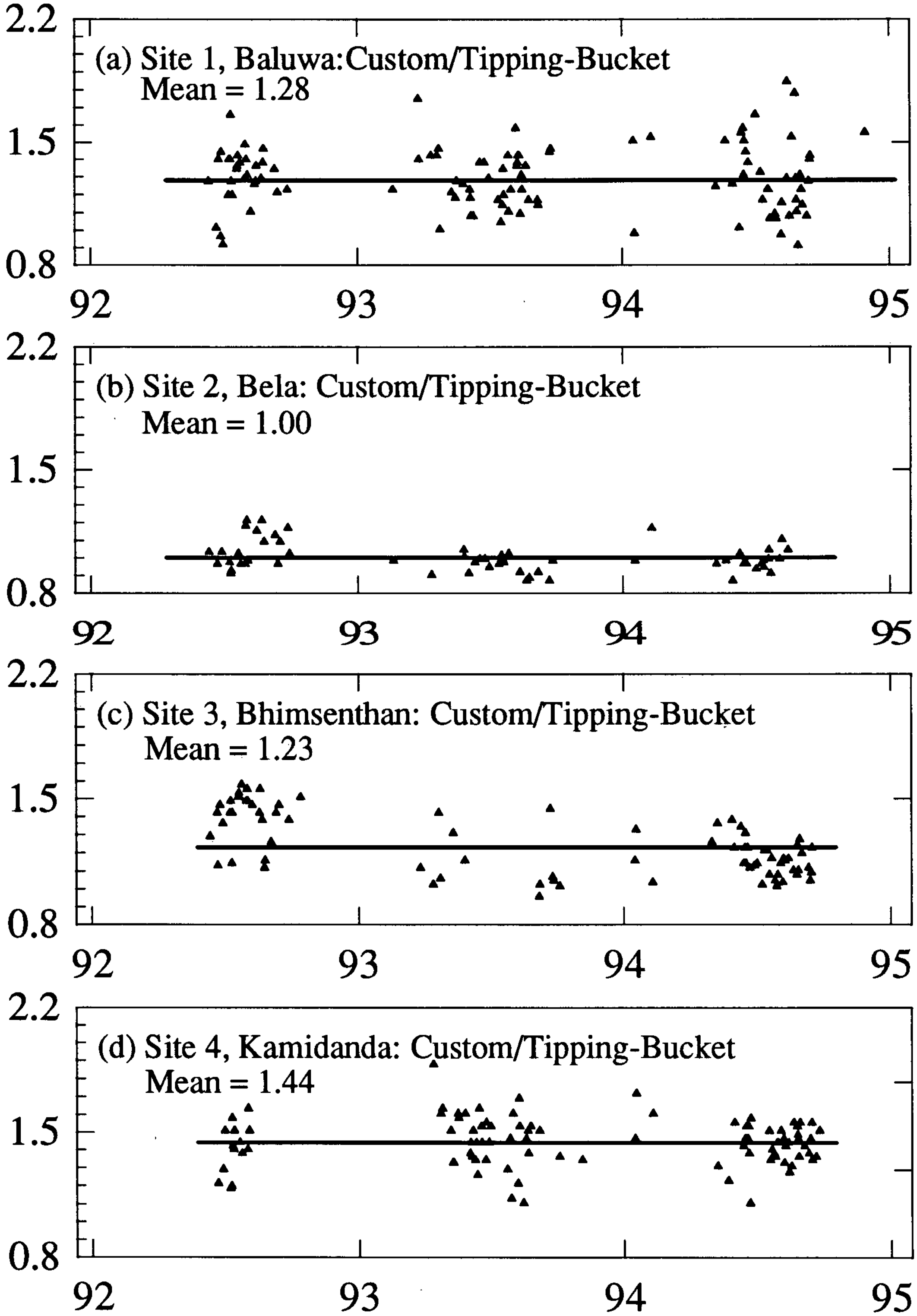
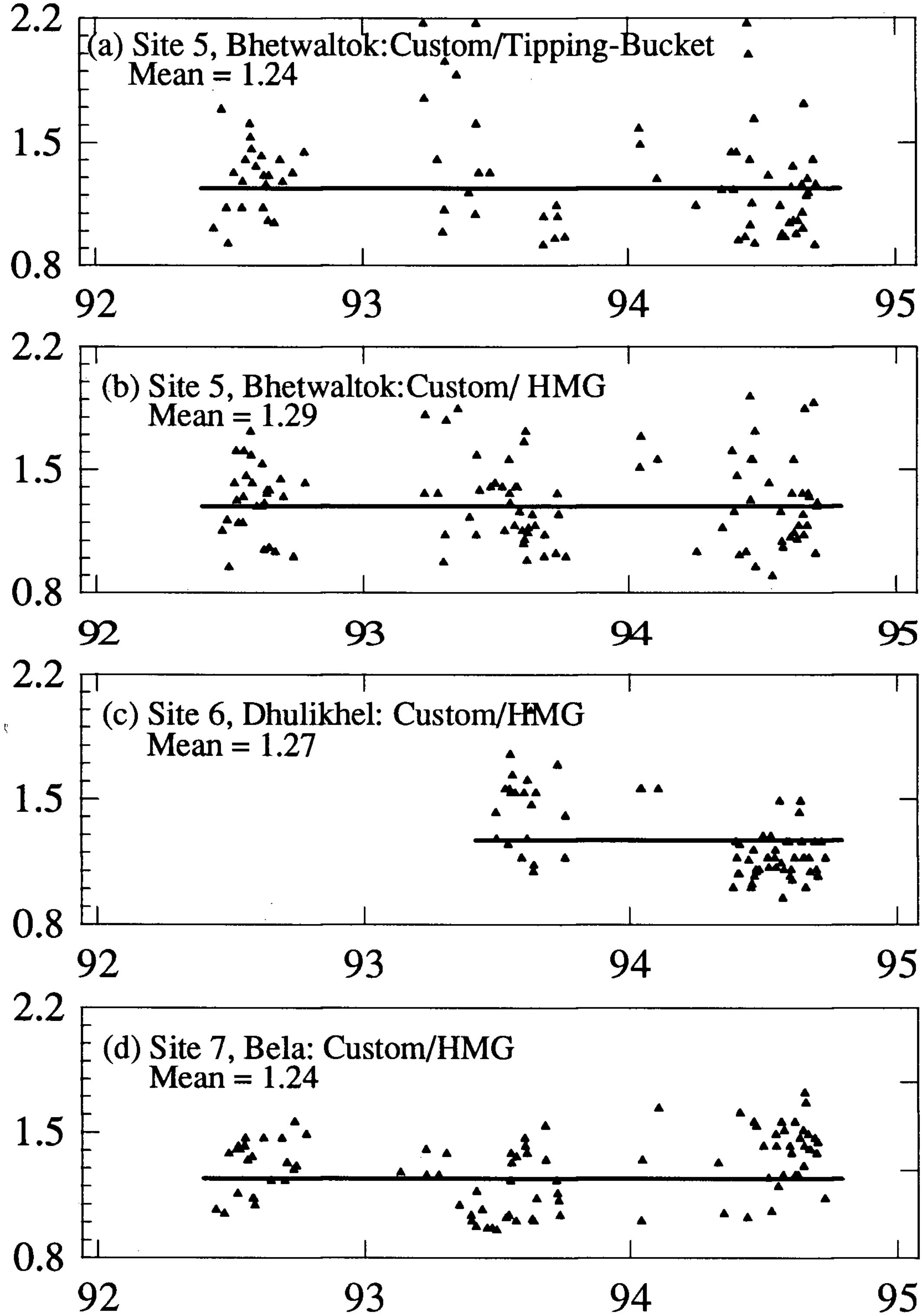


Figure A3.2 Catch ratios (Custom/Tipping-bucket & Custom/HMG) at Sites 5, 6, and 7.



Appendix A4 Questionnaires

A4.1 Perceptions, attitudes, and approaches (1991)

Soil erosion

- Is soil erosion good or bad for your land? Does the soil need protecting?
- What kinds of soil erosion occur?
- How much time each year do you spend maintaining the bari terraces and risers? The khet terraces and risers?

Water management

- Does water need management?
- When it rains, where does the bari soil go?
- What functions do canals serve in the farming system besides irrigation?
- What month is the worst time for a heavy rain in the *bari*? In the *khet*?

Awareness

- Why is there flooding in India? Do you think your farming practices affect flooding in India?
- Do you think farmers here are doing enough to protect the soil?
- If there are ways to protect the soil that you don't know about, would you be interested in learning about them?

A4.2 Soil classification (1992)

Farmers are presented 16 soils on white paper and asked the following questions:

a) What is the name of each soil?

b) Which of these soils is the best and worst with respect to erosion?

c) Which of these soils is the best and worst with respect to production?

d) Which of these soils is the best overall?

e) Do soils change over time? If so, how?

A4.3 *Khet*-accumulation management (1992/3)

Soil-accumulation pins were installed in 1992/3 in khet along the Andheri River. The individuals who farm the fields where these pins were installed were asked the following questions:

General information about khet management

- What is the name of your *khet*? Who is the khet owner and what is his place of residence?
- What is the name of the irrigating canal?
- What is the khet type? What is the soil type?
- Describe the productivity of this khet (h/m/l).
- How many crop rotations do you have in one year in this khet?
- What are the dry season crops?
- How is water availability in this khet?
- What is the annual maintenance requirements in this khet? Type of repairs? Number of days required per year?
- Is soil erosion a concern in this khet? Is soil accumulation a concern in this khet?

Information about the khet specifically in 1992

- On what date was the rice planted?
- When was the rice harvested?
- What type of rice was planted?
- Describe this year's rice harvest.
- Describe the fertilizer regime (type and amount, per ropani).
- Describe the water availability.
- Describe the required maintenance this year.
    - Type of repairs.
    - Number of days required.
- Did anything irregular or outstanding occur to/in this khet this year?

A4.4 Soil classification (1993)

Farmer is asked to select a soil on the land that he/she farms and that he/she knows well.

1. Describe the following characteristics:

a) colour (specify the colour or range of colours found)

b) stickiness (L/M/H)

c) texture (fine, medium, coarse)

d) stoniness {**amount**: L/M/H and specify **type**(s)}

e) where is this soil typically found? (bari, khet, steep slopes, valley bottom,...)

f) how deep is this soil, typically?

g) describe the soil's capacity to **hold** water (L/M/H)

h) compared to other soils, does rainfall **runoff** or **go into** this soil?

i) when dry, how workable is this soil? (Easy, Medium, Difficult)

j) when wet, how workable is this soil? (E/M/D)

k) is this well-suited or poorly-suited for steeply-sloping terraces?

l) is this well-suited or poorly-suited for flat terraces (on steep land)?

m) how long can terraces be with this soil (short/medium/long)?

n) any special considerations about the *bhaal* size/slope ?

o) for a dry year, describe the yield from this soil (L/M/H)

p) in a wet year, describe the yield from this soil (L/M/H)

q) compared to other soils, describe the average yield from this soil (L/M/H)

r) describe this soil's requirements for synthetic fertilizer (**amount**: L/M/H and specify **type**)

s) describe this soil's requirements for compost fertilizer (**amount**: L/M/H)

t) list which crops are best suited for this soil (maize, rice, peanuts, tomato, oilseed, garlic, potato, etc)

u) how many times do you plough this soil for one crop?

A4.5 *Bari*-erosion management (1993)

In 1992, bari fields were selected for detailed soil analyses (infiltration measurements, soil classification interviews, etc). The owners of these fields were asked to answer the following questions:

- Are you the owner? If not, what is the owner's name and village? If yes, do you farm the land?

General characteristics

- What is the age of this bari?
- What type of bari is it?
- What is the soil type?
- Is this bari stoney? Is this good or bad?
- How workable is this soil when dry? When wet?

Cropping

- How many crops do you grow here per year? What types?
- What fertilizers do you use? How much and when are they applied?
- What is this bari's productivity in a very dry year? In a very wet year?

Soil erosion management

- In general, is soil erosion a concern on this bari? If so, when? What type of erosion?
- Did this bari experience any soil loss this year? Last year? What were the dates and describe the type of erosion.
- Do you use runoff ditches in this bari? If yes, explain how you design/choose the number, depth, width, and length.
- Do you cut back the terrace risers? If so, why? How many times per year? When? Where do you put the soil?

A4.6 Irrigation-dam management (1993)

Dam

- Who looks after this dam ?
- How long has there been a dam in that location?
- Describe what happened to the dam in 1992. On what date was it rebuilt?
- How many person-days were required to rebuild it?
- Before 1992, can you remember when the dam was previously destroyed/damaged?
- How long does it take for soil to accumulate fully, upstream of the dam?
- Do you ever put soil behind the dam from your fields? If so, where does this soil come from? How often do you do this? How much do you put there?
- Do you ever remove soil from behind the dam? If so, why? How often? How much?

Canal

- Is it functional now? If not, why? When will it be fixed?
- Does soil accumulate in the canal? If so, where? (be specific) How much? Where do you put this soil?
- When do you clean the canal?
- How long do you spend on this cleaning each year? (person days)

Khet

- How many ropani of khet does this canal irrigate?
- Do you cut back the terrace risers in the khet?
- Each year, when do you cut them back (be specific)?
- How much do you cut back?
- Why do you cut them back? (give multiple reasons if so)
- Where do you put the soil?

A4.7 Site descriptions of soils described by farmers (1992 & 1993 interviews)

Table A4.1 Summary of site data for 11 soils selected and described by farmers in 1993.

Soil Number	Slope	Aspect	Elevation
1	15	ENE	1320
2	13	NNE	1105
3	18	NE	1145
4	14	W	1210
5	3	Flat	880
6	0	SW/FLAT	860
7	12	W	1030
8	0	W	1215
9	12	WNW	1220
10	7.5	S	1260
11	0	WSW	990

Note: all soils taken from *bari* except #11 (*khet*).

Table A4.2 Summary of site data for 16 soils selected and described by farmers in 1992.

Soil No.	Landuse	Slope	Aspect	Elevation	Horizon
1	degraded grassland	1	SSW	890	B
2	*bari*	0	WSW	880	Bt
3	*bari*	0	WNW	910	Ap
4	*bari*	n/a	NNE	1388	Ap
5	*bari*	30	NNW	1260	B1
6	*bari*	30	NNE	1240	A
7	grassland	24	S	1190	AB
8	*bari*	0	WNW	910	B
9	grassland	24	S	1190	A
10	*bari*	1	WSW	880	Ap
11	*bari*	30	NNE	1240	C
12	*bari*	n/a	NNE	1388	A
13	*bari*	0	WSW	880	AB
14	*bari*	30	NNW	1260	Ap
15	*bari*	15	WSW	1325	Ap/B
16	forest	37	WSW	1300	A

Appendix A5 Stage-Discharge Relations

Figure A5.1 Stage-discharge relationship at station 1, Jhikhu River at Bhendabaribesi.

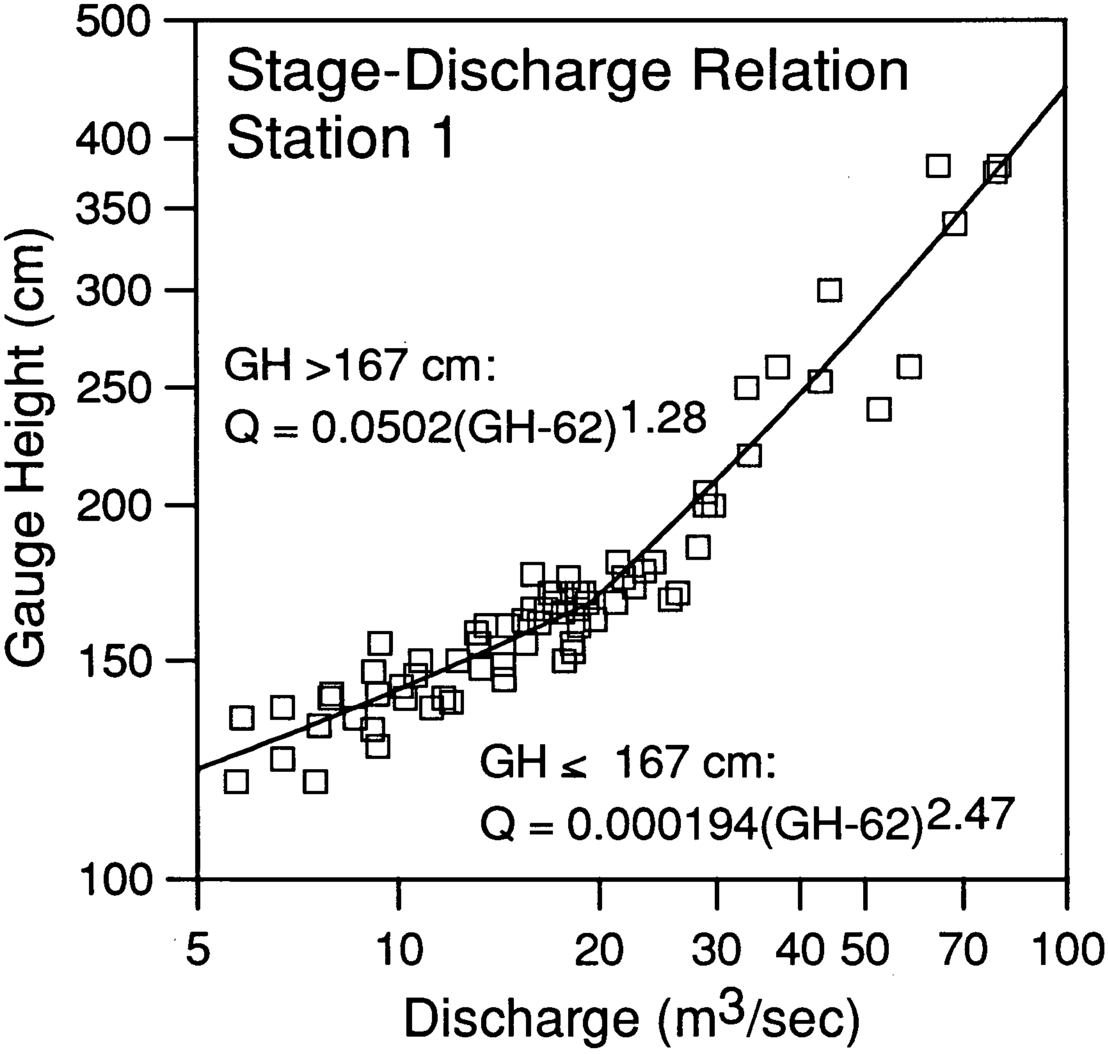


Figure A5.2 Stage-discharge relationship at station 2, Lower Andheri River.

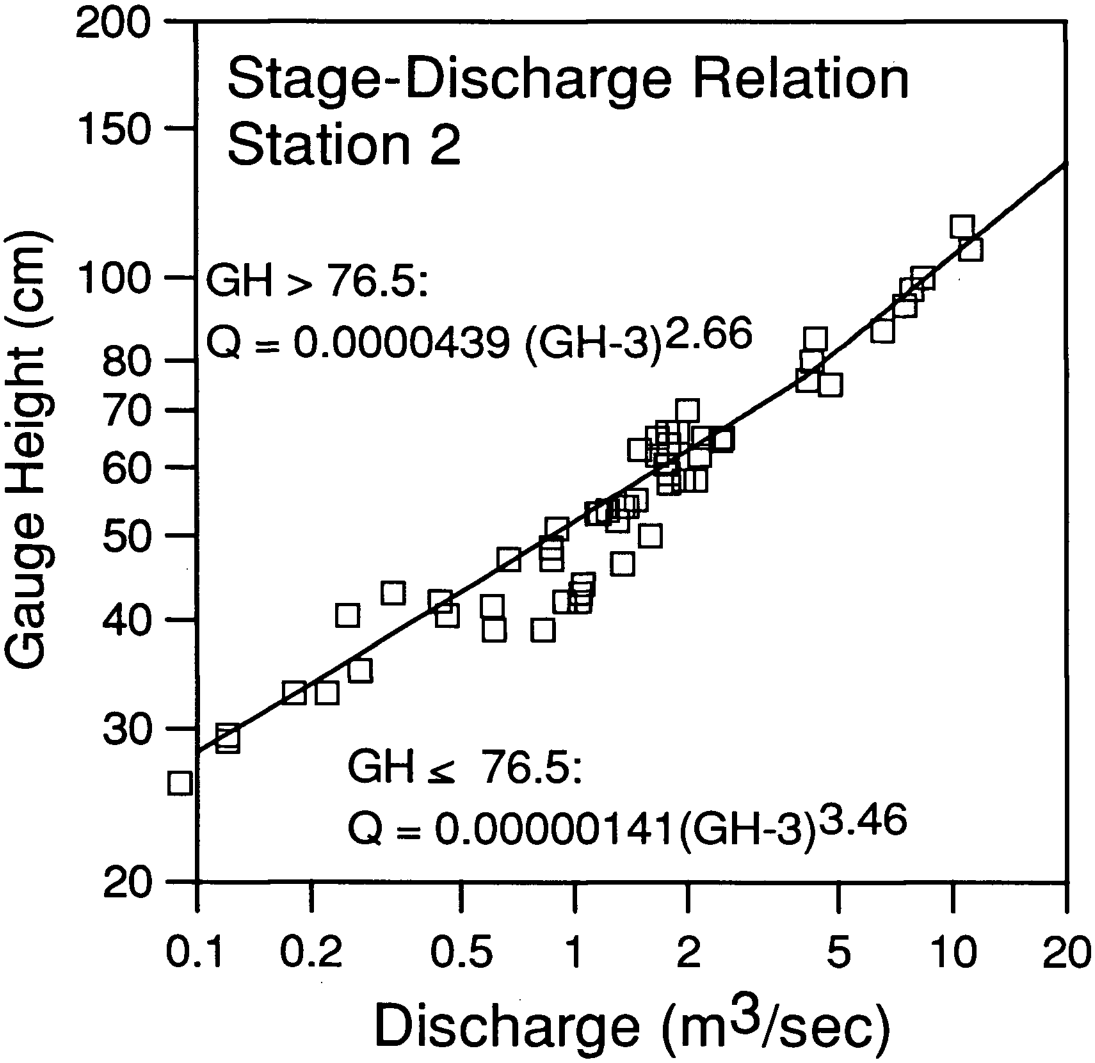


Figure A5.3 Stage-discharge relationship at station 3, Dhap River at Shree Rampati.

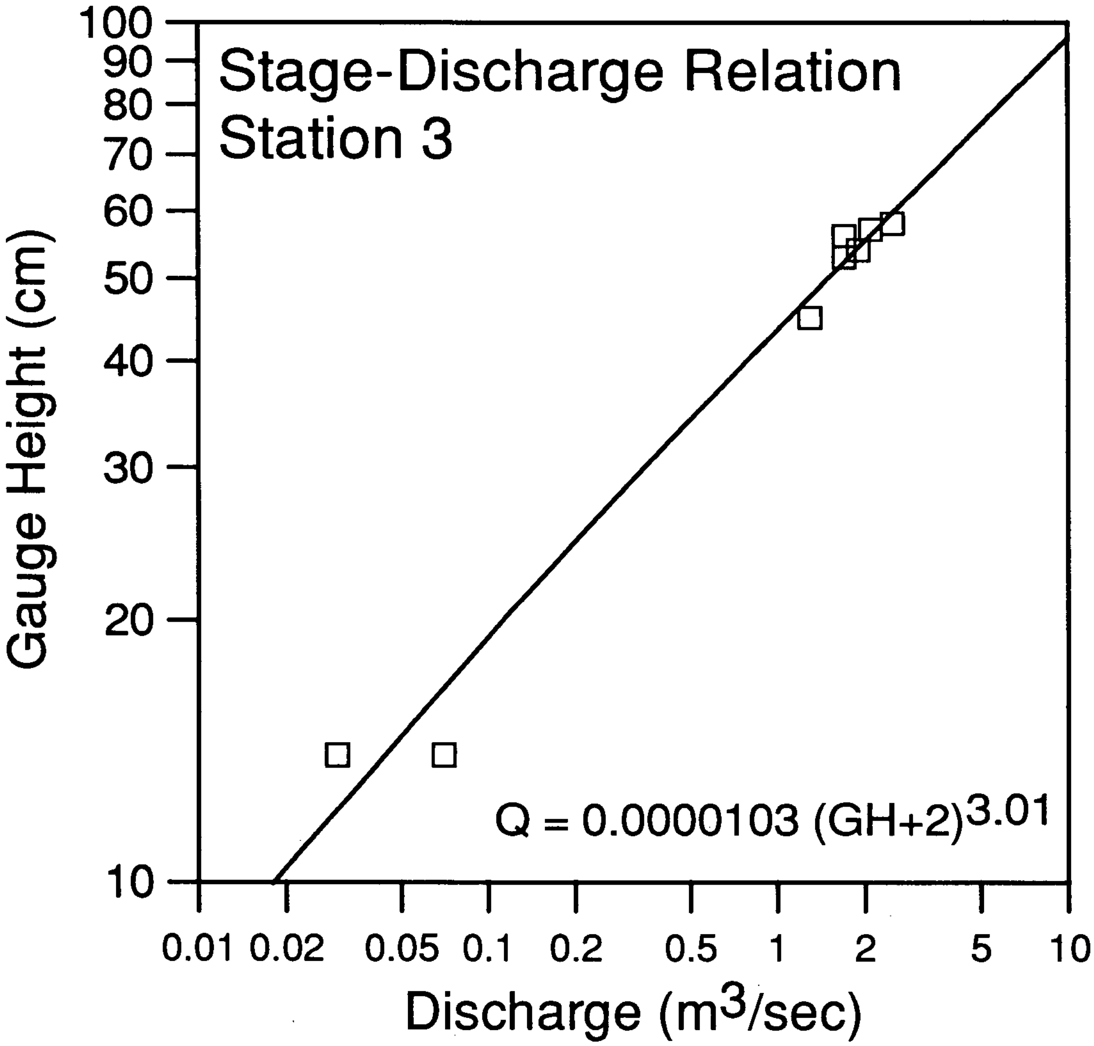


Figure A5.4 Stage-discharge relationship at station 9, Upper Andheri River.

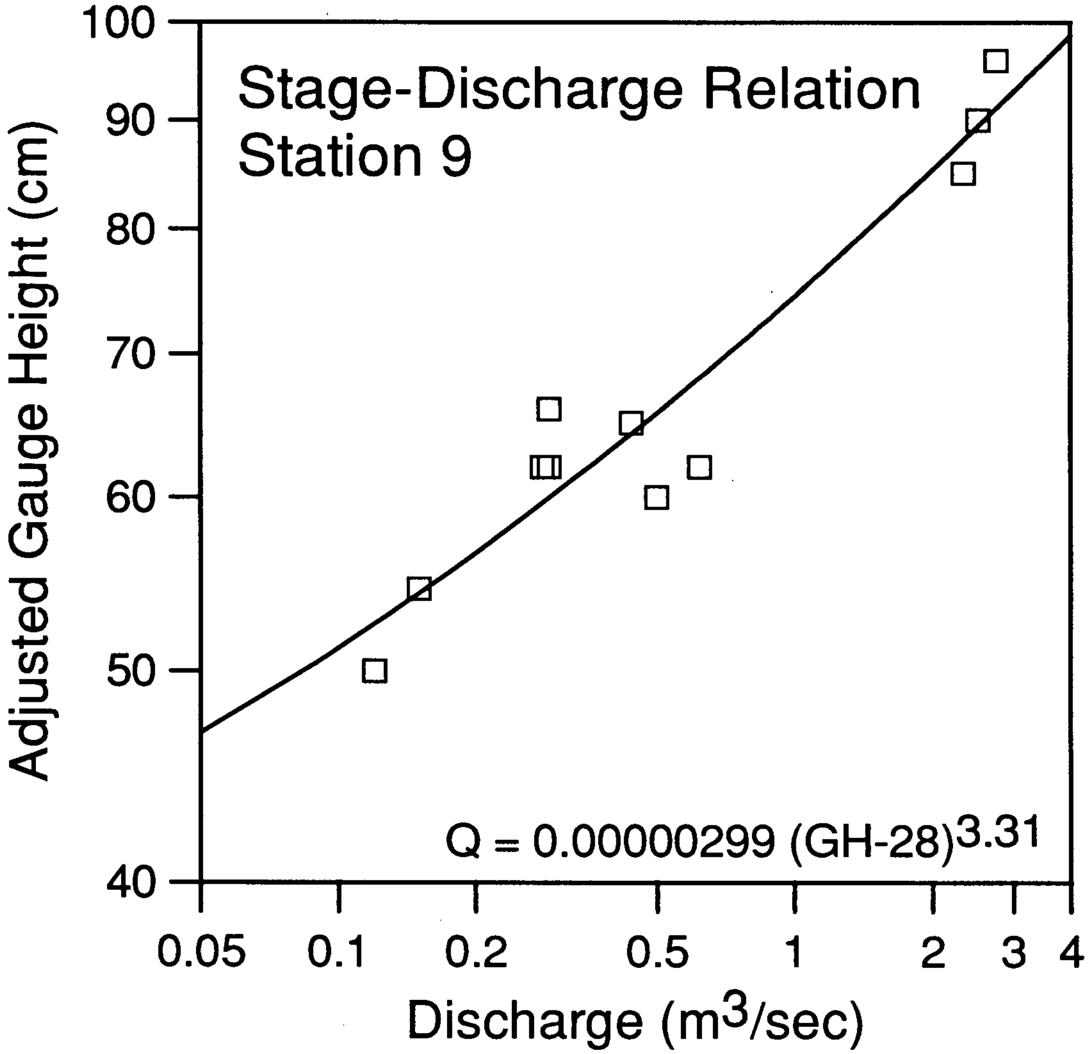
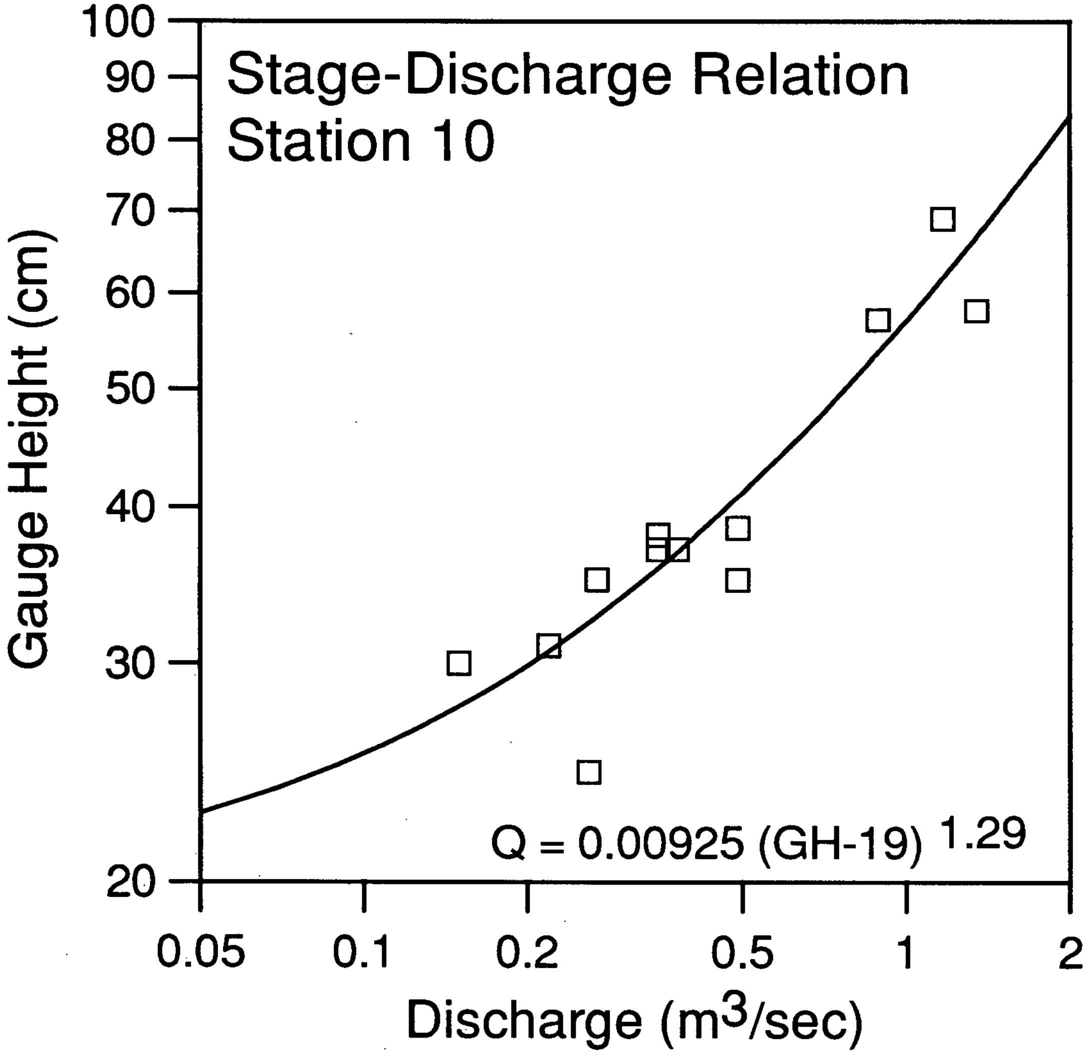


Figure A5.5 Stage-discharge relationship at station 10, Kukhuri River at Andheri River.



Appendix A6 1992 Survey of Mass Wasting

In 1992, ground surveys of episodic surface erosion and mass wasting were carried out following the large event of July 10, 1992 (estimated to be the ten-year flood event). These detailed measurements of erosion within the Kukhuri basin are presented in Tables A6.1 and A6.2 for those items respectively caused by inadequate water management and streambank erosion from high-flow. The source of the sediment according to landuse is indicated by:

BA *Bari*

BD Stream Bed

BK stream BanK

C Canal

G Grassland

K *Khet*

R Road

T Trail

The quantity and character of sediment produced and its delivery percentage to the fluvial system are identified. These tables reveal that sediment delivery within the Kukhuri basin resulting from the event of July 10 was dominated (68%) by erosion due to channelised runoff flowing unmanaged downslope. The remainder was related to erosion of stream banks due to the rapid runoff in the swollen channel.

Table A6.1 Summary of sediment production and delivery of episodic erosion attributed to inadequate runoff management from the event of July 10, 1992.

Item No.	Source Type	Elevation (m)	Total Production (m^3)	Percent Fines (%)	Delivery Rate (%)	Fine-Sediment Delivery (m^3)
1	R	1375	7.5	30	50	1.1
2	R	1390	20	70	50	7.0
3	R/BA	1321	9	70	100	6.3
4	R/G	1318	14.7	30	50	2.2
5	BA	1345	1.9	90	100	1.7
6	BA	1310	1.8	90	100	1.6
7	BA	1345	5.6	70	100	3.9
8	BA	1185	6.2	70	100	4.3
9	BA	1155	1	70	100	0.7
10	BA	n/a	9.5	70	100	6.7
11	BA	n/a	43	50	100	21.5
12	BA	1180	3	90	100	2.7
13	BA	many	72	70	50	25.2
14	K	n/a	6	100	100	6.0
15	K	1140	176	70	100	123.2
16	T	n/a	11.7	70	100	8.2
17	T	n/a	3.3	50	100	1.7
18	T	1195	0.9	30	100	0.3
						224.3

Note: Numerous small terrace slumps (< 1 m^3) also noted, most with limited delivery to the channel.

Table A6.2 Summary of sediment production and delivery of episodic erosion attributed to streambank erosion due to high-flow conditions from the event of July 10, 1992.

Item No.	Source Type	Elevation (m)	Total Production (m^3)	Percent Fines (%)	Delivery Rate (%)	Fine-Sediment Delivery (m^3)
19	BD	1370	100	10	100	10
20	BK	1320	100	50	100	50
21	BK	n/a	26.3	70	100	19.4
22	BK	1180	4.7	70	100	3.3
23	BK	n/a	0.3	50	100	0.2
24	C	1335	1.1	70	100	0.8
25	C/BK	1184	4.5	50	100	2.3
26	C/BK	n/a	2.0	70	100	1.4
27	G/BK	1190	3.8	70	100	2.6
28	G/BK	n/a	1.8	70	100	1.3
29	G/BK	n/a	7.5	70	100	5.3
						95.6

Literature Cited

Alemayehu M (1992) *The Effect of Traditional Ditches on Soil Erosion and Production*, University of Berne, Berne, Switzerland, 33 pp.

American Society of Civil Engineers (1975) *Sedimentation Engineering*, ed.: Vanoni VA ASCE, New York, 745 pp.

Anderson B and Potts DF (1987) Suspended sediment and turbidity following road construction and logging in western Montana, *Water Resources Bulletin*, **23**:681-690.

Anderson HW (1972) Water yield as an index of lee and windward topographic effects on precipitation. *In: Distribution of Precipitation in Mountainous Areas (Geilo Symposium, Norway - July 31 to August 5, 1972)*, World Meteorological Organisation No. 326, 346-358.

Anderson HW (1981) Sources of sediment-induced reductions in water quality appraised from catchment attributes and land use, *Journal of Hydrology*, **51**:347-358.

Arnborg L, Walker HJ, and Peippo J (1967) Suspended load in the Colville River, Alaska, 1962, *Geografiska Annaler*, **49**:131-144.

Babu R, Tejwani KG, Agarwal MC, and Bhushan LS (1978) Distribution of erosion index and iso-erodent map of India, *Indian Journal of Soil Conservation*, **6**:1-12.

Bajracharya D (1983) Fuel, food or forest? Dilemmas in a Nepali village, *World Development*, **11**:1057-1074.

Baker VR (1977) Stream-channel response to floods, with examples from central Texas, *Geological Society of America Bulletin*, **88**:1057-1071.

Barry RG and Chorley RJ (1992) *Atmosphere, Weather and Climate*, Routledge, London and New York, 392 pp.

Baskerville GL (1972) Use of logarithmic regression in the estimation of plant biomass, *Canadian Journal of Forestry*, **2**:49-53.

Beauchamp JJ and Olson JS (1973) Corrections for bias in regression estimated after logarithmic transformations, *Ecology*, **54**:1403-1407.

Beers Y (1957) *Introduction to the Theory of Error*, Addison-Wesley Publishing Company, Reading, Massachusetts, 66 pp.

Beschta RL (1978) Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range, *Water Resources Research*, **14(6)**:1011-1016.

Bjonness I-M (1986) Mountain hazard perception and risk avoiding strategies among the Sherpas of Khumbu Himal, Nepal, *Mountain Research and Development*, **6**:277-292.

Bogen J (1980) The hysteresis effect of sediment transport systems, *Norsk Geografisk Tidsskrift*, **34**:45-54.

Bogen J (1992) Monitoring grain size of suspended sediments in rivers, In: *Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). IAHS Publication No. 210,* eds.: Bogen J, Walling DE, and Day TJ. 183-190.

Booker Agriculture International Limited (1984) *Booker Tropical Soil Manual*, ed.: Landon JR Pitman Press Limited, Bath, UK, 441 pp.

Bovis M, J. (1982) The spatial variation of soil loss and soil loss controls, In: *Space and time in geomorphology,* ed.: Thorn C, E. George Allen and Unwin, Ch 1, 1-24.

Brady NC (1990) *The Nature and Properties of Soils*, MacMillan, New York, 621 pp.

Brizga SO and Finlayson BL (1994) Interactions between upland catchment and lowland rivers: an applied Australian case study, *Geomorphology,* **9**:189-201.

Brower B (1990) Range conservation and Sherpa livestock management in Khumbu, Nepal, *Mountain Research and Development,* **10**:34-42.

Brown AG (1985) The potential use of pollen in the identification of suspended sediment sources, *Earth Surface Processes and Landforms,* **10**:27-32.

Brown GW and Krygier JT (1971) Clear-cut logging and sediment production in the Oregon Coast Range, *Water Resources Research,* **7**:1189-1198.

Brown MJ and Peck EL (1962) Reliability of precipitation measurements as related to exposure, *Journal of Applied Meteorology,* **1**:203-207.

Brown RB and Brubaker LB (1979) Tracing and dating the movement and storage of sediment, In: *Sediment Budgets and Routing in Forested Drainage Basins,* eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 143-145.

Bruijnzeel LA and Bremmer CN (1989) *Highland-lowland interactions in the Ganges Brahmaputra river basin: a review of published literature,* ICIMOD Occasional Paper No. 1, Kathmandu,

Brunsden D and Thornes JB (1979) Landscape sensitivity and change, *Institute of British Geographers, Transactions,* **4**:463-484.

Bryant E (1991) *Natural hazards*, Cambridge University Press, Cambridge,

Buchanan TJ and Somers WP (1969) Discharge measurements at gaging stations, In: *Techniques of water-resources investigations of the United States Geological Survey,* Bk. 3, Ch. A8, Washington. 1-65.

Bull LJ, Lawler DM, Leeks GJL, and Marks S (1995) Downstream changes in suspended sediment fluxes in the River Severn, UK. *In: Effects of Scale on Interpretation and Management of Sediment and Water Quality (Proceedings of a Boulder Symposium, July 1995)*, ed.: Osterkamp WR, IAHS Publication No. 226, 27-37.

Burns RG (1979) *An Improved Sediment Delivery Model for Piedmont Forests*, Georgia Institute of Technology, Atlanta, Georgia.

Burt TP (1989) Storm runoff generation in small catchments in relation to the flood response of large basins, In: *Floods: Hydrological, Sedimentological and Geomophological Implications*, eds.: Beven K and Carling P. John Wiley and Sons, Chichester. Ch 2, 11-35.

Campbell FB and Bauder HA (1940) A rating-curve method for determining silt-discharge of streams, *American Geophysical Union Transactions*, **21**:603-607.

Carson B (1985) *Erosion and Sedimentation Processes in the Nepalese Himalaya*, In: ICIMOD Occasional Paper No. 1.International Centre for Integrated Mountain Development, Kathmandu, 39 pp.

Carson B (1992) *The Land, the Farmer, and the Future - A Soil Fertility Management Strategy for Nepal*, In: ICIMOD Occasional Paper No. 21.Kathmandu, Nepal, 74 pp.

Chitrakar PL (1990) *Planning, agriculture, and farmers: strategy for Nepal*, Mrs. Ganesh Devi Chitrakar, Kathmandu, 332 pp.

Church M and Hassan MA (1992) Size and distance of travel of unconstrained clasts on a streambed, *Water Resources Research*, **28**:299-303.

Church M, Kellerhals R, and Day TJ (1989) Regional clastic sediment yield in British Columbia, *Canadian Journal of Earth Sciences*, **26**:31-45.

Church M and Mark DM (1980) On size and scale in geomophology, *Progress in Physical Geography*, **4 (3)**:342-390.

Church M and Slaymaker O (1989) Disequilibrium of Holocene sediment yield in glaciated British Columbia, *Nature*, **337**:452-454.

Coakley JP and Long BFN (1990) *Tracing the movement of fine-grained sediment in aquatic systems: a literature review*, Inland Waters Directorate, Environment Canada, Burlington, Ontario, 21 pp.

Cochran WG (1977) *Sampling Techniques*, John Wiley and Sons, New York, 413 pp.

Colby BR and Hembree CH (1955) *Computations of Total Sediment Discharge Niobrara River Near Cody, Nebraska*, U.S. Government Printing Office, Washington, 119 pp.

Colby BR and Hembree CH (1961) *Simplified Methods for Computing Total Sediment Discharge with the Modified Einstein Procedure*, U.S. Government Printing Office, Washington, 17 pp.

Collinge VK and Jamieson DG (1968) The spatial distribution of storm rainfall, *Journal of Hydrology*, **6**:45-57.

Conklin HC (1975) *Hanunoo Agriculture in the Philippines*, in FAO Development Paper 710.12, Rome, 209 pp.

Conrad V and Pollack LW (1950) *Methods in Climatology*, Harvard University Press, Cambridge, Massachusetts, 459 pp.

Danard M (1971) A simple method of computing the variation of annual precipitation over mountainous terrain, *Boundary-Layer Meteorology*, 2:188-206.

Das PK (1987) Short- and long-range monsoon prediction in India, In: *Monsoons*, eds.: Fein JS and Stephens PL. John Wiley and Sons, New York. Ch 17, 549-578.

Department of Hydrology and Meteorology (1977) *Climatological Records of Nepal (1971-1975)*, His Majesty's Government of Nepal Department of Irrigation, Hydrology and Meteorology, and Ministry of Food, Agriculture and Irrigation, Kathmandu, 366 pp.

Department of Hydrology and Meteorology (1977) *Climatological Records of Nepal (1921-1975) - Special Supplement*, His Majesty's Government of Nepal Department of Irrigation, Hydrology and Meteorology, and Ministry of Food, Agriculture and Irrigation, Kathmandu, 129 pp.

Department of Hydrology and Meteorology (1982) *Climatological Records of Nepal (1976-1980)*, His Majesty's Government of Nepal Department of Irrigation, Hydrology and Meteorology, and Ministry of Water Resources, Kathmandu, 410 pp.

Department of Hydrology and Meteorology (1984) *Climatological Records of Nepal (1981-1982)*, His Majesty's Government of Nepal Department of Irrigation, Hydrology and Meteorology, and Ministry of Water Resources, Kathmandu, 174 pp.

Department of Hydrology and Meteorology (1986) *Climatological Records of Nepal (1983-1984)*, His Majesty's Government of Nepal Department of Irrigation, Hydrology and Meteorology, and Ministry of Water Resources, Kathmandu, 187 pp.

Department of Hydrology and Meteorology (1988) *Climatological Records of Nepal (1985-1986)*, His Majesty's Government of Nepal Department of Hydrology and Meteorology, and Ministry of Water Resources, Kathmandu, 232 pp.

Department of Hydrology and Meteorology (1992) *Climatological Records of Nepal (1987-1990)*, His Majesty's Government of Nepal Department of Hydrology and Meteorology, and Ministry of Water Resources, Kathmandu, 253 pp.

Department of Soil Conservation and Watershed Management (1991) *Runoff and Soil Loss Studies in the Kulekhani Watershed (Results 1985-1990)*, DSCWM Watershed Management Project, HMG Nepal, Nepal, 13 pp.

Dhital MR, Khanal N, and Thapa KB (1993) *The Role of Extreme Weather Events, Mass Movements, and Land Use Changes in Increasing Natural Hazards*, International Centre for Integrated Mountain Development, Kathmandu, Nepal, 123 pp.

Dietrich WE, Duncan SH, Humphrey NF, and Reid LM (1979) Construction of sediment budgets for drainage basins, In: *Sediment Budgets and Routing in Forested Drainage Basins*, eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 5-23.

Dietrich WE and Dunne T (1978) Sediment budget for a small catchment in mountainous terrain, *Zeitschrift fur Geomorphologie Neue Folge Supplementband,* **29**:191-206.

Dingman SL (1981) Elevation: a major influence on the hydrology of New Hampshire and Vermont, USA, *Hydrological Sciences Bulletin,* **26**:399-413.

Dittmann E (1970) Statistische Untrsuchungen zur Struktur der Niederschlaege in Nepal, *Khumbu Himal,* **7**:47-60.

Domroes M (1979) Temporal and spatial variations of rainfall in the Himalaya with particular reference to mountain ecosystems, *Journal of the Nepal Research Centre,* **2/3**:50-64.

Dongol G (1991) Geological Data Base of the Jhikhu Khola Watershed, In: *Soil fertility and erosion issues in the Middle Mountains of Nepal, proceedings of a workshop held April 22-25 in Dhulikhel, Nepal,* eds.: Shah PB, Schreier H, Brown SJ, and Riley KW. International Development Research Centre, Ottawa. 180-187.

Doty RD, Wood HB, and Merriam RA (1981) Suspended sediment production from forested watersheds on Oahu, Hawaii, *Water Resources Bulletin,* **17(3)**:399-405.

Douglas I (1967) Man, vegetation and the sediment yield of rivers, *Nature,* **215**:925-928.

Duncan SH, Bilby RE, Ward JW, and Heffner JT (1987) Transport of road-surface sediment through ephemeral stream channels, *Water Resources Bulletin,* **23**:113-119.

Dunne T (1984) The prediction of erosion in forests, In: *Symposium on effects of forest land use on erosion and slope stability, Honolulu, Hawaii,* eds.: O'Loughlin CL and Pearce AJ. 3-11.

Dunne T and Leopold LB (1978) *Water in Environmental Planning*, W.H. Freeman and Company, San Francisco, 818 pp.

Dvorak KA (1988) *Indigenous Soil Classification in Semi-Arid Tropical India*, In: Resource Management Program Economics Group Progress Report-84.International Crops Research Institute for the Semi-Arid Tropics, India, 38 pp.

East TJ (1985) A factor analytic approach to the identification of geomorphic processes from soil particle size characteristics, *Earth Surface Processes and Landforms,* **10**:441-463.

Eckholm EP (1975) The deterioration of mountain environments, *Science,* **189**:764-770.

Ehrenfeld D (1992) Ecosystem health and ecological theory, In: *Ecosystem Health: New Goals for Environmental Management,* eds.: Costanza R, Norton BG, and Haskell BD. Island Press, 135-145.

Einstein HA (1943) Discussion on "Distribution graphs of suspended-matter concentration", *American Society of Civil Engineers Transactions,* **69**:957-958.

Einstein HA (1950) *The Bedload Function for Sediment Transportation in Open Channel Flows*, In: Technical Bulletin 1026.U.S. Dept. of Agriculture, 70 pp.

El-Swaify SA (1990) Research needs and applications to reduce erosion and sedimentation in the tropics, In: *Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steeplands (Proceedings of the Fiji Symposium, June 1990)*, International Association of Hydrological Sciences Publ. No. 192,International Association of Hydrological Sciences, 3-13.

Elwell HA (1984) Soil loss estimation: a modelling technique, In: *Erosion and Sediment Yield: Some Methods of Measurement and Modelling*, eds.: Hadley RF and Walling DE. University Press, Cambridge. Ch 2, 15-36.

Elwell HA and Stocking MA (1975) Parameters for estimating annual run-off and soil loss from agricultural lands in Rhodesia, *Water Resources Research*, **11**:601-605.

Euphrat FD (1987) *A Delicate Imbalance: Erosion and Soil Conservation in Pipal Chaur Watershed, Kabrepalanchouk District, Nepal*, Master of Science thesis, Wildland Resource Science. Berkeley, CA: University of California, 80 pp.

Farmer EE and Fletcher JE (1972) Some intra-storm characteristics of high-intensity rainfall bursts. *In: Distribution of Precipitation in Mountainous Areas (Geilo Symposium, Norway - July 31 to August 5, 1972)*, World Meteorological Organisation No. 326, 525-531.

Fenn CR and Gomez B (1989) Particle size analysis of the sediment suspended in a proglacial stream: Glacier de Tsidjiore Nouve, Switzerland, *Hydrological Processes*, **3**:123-135.

Fisher RJ (1989) *Indigenous systems of common property forest management in Nepal*, East-West Centre, Honolulu, Hawaii, 23 pp.

Fleming G and Poodle T (1970) Particle size of river sediments, *ASCE, Journal of the Hydraulics Division*, **96**:431-439.

Foster GR (1988) Modeling soil erosion and sediment yield, In: *Soil Erosion Research Methods*, ed.: Lal R. Soil and Water Conservation Society, Ch 5, 97-117.

Foster GR, Young RA, and Neibling WH (1985) Sediment composition for nonpoint source pollution analyses, *Transactions of the American Society of Agricultural Engineers*, 133-146.

Foster IDL, Millington R, and Grew RG (1992) The impact of particle size controls on stream turbidity measurement; some implications for suspended sediment yield estimation, In: *Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). IAHS Publication No. 210*, eds.: Bogen J, Walling DE, and Day TJ. 51-62.

Froehlich W and Starkel L (1993) The effects of deforestation on slope and channel evolution in the tectonically active Darjeeling Himalaya, *Earth Surface Processes and Landforms*, **18**:285-290.

Galay V (1997) *Sediment Yield in the Nepal Himalaya*, Report to the Nepal Electrical Authority, Medium Hydropower Study, Northwest Hydraulic Consultants Ltd. Vancouver, Canada.

Galay VJ, Okaji T, and Nishino K (1995) Erosion from the Kulekhani watershed, Nepal during the July 1993 rainstorm, In: *Challenges in Mountain Resource Management in Nepal - Processes, Trends, and Dynamics in Middle Mountain Watersheds,* International Centre for Integrated Mountain Development, Kathmandu, Nepal. 13-24.

Gill G, J. (1991) Indigenous Erosion Control Systems in the Jhikhu Khola Watershed, In: *Soil Fertility and Erosion Issues in the Middle Mountains of Nepal,* University of British Columbia, Vancouver, Canada. 152-164.

Gilmour DA (1984) People, Forests, and Erosion - Experiences from the Middle Hills of Nepal. *In: Effects of Forest Land Use on Erosion and Slope Stability, IUFRO Symposium, Hawaii 7-11 May, 1984,* IUFRO, 15-21.

Gilmour DA (1986) Not seeing the trees for the forest: a re-appraisal of the deforestation crisis in two hill districts of Nepal, *Mountain Research and Development,* **8**:343-350.

Gilmour DA (1989) *Forest resources and indigenous management in Nepal,* Working Paper No. 17, East-West Centre, Honolulu, Hawaii, 15 pp.

Gilmour DA (1991) Trends in forest resources and management in the Middle Mountains of Nepal, In: *Soil Fertility and Erosion Issues in the Middle Mountains of Nepal; Workshop Proceedings April 22-25,* eds.: Shah PB, Schreier H, Brown SJ, and Riley KW. International Development Research Centre, Kathmandu, Nepal. 33-46.

Gilmour DA and Fisher RJ (1991) *Villagers, Forests and Foresters,* Sahayogi Press, Kathmandu, Nepal, 212 pp.

Givone C and Meignien X (1988) Influence of topography on spatial distribution of rain, In: *Hydrology of Mountainous Areas,* Proceedings of the Strbske Pleso Workshop,IAHS Pub. No 190, Czechoslovakia. 57-65.

Glymph LM (1954) *Studies of sediment yields from watersheds,* In: IAHS Publication No. 36.191 pp.

Goswami DC (1985) Brahmaputra river, Assam, India: physiography, basin denudation, and channel aggradation, *Water Resources Research,* **21**:959-978.

Gregory KJ and Walling DE (1973) *Drainage Basin Form and Process,* Edward Arnold, London, 456 pp.

Griffiths GA (1979) High sediment yields from the major rivers of the Western Southern Alps, New Zealand, *Nature,* **282**:61-63.

Griffiths GA (1981) Some suspended sediment yields from South Island catchments, New Zealand, *Water Resources Bulletin (AWRA),* **17**:662-671.

Griffiths GA (1982) Spatial and temporal variability in suspended sediment yields of North Island basins, New Zealand, *Water Resources Bulletin,* **18**:575-584.

Grimshaw DL and Lewin J (1980) Source identification for suspended sediments, *Journal of Hydrology,* **47**:151-162.

Gupta AK and Ura K (1990) Blending Cultural Values, Indigenous Technology and Environment: Experiences in Bhutan. *In: International Symposium on Strategies for Sustainable Mountain Agriculture, September 10-14, 1990,* International Centre for Integrated Mountain Development, Kathmandu, Nepal, 1-31.

Gurung SM (1989) Human perception of mountain hazards in the Kakani-Kathmandu area: experiences from the Middle Mountains of Nepal, *Mountain Research and Development,* **9(4)**:353-364.

Guy HP and Norman VW (1970) Field methods for measurement of fluvial sediment, In: *Techniques of water-resources investigations of the United States Geological Survey,* Bk. 3, Ch. C2, USGS, Washington. 1-59.

Hamilton LS (1987) What are the impacts of Himalayan deforestation on the Ganges-Brahmaputra lowlands and delta? Assumptions and facts, *Mountain Research and Development,* **7**:256-263.

Hamlett JM, Baker JL, and Johnson HP (1987) Size distribution of sediment transported within and from small agricultural watersheds, *Transactions of the ASAE,* **30**:998-1004.

Harden C (1990) Evaluation of soil tropical erosion at the catchment/basin scale, In: *Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steeplands,* IAHS Publ. No. 192,International Association of Hydrological Sciences, 270-278.

Harden DR, Ugolini F, and Danda RJ (1979) Weathering and soil profile development as tools in sediment routing and budget studies, In: *Sediment Budgets and Routing in Forested Drainage Basins,* eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric For. Serv. Gen. Tech., Report PNW-141, 146-149.

Hassan MA, Schick AP, and Laronne JB (1984) The recovery of flood-dispersed coarse sediment particles, In: *Channel Processes - Water, Sediment, Catchment Controls,* ed.: Schick AP. Catena Verlag, Braunschweig. 153-162.

Hausler S (1993) Community forestry: a critical assessment - the case of Nepal, *The Ecologist,* **23**:84-86.

Heidel SG (1956) The progressive lag of sediment concentration with flood waves, *Transactions, American Geophysical Union,* **37 (1)**:56-66.

Henderson RD (1993) Extreme storm rainfalls in the Southern Alps, New Zealand, In: *Extreme Hydrological Events: Precipitation, Floods, Droughts (Proceedings of the Yokahama Symposium, July 1993) IAHS Publ. No. 213,* eds.: Kundzewicz, Rosbjerg, Simonovic, and Takeuchi. IAHS, 113-120.

Henry AJ (1919) Increase of precipitation with altitude, *Monthly Weather Review,* **47**:33-41.

Hershfield DM (1962) Extreme rainfall relationships, *American Society of Civil Engineers, Jourrnal of the Hydraulics Division,* **88**:73-92.

Hjulstrom F (1935) Studies of the morphological activity of rivers as illustrated by the river Fyris, **25**:221-527.

Hofer T (1993) Deforestation - changing discharge and increasing floods: myth or reality? *Mountain Research and Development,* **13**:213-233.

Hoyt JC (1912) *River Discharge*, John Wiley and Sons, New York, 173 pp.

Hudson N (1981) *Soil Conservation*, Cornell University Press, Ithaca, NY, 324 pp.

Huff FA (1967) Time distribution of rainfall in heavy storms, *Water Resources Research,* **3**:1007-1019.

Hurni H (1985) Erosion-Productivity-Conservation Systems in Ethiopia. *In: Soil Conservation and Productivity, Proceedings IV International Conference on Soil Conservation (2 vols), Maracay, Venezuala, Nov 3-9, 1985*, 654-674.

Husch B, Miller CI, and Beers TW (1972) *Forest Mensuration*, The Ronald Press Company, New York, 410 pp.

Ichim I (1990) The relationship between sediment delivery ratio and stream order: a Romanian case study. *In: Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987)*, IAHS Publication No. 189, 79-85.

Imeson AC (1974) The origin of sediment in a moorland catchment with particular reference to the role of vegetation, In: *Fluvial Processes in Instrumented Watersheds,* Institute of British Geographers Special Publication No. 6,eds.: Gregory KJ and Walling DE. Institute of British Geographers, London. Ch 6, 59-72.

Impat P (1981) *Hydrometeorology and Sediment Data for Phewa Watershed 1979 Data*, DSCWM, HMG/UNDP/FAO, IWM Project, Nepal.

Ishihara T and Ikebuchi S (1972) Stochastic structures in space and time of daily precipitation and their simulation. *In: Floods and Droughts (Proceedings of the Second International Symposium in Hydrology, Fort Collins, Colorado - September 11-13, 1972)*, eds.: Schulz EF, Koelzer VA, and Mahmood K, 615-626.

Ives JD (1987) Repeat photography of debris flows and agricultural terraces in the Middle Mountains, Nepal, *Mountain Research and Development,* **7**:189-199.

Ives JD and Messerli B (1989) *The Himalayan dilemma: reconciling development and conservation*, Routledge, London, 295 pp.

Jackson IJ (1989) *Climate, Water and Agriculture in the Tropics*, Longman, England, 377 pp.

Johnson JW (1942) Distribution graphs of suspended-matter concentration, *American Society of Civil Engineers Transactions,* **69**:941-956.

Johnson K, Olsen EA, and Manandhar S (1982) Environmental knowledge and response to natural hazard in mountainous Nepal, *Mountain Research and Development,* **2**:175-188.

Kandel GP (1978) *Report on Suspended Sediments in Kathmandu Valley*, Integrated Watershed Management Project, DSCWM, Ministry of Forests, Kathmandu, 17 pp.

Katsumasa Y, Tsuchiya Y, and Michiue M (1969) Studies on the sand transport in streams with tracers, **18**:1-16.

Keller HM (1972) Factors affecting the estimate of areal average summer and winter precipitation - in a small catchment of the Swiss Prealps. *In: Distribution of Precipitation in Mountainous Areas (Geilo Sumposium, Norway - July31 to August 5, 1972)*, World Meteorological Organisation No. 326, 484-496.

Keller HM and Weibel P (1991) Suspended sediments in streamwater - indicators of erosion and bedload transport in mountainous basins, In: *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanations*, IAHS Publ. No. 203,International Association of Hydrological Sciences, 53-61.

Kelsey HM (1979) Hillslope evolution and sediment movement in a forested headwater basin, Van Duzen River, north coastal California, In: *Sediment Budgets and Routing in Forested Drainage Basins*, eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 86-96.

Kendall MG and Stewart A (1979) *Inference and Relationship*, Charles Griffin & Compnay Limited, London, 747 pp.

Kennedy VC (1964) *Sediment Transport by Georgia Streams*, U.S. Government Printing Office, Washington, 101 pp.

Kenting Earth Sciences Limited (1986) *Land Resource Mapping Project - Land Utilisation Report*, 114 pp.

Kenting Earth Sciences Ltd. (1984) *The Land Resource Mapping Project in Nepal: Water Resources Report*, HMG Nepal and the Government of Canada, Kathmandu and Ottawa, 273 pp.

Klages MG and Hsieh YP (1975) Suspended solids carried by the Gallatin River of Southwestern Montana: II Using mineralogy for inferring sources, *Journal of Environmental Quality*, **4**:68-73.

Kung S-Y and Chiang T-C (1977) *Soil Erosion and Its Control in Small Gully Watersheds in the Rolling Loess Area of the Middle Mountains of the Yellow River*, Peking, 22 pp.

Laban P (1977) A preliminary appraisal of mass movements in Nepal, In: *Proceedings of Seminar on Mountain Ecosystems, November 1977*, Kathmandu.

Laban P (1978) *Field measurements on erosio and sedimentation in NEpal*, Dept. of Soil and Water Conservation, FAO/HMG/UNDP, IWM/SP/05. Kathamandu,

Laflen JM, Lane LJ, and Foster GR (1991) WEPP: a new generation of erosion prediction technology, *Journal of Soil and Water Conservation*, **46**:34-38.

Lal R (1976) Soil erosion on alfisols in western Nigeria - effects of rainfall characteristics, *Geoderma*, **16**:389-401.

Lal R (1982) Effects of slope length and terracing on runoff and erosion on a tropical soil. *In: Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982)*, IAHS Publication No. 137, 23-31.

Lal R (1988) Soil erosion research on steep lands, In: *Conservation Farming on Steep Lands,* eds.: Moldenhauer WC and Hudson NW. Soil and Water Conservation Society, Ankeny, Iowa. Ch 6, 45-53.

Lauterburg A (1985) The Himalayan highland-lowland interactive system: do land use changes in the mountains affect the plains? *Geographica Bernensia,* **G38**:21-30.

Lavkulich LM (1978) *Methods Manual - Pedology Laboratory*, Department of Soil Science, University of British Columbia, Vancouver, B.C., pp 224,

Lee CY (1994) Comparison of two correction methods for the bias due to the logarithmic transformation in the estimation of biomass, *Canadian Journal of Forestry Research,* **12**:326-331.

Lehre AK (1979) Sediment budget of a small Coast Range drainage basin in north-central California, In: *Sediment Budgets and Routing in Forested Drainage Basins,* eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 67-77.

Leopold LB, Wolman MG, and Miller JP (1964) *Fluvial processes in geomorphology*, W.H. Freeman, San Fransisco.

Lewin J (1989) Floods in fluvial geomorphology, In: *Floods: Hydrological, Sedimentological and Geomorphological Implications,* eds.: Beven K and Carling P. John Wiley and Sons, Ch 16, 265-284.

Loshali DC, Upadhyay VP, and Singh RP (1990) Overland flow and soil movement from forests in Kumaun Himalaya, *Canadian Journal of Forest Research,* **20**:606-608.

Loughran RJ (1976) The calculation of suspended-sediment transport from concentration v. discharge curves: Chandler River, N.S.W, *Catena,* **3**:45-61.

Loughran RJ, Campbell BL, and Elliott GL (1986) Sediment dynamics in a partially cultivated catchment in New South Wales, Australia, *Journal of Hydrology,* **83**:285-297.

Loughran RJ, Campbell BL, Shelly DJ, and Elliott GL (1992) Developing a sediment budget for a small drainage basin in Australia, *Hydrological Processes,* **6**:145-158.

Loukas A (1994) *Mountain precipitation analysis for the estimation of flood runoff in coastal British Columbia*, Doctor of Philosophy thesis, University of British Columbia, 297 pp.

Low FK (1967) Estimating potential erosion in developing countries, *Journal of Soil and Water Conservation,* **22**:147-148.

Luk S, Abrahams AD, and Parsons AJ (1993) Sediment sources and sediment transport by rill flow and interrill flow on a semi-arid piedmont slope, southern Arizona, *Catena,* **20**:93-111.

Lund LJ, Kohnke H, and Paulet M (1972) An interpretation of reservoir sedimentation: II Clay mineralogy, *Journal of Environmental Quality,* **1**:303-307.

Lyons JK and Beschta RL (1983) Land use, floods, and channel changes: upper Middle Fork Willamette River, Oregon (1936-1980), Water Resources Research **19**:463-471.

Mahat TBS (1987) *Forestry-Farming Linkages in the Mountains*, ICIMOD Occasional Paper No. 7, International Centre for Integrated Mountain Development, Kathmandu, Nepal, 48 pp.

Maner SB (1958) Factors affecting sediment delivery rates in the Red Hills physiographic area, *Transactions, American Geophysical Union,* **39**:669-675.

Mark DM and Church M (1977) On the misuse of regression in earth science, *Mathematical Geology,* **9**:63-75.

McGuinness JL and Vaughan GW (1969) Seasonal variation in rain gage catch, *Water Resources Research,* **5**:1142-1146.

McPherson HJ (1975) Sediment yields from intermediate-sized stream basins in southern Alberta, *Journal of Hydrology,* **25**:243-257.

Megahan WF and Kidd WJ (1972) Effects of logging and logging roads on erosion and sediment deposition from steep terrain, *Journal of Forestry,* **70**:136-141.

Messerschmidt D (1990) What is a tree? *Forests, Trees, and People Newsletter,* :4-6.

Metz JJ (1989) Himalayan political economy: more myths in the closet? *Mountain Research and Development,* **9**:175-181.

Middleton WEK and Spilhaus AF (1953) The measurement of precipitation and evaporation, In: *Meteorological Instruments,* Third edition. University of Toronto Press, Ch 5, 118-131.

Miller DM (1984) Reducing transformation bias in curve fitting, *The American Statistician,* **38(2)**:124-126.

Moench M and Bandyopadhyay J (1986) People-forest interaction: a neglected parameter in Himalayan forest management, *Mountain Research and Development,* **6**:3-16.

Moore JE (1961) Petrography of northeastern Lake Michigan bottom sediments, *Journal of Sedimentary Petrology,* **31**:402-436.

Morgan RPC (1977) *Soil Erosion in the United Kingdom: Field Studies in the Silsoe Area 1973-75,* In: National College of Agricultural Engineering, Occasional Paper No.4.

Mountjoy DC and Gliessman SR (1988) Traditional management of a hillside agroecosystem in Tlaxcala, Mexico: an ecologically based maintenance system, **3**:3-10.

Mulder R (1978) *Erosion Plot Measurement in the Phewa Tal Catchment*, In: Phewa Tal Technical Report No. 6.Integrated Watershed Management, Department of Soil and Water Conservation, Kathmandu.

Muller-Boker U (1990) Traditional Technology in the Kathmandu Valley: the Utilization of the Soils and Sediments. *In: Seminar of Nepalese Studies: Proceedings of an International Conference in Stockholm, June 1987*, ed.: Lienhard S, CESMEO, Turin, 89-97.

Muller-Boker U (1991) Knowledge and evaluation of the environment in traditional societies of Nepal, *Mountain Research and Development*, **11**:101-114.

Muller-Boker U (1992) Two Ecological-Geographical Approaches concerning the Topic Man and His Environment in Nepal. *In: Aspects of Nepalese Traditions - Proceedings of a Seminar held under the auspices of Tribhuvan University Research Division and the German Research Council, Kathmandu 1990; Publication of the Nepal Research Centre, 19*, ed.: Kolver B, Franz Steiner Verlag, Stuttgart, 1-30.

Mutchler CK, Murphree CE, and McGregor KC (1988) Laboratory and field plots for soil erosion studies, In: *Soil Erosion Research Methods*, ed.: Lal R. Soil and Water Conservation Society, Ch 2, 9-36.

Myers N (1986) Environmental repercussions of deforestation in the Himalayas, *Journal of World Forest Resource Management*, **2**:63-72.

Nakarmi G (1995) Indigenous water management systems in the Andheri Kholh sub-watershed. *In: Challenges in Mountain Resources Management in Nepal: Processes, Trends, and Dynamics in Middle Mountain Watersheds - Proceedings of a Workshop held in Kathmandu, Nepal 10-12 April 1995*, IDRC/ICIMOD/UBC, Kathmandu, Nepal, 211-225.

Narayana VVD and Babu R (1983) Estimation of soil erosion in India, *American Society of Civil Engineering, Journal of Irrigation and Drainage Engineering Division*, **109**:419-434.

Nistor C (1996) *Temporal Patterns in the Normal-Regime Fine-Sediment Cascade in Russell Creek Basin, Vancouver Island*, M.Sc. thesis, University of British Columbia, 236 pp.

Nordin CF, Jr. (1963) *A Preliminary Study of Sediment Transport Parameters Rio Puerco Near Bernardo New Mexico: Sediment Transport in Alluvial Channels*, United States Government Printing Office, Washington, 21 pp.

Nordin CF, Jr. (1985) The sediment loads of rivers, In: *Facets of Hydrology*, ed.: Rodda JC. John Wiley and Sons Ltd. Chichester, UK. Ch 7, 197-204.

Olive LJ and Rieger WA (1985) Variation in suspended sediment concentration during storms in five small catchments in southeast New South Wales, *Australian Geographical Studies*, **23**:38-51.

Ongley ED (1982) Influence of season, source and distance on physical and chemical properties of suspended sediment, In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield*, ed.: Walling DE. International Association of Hydrological Sciences, Washington, DC. 371-383.

Ongley ED, Bynoe MC, and Percival JB (1981) Physical and geochemical characteristics of suspended solids, Wilton Creek, Ontario, *Canadian Journal of Earth Sciences*, **18**:1365-1379.

Overseas Development Agency (1995) *Land Use, Soil Conservation and Water Resource Management in the Nepal Middle Hills*, UK Institute of Hydrology, Royal Geographic Society, various pagination.

Packham RF (1960) A mineralogical examination of suspended solids from nine english rivers, *Clay Minerals Bulletin,* **4**:239-242.

Page MJ, Trustrum NA, and Dymond JR (1994) Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand, *Geomorphology,* **9**:169-188.

Pakhribas Agricultural Centre (1990) *Samuhik Bhraman on Some Red Soils Areas of Dhankuta and Bhojpur Districts*, PAC, Kathmandu, Nepal, 24 pp.

Pandey AN, Pathak PC, and Singh JS (1983) Water, sediment and nutrient movement in forested and non-forested catchments in Kumaun Himalaya, *Forest Ecology and Management,* **7**:19-29.

Pardo R (1993) Back to the future - Nepal's new forestry legislation, *Journal of Forestry,* **91**:22-26.

Parker RS (1988) Uncertainties in defining the suspended sediment budget for large drainage basins, In: *Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988),* IAHS Publ. No. 174,International Association of Hydrological Sciences, 523-532.

Pathak PC, Pandey AN, and Singh JS (1984) Overland flow, sediment output and nutrient loss from certain forested sites in the central Himalaya, India, *Journal of Hydrology,* **71**:239-251.

Paturel E and Chocat B (1993) Analysis of the rain phenomenon at a fine spatial scale. *In: Sixth International Conference on Urban Stormwater Drainage (Niagara Falls, Canada - September 12-17, 1993)*, eds.: Marsalek J and Tovno HC, 31-36.

Paustian SJ and Beschta RL (1979) The suspended sediment regime of an Oregon Coast Range stream, *Water Resources Bulletin (AWRA),* **15 (1)**:144-154.

Pearce AJ (1986) Geomorphic effectiveness of erosion and sedimentation events. *In: International Symposium on Erosion and Sedimentation in Arab Countries*, 1-19.

Peart MR and Walling DE (1982) Particle size characteristics of fluvial suspended sediment, In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium). IAHS Publication No. 137,* 397-407.

Peart MR and Walling DE (1986) Fingerprinting sediment sources: the example of a drainage basin in Devon, UK, In: *Drainage Basin Sediment Delivery,* IAHS Publication No. 159,ed.: Hadley RF. International Association of Hydrological Sciences, Wallingford. 41-55.

Perino JM (1993) *Paired Catchment Approach Hydrology Study within the Kulekhani and the Phewa Tal Watersheds*, In: IWMP Technical Paper No. 93.Integrated Watershed Management Project, DSCWM, Kathmandu, Nepal, 47 pp plus appendices.

Pinczes Z (1982) Variations in runoff and erosion under various methods of protection. *In: Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982)*, IAHS Publication No. 137, 49-57.

Porterfield G (1972) Computation of fluvial-sediment discharge, In: *Techniques of water-resources investigations of the United States Gelogical Service*, Bk. 3, Ch. C3, USGS.

Rakoczi L (1977) The significance of infrequent, high suspended sediment concentrations in the estimation of annual sediment transport, In: *Erosion and Matter Transport in Inland Waters*, International Association of Hydrological Sciences, UK. 19-25.

Rakoczi L (1985) *Improvement and Development of Sediment Data Collection in Nepal*, HMG - Ministry of Water Resources, Department of Irrigation, Hydrology and Meteorology, Hydrology Section, 16 pp.

Ramsay WJH (1986) Erosion problems in the Nepal Himalaya - an overview, In: *Nepal Himalaya; Geo-Ecological Perspectives*, ed.: Joshi SC. Himalayan Research Group, Naini Tal, India. 359-392.

Rawat JS (1987) Modelling of water and sediment budget: concepts and strategies, In: *Geomorphological Models - Theoretical and Empirical Aspects*, ed.: Ahnert F., Catena Supplement No. 10, CATENA VERLAG, Braunschweig. 147-159.

Reid LM (1979a) Evaluating and mapping sources and temporary storage areas of sediment, In: *Sediment Budgets and Routing in Forested Drainage Basins*, eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 138-142.

Reid LM (1979b) The use of flow charts in sediment routing analysis, In: *Sediment Budgets and Routing in Forested Drainage Basins*, eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 154-156.

Reid LM and Dunne T (1984) Sediment production from forest road surfaces, *Water Resources Research*, **20**:1753-1761.

Reid LM, Dunne T, and Cederholm CJ (1981) Application of sediment budget studies to the evaluation of logging road impact, *New Zealand Journal of Hydrology*, **20(1)**:49-62.

Reij C (1991) *Indigenous Soil and Water Conservation in Africa*, Sustainable Agricultural Programme of the International Institute for Environmental Development, London, 35 pp.

Renard KG, Foster GR, Weesies GA, and Porter JP (1991) RUSLE: revised universal soil loss equation, *Journal of Soil and Water Conservation*, **46**:30-33.

Rhoton FE, Smeck NE, and Wilding LP (1979) Preferential clay mineral erosion from watersheds in the Maumee River Basin, *Journal of Environmental Quality*, **8**:547-550.

Richter G and Kertesz A (1987) Seasonal variations of runoff rates from field plots in the Federal Republic of Germany and in Hungary during dry years. *In: Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987)*, IAHS Publication No. 189, 161-168.

Ries J (1991) Man made soil erosion and soil conservation in the high mountain region eastern Himalayas: case study in Bamti/Bhandar, In: *Soil Fertility and Erosion Issues in the Middle Mountains of Nepal; Workshop Proceedings April 22-25,* eds.: Shah PB, Schreier H, Brown SJ, and Riley KW. International Development Research Centre, Kathmandu, Nepal. 121-127.

Ries JB (1994) *Soil Erosion in the High Mountain Region, Eastern Central Himalaya: A Case Study in the Bamti/Bhandar/Surma Area, Nepal*, PhD thesis, Heft 42, Freiburger Geographische Hefte, 392 pp.

Risse LM, Nearing MA, Lui BY, Zhang XC, Baffault C, and Laflen JM (1995) WEPP: validation and applications. *In: Carrying the Torch for Erosion Control: An Olympic Task (Proceedings of Conference XXVI),* International Erosion Control Association, Atlanta, Georgia, 469-485.

Roberts RG and Church M (1986) The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia, *Canadian Journal of Forestry Research,* **16**:1092-1106.

Rodriguez-Iturbe I and Eagleson PS (1987) Mathematical Models of rainstorm events in space and time, *Water Resources Research,* **23**:181-190.

Roehl JE (1962) *Sediment source areas, delivery ratios and influencing morphological factors,* In: IAHS Publication No. 59.213 pp.

Saijo K (1991) Hillslope evolution in geological time and its significance on active erosion processes in the Jhikhu Khola watershed, In: *Soil fertility and erosion issues in the Middle Mountains of Nepal, proceedings of a workshop held April 22-25 in Dhulikhel, Nepal,* eds.: Shah PB, Schreier H, Brown SJ, and Riley KW. International Development Research Centre, Ottawa. 188-194.

Sastry G and Narayana D (1984) Watershed responses to conservation measures, *Journal of Irrigation and Drainage Engineering, ASCE, ISSN,* **110**

Sattaur O (1987) Trees for the people, *New Scientist,* **10**:58-62.

Schmidt M (1992) *Land use dynamics and soil fertility in a mountain watershed in Nepal*, Ph.D. thesis, University of British Columbia, 191 pp.

Schreier H, Brown S, Schmidt M, Shah PB, Shrestha B, Nakarmi G, Khagendra S, and Wymann S (1994) Gaining forests but losing ground: a GIS evaluation in a Himalayan watershed, *Environmental Management,* **18**:139-150.

Schroeder RF (1985) Himalayan subsistence systems indigenous agriculture in rural Nepal, *Mountain Research and Development,* **5(1)**:31-44.

Schumm SA (1977) *The Fluvial System,*

Schweizer P (1992) *Environmental Knowledge, Attitude, and Behaviour towards Natural Resource Use in the Himalaya. A Case Study: Bamti/Bhandar in the High Mountain Region, Nepal*, Diploma thesis, Albert Ludwigs Universitat, Institute of Psychology, 121 pp.

Shah PB (1995) Indigenous agricultural land and soil classifications. *In: Challenges in Mountain Resource Management in Nepal: Processes, Trends, and Dynamics in Middle Mountain Watersheds*, ICIMOD, IDRC, UBC, Kathmandu, Nepal, 203-210.

Shah PB, Nakarmi G, Shrestha B, Pathak AR, Adhikari HM, Schreier H, Brown S, Carver M, and Srivastava L (1994) *Resource Dynamics, Biomass Production and Degradation in a Middle Mountain Watershed*, Mountain Resource Management Project No. 91-1042-01, ICIMOD and Resource Management and Environmental Studies, University of British Columbia, Kathmandu and Vancouver, 59 pp.

Sharma CK (1977) *River systems of Nepal*, Mrs. Sangreeta Sharma, Kathmandu,

Sharma PD, Goel AK, and Minhas RS (1991) Water and sediment yields into the Sutlej river from the High Himalaya, *Mountain Research and Development*, **11**:87-100.

Shaw EM (1972) A hydrological assessment of precipitation in the western highlands of New Guinea. *In: Distribution of Precipitation in Mountainous Areas (Geilo Symposium, Norway - July 31 to August 5, 1972)*, World Meteorological Organisation No. 326, 532-543.

Shen HW and Li RM (1976) Watershed sediment yield, In: *Stochastic Approaches to Water Resources*, ed.: Shen HW. H.W. Shen, Fort Collins, Colorado. Ch 21, 21-1-21-68.

Sherchan DP, Gurung GB, and Chand SP (1991) A review of current soil related research activities at Pakhribas Agricultural Centre, In: *Soil Fertility and Erosion Issues in the Middle Mountains of Nepal; Workshop Proceedings April 22-25*, eds.: Shah PB, Schreier H, Brown SJ, and Riley KW. International Development Research Centre, Kathmandu, Nepal. 83-104.

Shrestha B and Brown SJ (1995) People, community dynamics and perceptions in the watershed, In: *Challenges in Mountain Resources Management in Nepal: Processes, Trends, and Dynamics in Middle Mountain Watersheds - Proceedings of a Workshop held in Kathmandu, Nepal April 10-12, 1995*, eds.: Shah PB and Schreier H. International Development Research Centre, Kathmandu, Nepal. 129-140.

Sidle RC and Campbell AJ (1985) Patterns of suspended sediment transport in a coastal Alaskan stream, *Water Resources Bulletin*, **21(6)**:909-917.

Sinclair MR (1993) A diagnostic study of the extratropical precipitation resulting from tropical cyclone Bola, *Monthly Weather Review*, **121**:2690-2707.

Singh JS, Pandey AN, and Pathak PC (1983) A hypothesis to account for the major pathways of soil loss from Himalaya, *Enviornmental Conservation*, **10**:343-345.

Singh KP and Durgunoglu A (1992) Predicting Sediment Loads, *Civil Engineering (ASCE)*, **62(10)**:64-65.

Smith LC and Olyphant GA (1994) Within-storm variations in runoff and sediment export from a rapidly eroding coal-refuse deposit, *Earth Surface Processes and Landforms*, **19**:369-375.

Smith RB (1989) Mechanisms of orographic precipitation, *Meteorological Magazine*, **118**:85-88.

Snowdon P (1991) A ratio estimator for bias correction in logarithmic correction, *Canadian Journal of Forest Research*, **21**:720-724.

Soil Taxonomy (1975) *A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, In: Agriculture Handbook No. 436.United States Department of Agriculture, Soil Survey Staff, 643 pp.

Spreen WC (1947) A determination of the effect of topography upon precipitation, *Transactions, American Geophysical Union*, **28**:285-290.

Sprugel DG (1983) Correcting for bias in log-transformed allometric equations, *Ecology*, **64**:209-210.

Starkel L (1972) The role of catastrophic rainfall in the shaping of the relief of the lower Himalaya (Darjeeling Hills), *Geographia Polonica*, **21**:103-147.

Sthapit BR, Gautam M, Ghale N, Gurung D, Gurung G, Gurung J, Gurung KJ, Paudel DRS, and Subedi KD (1988) *The results of a soil fertility thrust Samuhik Bhraman: traditional methods of sustaining crop productivity in the Lower Hills (300-700m) The problems and potential*, Technical Paper 1988/19, LUMLE Agricultural Centre, Nepal, 31 pp.

Stone M and Saunderson H (1992) Particle size characteristics of suspended sediment in southern Ontario rivers tributary to the Great Lakes, *Hydrological Processes*, **6**:189-198.

Storr D and Ferguson HL (1972) The distribution of precipitation in some mountainous Canadian watersheds. *In: Distribution of precipitation in mountainous areas (Geilo Symposium, Norway - July 31 to August 5, 1972)*, World Meteorological Organisation No. 326, 243-263.

Subedi KD, Gurung GB, Paudel DRS, Gurung KJ, Gurung DB, and Gurung JB (1989) *Traditional methods of maintaining soil fertility in the Mid Hills and High Hills of the western development region of Nepal (Kaski and Lamjung Districts) Problems and Potentials*, Working Paper No. 3, LUMLE Agricultural Centre, Nepal, 20 pp.

Sundborg A (1967) Some aspects on fluvial sediments and fluvial morphology. 1. General views and graphic methods, *Geografiska Annaler*, **49A**:333-343.

Sutherland RA and Bryan RB (1989) Variability of particle size characteristics of sheetwash sediments and fluvial suspended sediment in a small semiarid catchment, Kenya, *Catena*, **16**:189-204.

Swanson FJ and Frederiksen RL (1979) Sediment routing and budgets: implications for judging impacts of forestry practices, In: *Sediment Budgets and Routing in Forested Drainage Basins*, eds.: Swanson FJ, Janda RJ, Dunne T, and Swanston DN. U.S. Dept. Agric. For. Serv. Gen. Tech., Report PNW-141, 129-137.

Swanson FJ, Janda RN, Dunne T, and Swanston DN (1979) Introduction: workshop on sediment budgets and routing in forested drainage basins, In: National Science Foundation, 1-4.

Symader W and Strunk N (1992) Determining the source material of suspended particulate material, In: *Erosion, Debris Flows, and Environment in Mountain Regions*, IAHS Publ. No. 209,International Association of Hydrological Sciences, 177-185.

Takahashi K and Arakawa H() (1981) *Climates of Southern and Western Asia*, Elsevier Scientific Publishing Company, Amsterdam, 333 pp.

Tamang D (1991) Indigenous Soil Fertility Management Systems in the Hills of Nepal, In: *Soil Fertility and Erosion Issues in the Middle Mountains of Nepal,* University of British Columbia, Vancouver, Canada. 135-150.

Tamang D (1992) *Indigenous Soil Fertility Management in the Hills of Nepal: Lessons from an East-West Transect*, HMG Ministry of Agriculture-Winrock International, Kathmandu, Nepal, 59 pp.

Tamang D (1993) *Living in a Fragile Ecosystem: Indigenous Soil Management in the Hills of Nepal*, Gatekeeper Series No. 41, International Institute for Environment and Development, London, 23 pp.

Thapa GB and Weber KE (1991) *Status and Management of Watersheds in the Hills of Nepal*, 35 pp.

Thompson M and Warburton M (1985) Uncertainty on a Himalayan scale, *Mountain Research and Development,* **5(2)**:115-135.

Trimble SW (1983) A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853-1977, *American Journal of Science,* **283**:454-474.

Tropeano D (1991) High flow events and sediment transport in small streams in the 'Tertiary Basin' area in Piedmont (Northwest Italy), *Earth Surface Processes and Landforms,* **16** **(4)**:323-339.

Turton CNR, Gurung GB, and Sherchan DP (1994) *Red Soils in the Eastern Hills of Nepal*, Pakhribas Agricultural Centre, Dhankuta, Nepal, 22 pp.

Upadhya M (1994) *Restoring Mountainous Regions - A Strategy at the Local Level*, Sigma Offset Press, Kathmandu, Nepal, 34 pp.

Upadhaya GP, Sthapit M, and Shrestha KN (1991) Runoff and soil loss studies in the Kulekhani Watershed (results 1985 - 1990), In: *Soil Fertility and Erosion Issues in the Middle Mountains of Nepal; Workshop Proceedings April 22-25,* eds.: Shah PB, Schreier H, Brown SJ, and Riley KW. International Development Research Centre, Kathmandu, Nepal. 25-32.

Upadhyay DS and Bahadur J (1982) On some hydrometeorological aspects of precipitation in Himalayas. *In: International Symposium on Hydrological Aspects of Mountainous Watersheds*, (1982).Manglik Prakashan, Saharanpur, Uttar Pradesh, India, 58-65.

Van Sickle John and Beschta RL (1983) Supply-based models of suspended sediment transport in streams, *Water Resources Research,* **19(3)**:768-778.

Vuichard D and Zimmermann M (1986) The Langmoche Flash-Flood, Khumbu Himal, Nepal, *Mountain Research and Development,* **6**:90-93.

Wall GJ and Wilding LP (1976) Mineralogy and related parameters of fluvial suspended sediments in Northwestern Ohio, *Journal of Environmental Quality,* **5**:168-173.

Walling DE (1974) Suspended sediment and solute yields from a small catchment prior to urbanization, In: *Fluvial Processes in Instrumented Watersheds,* Institute of British Geographers Special Publication No. 6,eds.: Gregory KJ and Walling DE. Institute of British Geographers, London. Ch 13, 169-192.

Walling DE (1977a) Assessing the accuracy of suspended sediment rating curves for a small basin, *Water Resources Research,* **13(3)**:531-538.

Walling DE (1977b) Limitations of the rating curve technique for estimating suspended sediment loads, with particular reference to British rivers, In: *Erosion and Solid Matter Transport in Inland Waters Symposium (IAHS Publication No. 122),* IAHS/UNESCO, UK. 34-48.

Walling DE (1978) Suspended sediment and solute reponse characteristics of the River Exe, Devon, England, In: *Research in Fluvial Systems,* eds.: Davidson-Arrott R and Nickling W. Geo Books, Norwich. Ch 8, 169-197.

Walling DE (1983) The sediment delivery problem, *Journal of Hydrology,* **65**:209-237.

Walling DE, Bradley SB, and Lambert CP (1986) Conveyance losses of suspended sediment within a flood plain system, In: *Drainage Basin Sediment Delivery,* IAHS Publication No. 159,ed.: Hadley RF. International Association of Hydrological Sciences, Wallingford, UK. 119-131.

Walling DE and Kane P (1982) Temporal variation of suspended sediment properties, In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield,* ed.: Walling DE. International Association of Hydrological Sciences, Washington, DC. 409-419.

Walling DE and Kane P (1984) Suspended sediment properties and their geomorphological significance, In: *Catchment Experiments in Fluvial Geomorphology,* eds.: Burt TP and Walling DE. Geo Books, Norwich, England. Ch 19, 311-334.

Walling DE and Moorehead PW (1987) Spatial and temporal variation of the particle-size characteristics of fluvial suspended sediment, *Geografiska Annaler,* **69**:47-59.

Walling DE and Moorehead PW (1989) The particle size characteristics of fluvial suspended sediment: an overview, *Hydrobiologia,* **176/177**:125-149.

Walling DE, Peart MR, Oldfield F, and Thompson R (1979) Suspended sediment sources identified by magnetic measurements, *Nature,* **281**:110-113.

Walling DE and Teed A (1971) A simple pumping sampler for research into suspended sediment transport in small catchments, *Journal of Hydrology,* **13**:325-337.

Walling DE and Webb BW (1981) The reliability of suspended sediment load data, In: *Erosion and sediment transport measurement (Proceedings of the Florence Symposium, June 1981) IAHS Publ. No. 133,* International Association of Hydrological Sciences, UK. 177-194.

Walling DE and Webb BW (1982) Sediment availability and the prediction of storm-period sediment yields, In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982),* IAHS Publication No. 137,327-337.

Webster PJ (1987) The Elementary Monsoon, In: *Monsoons*, eds.: Fein JS and Stephens PL. John WIley and Sons, Washington DC. Ch 1, 3-32.

Wendelaar EE (1978) *Applying the Universal Soil Loss Equation in Rhodesia*, Departmental Report, Department of Extension, Causeway, Zimbabwe.

Weinstock (1984) Getting the right feel for the soil: traditional methods of crop management, *The Ecologist*, **14**:146-149.

Wiant VW and Harner EJ (1979) Percent bias and standard error in logarithmic regression, *Forest Science*, **25**:167-168.

Wilken GC (1987) *Good Farmers - Traditional Agricultural Resource Management in Mexico and Central America*, University of California Press, Berkeley, 302 pp.

Williams GP (1989) Sediment concentration versus water discharge during single hydrologic events in rivers, *Journal of Hydrology*, **111**:89-106.

Winiger M (1983) Stability and instability of mountain ecosystems - definitions for evaluation of human systems, *Mountain Research and Development*, **3**:103-111.

Winkler JA, Skeeter BR, and Yamamoto PD (1988) Seasonal variations in the diurnal characteristics of heavy hourly precipitation across the United States, *Monthly Weather Review*, **116**:1641-1658.

Wischmeier WH (1976) Use and misuse of the universal soil loss equation, *Journal of Soil and Water Conservation*, **Jan-Feb**:5-9.

Wischmeier WH and Smith DD (1978) *Predicting Rainfall Erosion Losses - A Guide for Conservation Planning*, In: Agriculture Handbook No. 537.Department of Agriculture, Washington , D.C. 58 pp.

Wolman MG and Gerson R (1978) Relative scales of time and effectiveness of climate in watershed geomorphology, *Earth Surface Processes*, **3**:189-208.

Wolman MG and Miller JP (1960) Magnitude and frequency of forces in geomorphic processes, *Journal of Geology*, **68**:54-74.

Wood PA (1977) Controls of variation in suspended sediment concentration in the River Rother, West Sussex, England, *Sedimentology*, **24**:437-445.

World Bank (1979) *Nepal development performance and prospects*, South Asia Regional Office, World Bank, Washington, DC Staff Report, 77 pp.

World Meteorological Organisation (1981) *Guide to Hydrological Practices - Data Acquisition and Processing*, World Meteorological Organisation, Geneva, Switzerland, various pagination.

Wymann S (1993) Land use changes and soil fertility status in a small watershed in the Middle Hills of Nepal: signs of pressure, *Geographica Bernensia*, **G38**:189-204.

Young RA, Olness AE, Mutchler CK, and Moldenhauer WC (1986) Chemical and physical enrichments of sediment from cropland, *Transactions of the ASAE,* **29**:165-169.

Young RA and Onstad CA (1978) Characterization of rill and interrill eroded soil, *Transactions of the ASAE,* **21**:1126-1130.

Young RA and Onstad CA (1982) The effect of soil characteristics on erosion and nutrient loss. *In: Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982),* IAHS Publication No. 137, 105-113.

Zurick DN (1990) Traditional knowledge and conservation as a basis for development in a west Nepal village, *Mountain Research and Development,* **10(1)**:23-33.