EROSION IN THE MIDDLE HIMALAYA, NEPAL
WITH A CASE STUDY OF THE PHEWA VALLEY

by

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Abstract

Data on erosion processes and other aspects of environmental change in the Himalaya are scarce and unreliable, and consequently policy decisions have been taken in a quantitative vacuum. Published estimates of denudation for large catchments in Nepal vary from 0.51 to 5.14 mm/yr, and indicate a dynamic geomorphological environment. A review of the literature on erosion in Nepal revealed a consensus that: (1) mass wasting is the dominant hillslope process; (2) activity is seasonal, with virtually all failures occurring during the monsoon; (3) geological factors are the most important determinants of slope stability; (4) sediment delivery to channels is high; (5) little quantitative evidence exists to link landsliding to deforestation. Although few data exist, loss of forest cover does appear to be related to surface erosion and gullying, and a hypothesis linking the expansion of unmanaged, eroding areas to reduced nutrient subsidies from the forest is proposed.

A reconnaissance survey of sediment production and transfer mechanisms in the 122 km^2 Phewa Valley in the Middle Mountains of Nepal identified a variety of mass movement processes. The commonest events were shallow translational failures on slopes of, typically, 36^0 to 45^0, with volumes $\leq 1 \times 10^3$ m^3, and with recovery taking less than ten years. Larger slides occurred on slopes oversteepened by fluvial action. Flows developed in areas of weak rock and unfavourable structure, and were associated with groundwater discharge. Flow velocities accelerated during the monsoon. The highly fractured and deeply weathered zones around faults were the sites of "mass movement catchments", complex failures responsible for approximately 90% of all sediment production by mass wasting in the watershed. A first estimate of surface lowering by mass movement processes in the Phewa Valley is 2–3 mm/yr. Locally, surface erosion on overgrazed pasture may be 5–6 mm/yr. No data were available on soil losses from cultivated areas, and, similarly, losses due to shallow creep, gullying and solution

remain unknown.

The fluvial transport system in the valley bottom is unable to transport all the material with which it is supplied. Sediment yield to the lake was not calculated owing to insufficient data. Discharge estimates and intensity-duration-frequency analysis of rainfall records indicate that in Pokhara storms of 275 mm/day have a return period of approximately 10 years.

The primary controls on mass movement processes in the Middle Himalaya of Nepal are geological and climatic, and therefore are not amenable to modification by man. However, surface erosion is a consequence of poor land management, and therefore can be controlled, given the right institutional environment.

Acknowledgements

I am indebted to my supervisor, Professor D.L. Golding, for his faith in the eventual completion of this thesis, and to the other members of my committee for their tolerance of erratic progress. Brian Carson and Sandy Burton have provided advice, friendship and hospitality both in Nepal and Vancouver. Gordon and Shirley Fisher kindly granted the leave of absence necessary for writing up.

The field work was carried out following a year spent with the United Nations Food and Agriculture Organization, in Pokhara, where Yadav Khatiwada and his staff at the office of the Department of Soil Conservation and Watershed Management were unfailingly helpful and good-humoured.

My most important debt is to my wife, Jane, for her assistance in the field and for her encouragement at home. Despite the leeches, she understands.

Dedication

To Sophie

who was never given a chance

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Chapter 1

INTRODUCTION AND LITERATURE REVIEW

"The concept of man as a modifier of his environment is an extremely ancient one which can be traced back to Sumerian times" (Glacken 1967).

1.1 THE HIMALAYAN ENVIRONMENT: PROBLEMS AND ASSUMPTIONS

In Nepal 53% of the population (Goldstein *et al.* 1983) live in the high relief-energy environment of the hills and mountains. These eight million people are largely dependent on subsistence agriculture for their livelihood. However, gross domestic product per capita has been declining over the last several decades (see e.g. World Bank 1979; Blaikie *et al.* 1980), and intense pressure on the resource base has given rise to fears of impending eco-catastrophe. The first warnings of this were given by expatriate foresters in the 1950's and 60's (e.g. Robbe 1954, Willan 1967), but it was not until the mid-1970's that the problems entered world consciousness, largely through the writings of Eckholm (1975a, 1975b, 1976). The position has been described succinctly by Ives and Messerli:

> "The Himalaya-Ganges-Brahmaputra system can be categorized as one of the world's largest highland-lowland interactive systems. A number of assumptions have been reiterated so often that they are now largely accepted as fact and, in turn, have had major impacts on the decision-making process and development-project design. Enumerated briefly these are: (1) population growth in the Himalaya generates deforestation as demands for fuelwood and croplands increase; (2) deforestation leads to soil erosion and landsliding, and disrupts the normal hydrological cycle; (3) this leads to more disastrous floods and massive siltation in the wet season and lower water levels in the dry season; (4) the increased sediment load of the Ganges and Brahmaputra is causing an island to form in the Bay of Bengal.
>
> "This so-called vicious circle is an intellectually satisfying concept; as a working hypothesis it seems so reasonable that it is not surprising that it is accepted as fact and many consequences for development flow from that acceptance. One interesting component of this "fact" is that it is the growing demand for fuelwood that is the cause of deforestation and, as the labour of walking greater distances to collect increasingly scarce fuel crosses a critical threshold, animal dung is increasingly used for fuel. This sets up another vicious circle: terrace soils, deprived of natural fertilizer, produce poorer crop yields, and weakened soil structure augments landslide

> incidence so that more trees are cut to make room for terraces, and agriculture spreads to increasingly steeper slopes and thus to more marginal land." (Ives and Messerli 1984, p. 67).

The development of these assumptions has been largely due to the uncertainties surrounding interdependent cause and effect relationships in a heterogeneous and extremely dynamic environment. The issue of uncertainty and its impact on both science and policy development in the region has been investigated by Thompson and Warburton (1985), in a provocative paper which should be required reading for all observers of the Himalayan scene. Their central thesis is that the traditional scientific approach of analysis in terms of deduced physical facts - *cis-science* - is inappropriate in a region where the quantitative data are so variable that any particular policy can be justified. Instead, investigators entering the area should be aware that they will have to operate in an environment where uncertainty is so high that, owing to the generation of expectations of what the answers should be by social processes, institutional forces, rather than objectivity, can confer and withdraw credibility. Consequently the methods of *trans-science* (Weinberg 1972) should be invoked. "Trans-science is the science of messes" (Thompson and Warburton 1985, p. 116), and involves, *inter alia*, the study of a particular perceived physical problem as a point of entry to the complex physical, social and cultural system responsible for generating the uncertainty. Thompson and Warburton support their argument with the example of per capita fuelwood consumption, a variable which is intrinsically measurable. Nevertheless, excluding unreliable extremes, published data on per capita consumption in the Himalaya varies by a factor of 26 (Thompson and Warburton 1985, p. 117, citing Donovan 1981)[1].

Fuelwood consumption is a field which has been relatively well studied in the region. Other aspects of resource use and degradation have received even less attention,

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[1] A recent comprehensive review and case study of wood utilization and biomass production in Nepal is available in Wiart (1983).

as Ives and Messerli lament:

> "... there is almost no data available on rates of soil loss under different cover types and land-use practices; the sources of origin (and amounts) of the flood waters and silt, whether the Siwaliks, Mahabarat Lek, Middle Mountains, Greater Himalaya, or Trans-Himalaya, are virtually unknown;"...."The catalogue could be extended almost indefinitely." (Ives and Messerli 1984, pp. 67-68).

What data there are should be treated with caution, and original sources referred to in order to clarify the context and methodology of the original study. Only in this way can the hazard of generalizing locally-derived data over wider physical and social environments be avoided.

1.2 OBJECTIVES

The objective of this thesis is to reduce the overall uncertainty concerning erosion processes and rates of sediment production in the Middle Mountains of Nepal. To this end:

(i) the literature on current rates of surface erosion and mass wasting in Nepal is reviewed, and a comprehensive bibliography prepared;

(ii) the results of a reconnaissance survey of geomorphological processes in a small watershed in the Middle Mountains near Pokhara are presented;

(iii) the results of the survey are summarized, and the implications for land management in Nepal are discussed.

The objectives of the case study near Pokhara were:

(i) to make a preliminary description of mass movement processes in the study area;

(ii) to make a preliminary description of fluvial aspects of the sediment transport system.

1.3 EROSION PROCESSES IN MOUNTAIN ENVIRONMENTS

Mountains are essentially geological ephemera. In comparison with geologic time there is no such thing as an "old" mountain range. This is due to the tendency of erosion to increase in effectiveness with both altitude (Price 1981, p. 166), and local relief (see e.g. Schumm 1963; Ruxton and McDougall 1967; Young 1969). The position was summed up as long ago as 1876 by the geologist J.W. Powell working in the western United States:

> "We may now conclude that the higher the mountain, the more rapid its degradation; that high mountains cannot live much longer than low mountains, and that mountains cannot remain long as mountains: they are ephemeral topographic forms. Geologically all existing mountains are recent; the ancients are gone." (Powell 1876, p. 193).

Geomorphological processes active in mountain environments include weathering, frost action, glaciation, nivation (essentially a transitional process between glacial and periglacial systems (Price 1981, p. 209)), mass movement, surface erosion, creep, solution processes, fluvial action, and the effect of wind. These phenomena are well described in a number of texts (e.g. Fairbridge 1968; Carson and Kirkby 1972; Slaymaker and McPherson 1972; Ives and Barry 1974; Price 1981), and are not reviewed again here.

In the Himalayan context it is as well to emphasize the distinctions between surface erosion, fluvial action, and mass movement, since they are frequently confused[2]. Surface erosion includes rainsplash, sheetwash, rilling, and the effect of wind, and is primarily a product of sparse or reduced reduced vegetation cover. Fluvial action involves erosion, sediment transport, and deposition by flowing water confined to channels, or during floods. Mass movement (synonymous with mass wasting) includes all gravity-induced movements except those in which material is carried by a transporting medium such as water, air or ice. In practice, processes sometimes merge into each

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[2] The Nepali term for landslides, *pahiro*, includes both mass movement and the high-angle fluvial gullies with which landslides are often associated. It is a logical descriptive term, but is less useful for analysis of process.

other and distinctions between them become arbitrary (Fairbridge 1968). Nevertheless, it is important that policy-makers appreciate the differences between these three general categories of erosion. They have fundamentally different causes and consequences, and whereas surface erosion is controllable, mass wasting often is not (at an economic price). Gullying can sometimes be checked by structural measures, but is best prevented before initiation by minimising uncontrolled runoff.

In the discussion which follows it is also useful to bear in mind a number of geomorphological concepts which can place the processes described in perspective. The simplest of these is the difference between *geological* and *accelerated* erosion. Although no different at the fundamental process level (Novak and van Vliet 1983), geological erosion has been defined as the "normal" process operating without the influence of man, whereas "accelerated" erosion results from man's activities on the land surface (U.N.F.A.O. 1965). Another relevant concept is that of *process domains* or sets of environmental conditions which, through the operation of a constant set of processes, produce over time a set of characteristic landforms, such as convex or concave hillslopes, debris fans, or river terraces (see e.g. Skempton 1953; Kirkby 1978). Central to the concept of process domains is that of *relaxation time*, the period following an event or impulse that carries out geomorphic work, and during which the responses to the initial impulse eventually produce a characteristic landform. For example, the recovery of a landslide scar after failure, becoming a stable, vegetated hollow. Brunsden and Thornes have reviewed this and related concepts in a seminal paper on landscape sensitivity and change (Brunsden and Thornes 1979), and suggest that, *inter alia*, both slope failure sites and the impact of deforestation may follow first-order exponential decay relaxation paths toward a characteristic form, i.e., the responses to these events slow down as time increases after the initial incident. Alternative system responses to impulses include either change to a new level of geomorphological activity (having crossed some critical stability threshold), or entrance to an area of reinforcement through positive feedback. An example of the former, given by Brunsden and Thornes, is soil compaction leading to reduced infiltration capacity, increased relative runoff, exceedence of critical thresholds, and gully initiation (Brunsden and Thornes 1979, p. 475)[3]. Feedback may occur where, for example, slope failure exposes bare ground causing increased runoff, which in turn causes the area of the failure scar to expand.

A fourth useful concept is that of the spatial propagation of an impulse through the landscape. Changes in some variables such as climate are ***ubiquitous***, occurring effectively simultaneously over the whole landscape. Others, such as changes in base level[4], are transmitted linearly along erosional axes, most importantly river channels, and diffuse out from these axes to slopes. As in other areas of high relative relief, this theme of ***slope–channel coupling*** (Brunsden and Thornes 1979) is central to an understanding of the efficiency of erosional processes in the Himalaya.

1.4 THE NEPALESE HIMALAYA

Regional physiography has been succinctly described by Brunsden *et al.* (1981) and is illustrated in Figure 1:

> "The Nepal Himalaya, an 800 km long unit of the 2400 km long Himalayan mountain system, may be divided into five strike–oriented, longitudinal relief units. The northern three units form an intimate association consisting of two mountain ranges, the Tibetan Marginal Range, which forms a 6000 to 7000 m high southern rampart to the Tibetan Plateau, and the Great or High Himalaya, a line of mountain masses with an average elevation of 6000 m and containing numerous peaks rising to above 8000 m. Between these occurs the Inner Himalaya, a number of "natural compartments" (Hagen 1965) standing at 2000 to 6000 m and surrounded by high peaks. South of the High Himalaya lies the broad belt of the Middle Himalaya[5] (generally 3700–4500[6] m) and the Outer, Fore or

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[3] For a discussion of the concept of thresholds in geomorphology see Schumm (1979).
[4] In this context, base level means the local level to which, in the absence of uplift, the land surface will eventually be reduced by erosion, i.e. the Terai.
[5] Sometimes termed the "Midlands".
[6] Probably a misprint for 700–2500 m.

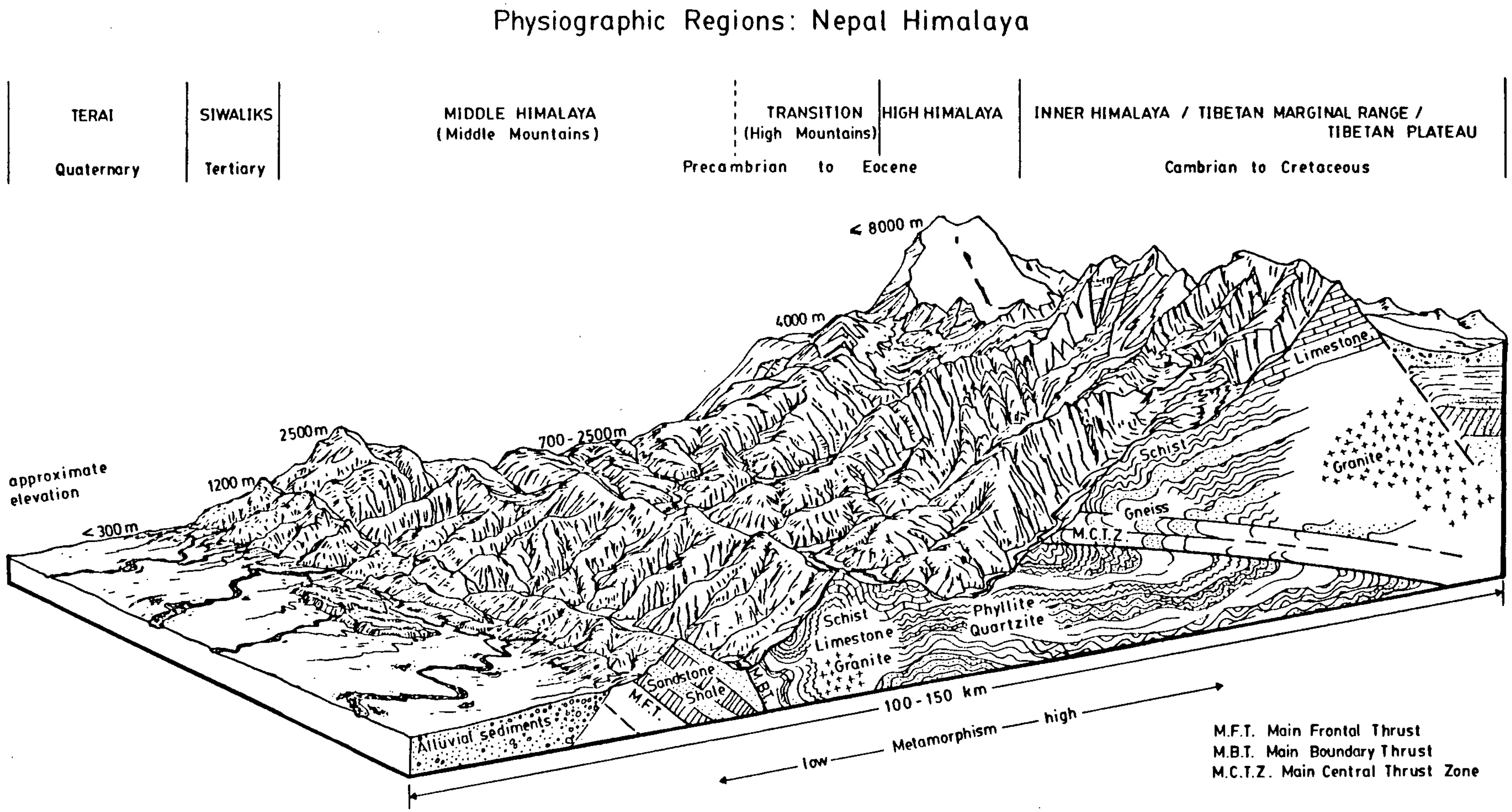

Figure 1. Schematic cross–section of the Nepal Himalaya showing physiographic regions.
Modified from: Nelson *et al.* (1980), and L.R.M.P. (1983).
Geological symbols after Gardiner and Dackombe (1983).

> Low Himalaya[7] (including the Siwalik Hills), the latter forming a foothill zone of variable width with ridges that usually rise to 900–1200 m and which overlook the low lying (<300 m) Ganges Plain, known locally as the Terai." (Brunsden *et al.* 1981).

The geology of the region has been comprehensively reviewed by Stocklin (1980)[8], and the Himalaya are acknowledged to be the world's youngest major mountain chain. Estimates of current uplift include *circa* 1 mm/yr for the Great Himalaya Range (Zeitler *et al.* 1982), about 1–4 mm/yr since the end of the Lower Pleistocene (Brunsden *et al.* 1981, based on Low 1968), of the order of 1 mm/yr for the Nepalese Himalaya (Iwata *et al.* 1984), and *circa* 9 mm/yr for the last half-million years in the Nanga Parbat area of Pakistan (Zeitler *et al.* 1982).

The climate is monsoonal, with precipitation decreasing from east to west along the range. Climax vegetation is forest up to the tree line, but over the centuries the vegetation cover has been extensively modified by man. For an introduction to the history of deforestation in northern India and the Himalaya readers should consult Tucker (1982, 1983). A useful introduction to both physical and cultural aspects of the current changes taking place in the Himalaya is Lall and Moddie (1981).

1.5 LITERATURE REVIEW: EROSION IN NEPAL

1.5.1 DENUDATION

An impression of the intensity of geomorphological processes operating in the Himalaya can be gained from denudation rates (vertical lowering of the land surface) estimated for the region, and for catchments of some of the main rivers (Table 1). The rates reported are high, up to five times or more higher than general estimates of erosion even in areas of steep relief (0.1–1.0 mm/yr: Saunders and Young 1983).

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[7] The Middle and Outer Himalaya together are sometimes termed the "Lesser Himalaya".

[8] See also Le Fort (1975).

Table 1. *Selected denudation rates for the Himalayan region* †

Location	Denudation Rate (mm/yr)	Comments	Author
Himalaya	1.0	Regional	Menard 1961
Ganges/Brahmaputra catchment	0.7	From present rate of influx to Bay of Bengal Fan	Curray amd Moore 1971
R. Hunza catchment	1.8	From sediment yield	Ferguson 1984
R. Tamur catchment	5.14	From sediment yield	Seshadri 1960[1]
R. Tamur catchment	4.7	From sediment yield 1948–1950	Ahuja and Rao 1958[1]
R. Tamur catchment	2.56		Williams 1977
R. Arun catchment	1.9	1947–1960	Pal and Bagchi 1974[1]
R. Arun catchment	0.51		Williams 1977, after Das 1968
R. Sun Kosi catchment	2.5		Pal and Bagchi 1974[1]
R. Sun (*sic*) catchment[2]	1.43		Williams 1977, after Das 1968
R. Kosi catchment[3]	0.98	From suspended sediment	Schumm 1963, based on Khosla 1953
R. Sapta Kosi catchment	1.00		Williams 1977, after Das 1968
R. Karnali catchment	1.5		U.N.D.P. 1966
Darjeeling area	0.5–5.0	Forested/deforested	Starkel 1972a
Darjeeling area	10.0–20.0	In catastrophic storms	Starkel 1972a

[1] In: Brunsden *et al.* (1981)
[2] Sun Kosi
[3] Sapta Kosi
† It should be noted that there is considerable uncertainty in these figures since: (1) measurements of suspended sediment are subject to major inaccuracies without rigorous sampling techniques and accurate data on discharge (see e.g. Walling 1977; Walling and Webb 1981; Dickinson 1981; Ward 1984); the characteristics of the rivers listed are such that measurements of both sediment transport and discharge are difficult, and therefore this constitutes a source of gross error; (2) the figures are generally based on measurements of suspended sediment alone; the contributions of the solution and bed loads are not included (see e.g. Brański 1981); the estimates are, therefore, subject to systematic error; (3) no allowance is made for catastrophic events outside the period of measurement, yet these may well be responsible for a high proportion of total sediment movement; (4) different authors have used different conversion factors and sediment delivery ratios to calculate denudation from sediment load. In Nepal, few authors except Zollinger (1979a, p. 28), have drawn any attention to these problems. See also Roehl (1962); Meade (1969); Warhaftig (1970); Meybeck (1976); and Trimble (1977).

Despite their inherent errors the figures suggest a very dynamic geomorphological environment. However, until recent years research effort has concentrated on the geology (e.g. Wadia 1957; Krishnan 1960; Bordet 1961; Gansser 1964; Hagen 1965, 1969; Sharma 1973; Remy 1975) and late Quaternary history of the Himalaya (e.g. Hooker 1854; De Terra and Patterson 1939; Bordet *et al.* 1971; Dollfus and Usselmann 1971; Hormann 1974; Mukerji 1975; Thouret 1975; Fort in press, 1979[9]; Fort and Freytet 1979, 1982; Freytet and Fort 1980; Yamanaka 1982; Yamanaka *et al.* 1982; Heuberger *et al.* 1984), with a view to determining the geological history of the area and to establishing a Pleistocene chronology for the existing depositional and erosional landforms.

With the increase in concern over the region, more attention has been paid to describing and understanding current processes of landform evolution. The key contribution to the geomorphological debate is a paper by Brunsden *et al.* (1981) who collated much of the data available to date on the Low Himalaya of eastern Nepal, added to it their own geomorphological observations from two field surveys for a road alignment (Dharan to Dhankhuta), and produced the first comprehensive description of current hillslope and fluvial processes and sediment systems. They found that the relative relief of their study area had been increasing throughout the Pleistocene owing to stream incision being greater than ridge crest lowering. The rapidly incising drainage network was transmitting the effects of tectonic and isostatic uplift to hillslopes, and this largely accounted for the lengthening and parallel retreat of basal slopes by undercutting and landsliding. Debris mobilized on the slopes flowed straight into river channels (giving a very high sediment delivery ratio[10]) for subsequent removal by fluvial action. This form of process integration has been termed *synchronised*

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[9] Contains excellent bibliography for introduction to the French literature.

[10] Ratio of sediment yield in a river to gross sediment production in the catchment upstream.

degradation by Starkel (1972b).

One of the consequences of this efficient slope–channel sediment system is that debris delivery to the valley bottom is not continuous. Material tends to arrive in waves during storm events, causing pulses of heavily–silted water to move downstream. Carson (in press) reports rapid fluctuations in the sediment load of the Narayani river, with values of up to 25,000 ppm being recorded regularly during the monsoon. He attributes these very high sediment loads to point sources, i.e. slope failures, and emphasizes the implications for the design of engineering structures such as irrigation intakes. Brunsden *et al.* (1981) observed the Leoti Khola (*khola* Nep. river) in eastern Nepal over the 1974 monsoon, and found that the sediments delivered to the channel tended to be deposited quickly as flood stages receded. The transfer of this material downstream is probably largely dependent on catastrophic events, which accomplish a very large amount of geomorphological work in a short time. For example, in August 1968 a landslide–dam at Labubensi on the Buri Gandaki river broke and caused disastrous flooding downstream (Sharma 1974), and more recently a dam–burst resulted in the River Tamur scouring its gorge in the Middle Mountains to a height of 20 m above the bed (Carson, in press). The frequency of such events in the Himalaya remains uncertain, but Starkel (1972b) has proposed a return period of 20–25 years for catastrophic rainfall in the Darjeeling Hills, and Brunsden *et al.* (1981) suggested that formative events for slope and valley landforms in eastern Nepal may occur on the order of once every ten years. Both authors emphasized the importance of heavy precipitation in achieving pronounced erosion, but did not omit seismicity as a possible trigger for major landslides[11].

Despite their finding that the Low Himalaya of eastern Nepal is one of the most rapidly denuding areas of the world (Table 1, R. Tamur catchment), Brunsden *et*

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[11] For a further discussion of the role of extreme meteorological events in slope evolution see Starkel (1976).

al. concluded that present landforms may be regarded as characteristic forms in equilibrium with current processes and the controlling tectonic, climatic and base level conditions (Brunsden *et al.* 1981, pp. 66 and 69). In this dynamic geomorphological environment, Brunsden *et al.*'s paper successfully identified both transport and storage processes, and recognized the linkages between them. However, quantification of these elements and the development of even a preliminary sediment budget for a watershed is at a very early stage in Nepal. Original studies are extremely scarce. Papers in the literature supplying original data on mass wasting, surface erosion, and gullying in Nepal are reviewed below.[12]

1.5.2 MASS WASTING

1.5.2.1 *Previous work*

Even casual visitors to the Siwaliks and Middle Mountains of Nepal are struck by the prevalence of landslides. Recent research has "concluded that mass wasting is the dominant process in the evolution of natural slopes throughout much of the Himalaya" (Carson, in press), although this opinion is due more to their spatial frequency rather than to any knowledge of quantities of material moved or data on failure frequency and slope retreat. The high incidence of landsliding is well illustrated by geomorphological maps such as those of the Low Himalaya of eastern Nepal in Brunsden *et al.* (1981), the valley of the Ankhu Khola in central Nepal (Thouret 1981a, 1981b), the Kathmandu–Kakani area north-west of Kathmandu (Kienholz *et al.* 1983, 1984), and Goorkha, Mustang and Myagdi Districts by, respectively, White, Fort and Shrestha (White *et al.* 1983; Fort *et al.* 1984). The largest documented landslide in Nepal occurred some 30,000 years ago in the Langtang valley, and involved some

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[12] According to Rieger (1978/79), an analysis of "about 500" titles pertaining to erosion, sedimentation, and environmental deterioration in the Himalaya is available in Rieger (1975). See also Rieger (1976).

15 km^3 of material (Heuberger *et al.* 1985).

For quantitative data on current rates of mass wasting most authors refer to Starkel's work carried out in the Darjeeling Hills east of Nepal (Starkel 1970, 1972a, 1972b). Starkel studied the response of slopes to a catastrophic rainfall event of 700–1100 mm over 3 days in 1968, and noted few signs of surface erosion. However, suffosional forms of mass movement (piping) and landslides were common. In response to rainfall intensities of 40–60 mm/hr "the considerable seepage pressure of water led to the formation of thousands of mudflows" and other forms of mass wasting (Starkel 1972b, p. 125). Starkel considered the role played by vegetation in inhibiting shallow failures to be "most important", with destruction in the forest being "10 to 20 times less than on the tea slopes" (Starkel 1972a, p. 142). However, forests had no effect on "deep landslides" (Starkel 1972b, p. 131). Mean degradation in the region was estimated to be 5 mm/yr, including the contribution from catastrophic events with a return period of 20–25 years (Starkel 1972a).

An earlier paper concerning landslides and soil erosion in the same area is that of Dutt (1966), who surveyed a number of watersheds in the Kalimpong Sub–Division of Darjeeling District following disastrous floods in North Bengal in 1954. He observed that the primary cause of the landslides surveyed appeared to be unfavourable geology, with subsidiary causes including the removal of forest, bamboo, and grass, overgrazing, concentrated runoff from livestock trails, and cultivation on slopes greater than 20^0 with no terracing. A major contributor of sediment to rivers was the collapse of terrace gravels due to undercutting.

Since the publication of these papers the only quantitative material to become available on current mass wasting processes in Nepal[13] of which the author is aware has been by Bansode and Pradhan (1975), Prasad (1975), Williams (1977), Laban

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[13] Apart from internal project reports with limited circulation.

(1978/79, 1979), Wagner (1981, 1983), Brunsden *et al.* (1981), and Caine and Mool (1982).[14] Numerous authors (e.g. Singh *et al.* 1983) have postulated pathways accounting for soil loss in the Himalaya, but without supporting numerical data.

Bansode and Pradhan (1975) carried out a reconnaissance survey of landslides along part of the channels of the Sun Kosi and Tamur rivers above Tribeni in 1963. Their impression was of high levels of mass movement activity contributing to high sediment loads in the rivers,

> " mostly due to heavy precipitation, deep weathering, steep dip-slopes of the valley walls, under-cutting of the banks due to high velocity of these rivers, unstable nature of the rocks due to their structural disposition, failure of the shear resistance of the accumulated debris, high seismicity of the area, unplanned deforestation, etc." (Bansode and Pradhan 1975, p. 253).

Failure surfaces were between 30° and 70° (n=19).

Prasad (1975) reported on 10 years' observations of seismicity, rainfall and landslide occurrence in the Durbasha watershed near Chatra in eastern Nepal (Appendix 1), and his paper constitutes the first published material relating these factors in the country. Overall, landslide incidence corresponded with high levels of both precipitation and seismic activity in July and August[15]. However, slides also occurred in years of low earthquake activity, and so Prasad concluded that "seismic shocks by themselves are not the main cause of occurrence of landslides in regions away from the epicentre" (Prasad 1975, p. 79). Hydrological conditions, i.e. high groundwater levels and intense precipitation, were considered to be more important.

Williams (1977), investigating the east to west shift of the Kosi river[16], used ERTS MSS5 satellite imagery to identify all slides larger than approximately 20 ha in the catchment of the Sapta Kosi in eastern Nepal, correlated these with data from

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[14] S. Matsuura is registered to give a paper entitled "The characteristics of landslides in the Midland area of Nepal Himalayas" at the forthcoming IVth International Conference and Field Workshop on Landslides, to be held in Tokyo from 23-31 August 1985, under the auspices of the Japanese Landslide Society.
[15] The author does not comment on the apparent seasonality of earthquakes.
[16] See also Gole *et al.* (1966).

1:63,360 topographic maps available for a small part of the basin, assumed a failure scar recovery period of 50 years, and used Simonett's (1967) empirical volume/area relationship derived for slides in New Guinea[17] to give a "total slide volume" for the Sapta Kosi basin over 50 years of 0.91×10^9 m^3. He estimated that these "large landslides" contributed 31% of the sediment load of the Sapta Kosi, with a further 64% coming from small slides, surface erosion and gullying. The assumptions concerning failure age, area and volume, and basin homogeneity required for this procedure leave the accuracy of William's figures open to question.

Laban (1979) carried out a reconnaissance slide intensity survey of the whole of Nepal, but expressed his data in terms of number of failures per linear km when viewing from one side of a light aircraft, by ecological region[18]. Perhaps his most useful observation was the severity of the impact caused by road and trail construction, to which he attributed 5% of all slides observed.

Wagner (1981, 1983) used a statistical analysis of geological and other characteristics of 100 landslides, mainly along roads in the Middle Mountains, to develop a site-specific landslide hazard assessment and mapping methodology based on the use of "equatorial Schmidt projections"[19]. He concluded that geological factors were of overriding importance in determining debris and rock-slide hazard.

Brunsden *et al.* (1981) made the crucial observations that (in their study area in eastern Nepal) mass movement phenomena were concentrated in two locations: low level undercut situations such as ravines and the outside of meander bends, and areas of structural discontinuity, suggesting an important role for "intensely shattered rock and preferred water movements". Modal angles for debris slides were 35^0-43^0, and they tentatively identified a slope angle of 30^0 as a lower limit for first-time shallow

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[17] See 3.3.3.1.
[18] See Nelson *et al.* (1980).
[19] A geometrical tool for studying the intersection of geological planes (see e.g. John 1968).

debris slides. "Mudslides"[20] occurred on slopes of 25°–39°. They also described "mass movement catchments", steep, rapidly eroding channels with active, expanding heads supplying material to the channels by debris slides, debris flows, rock-debris chutes, and gullies. Gullying in areas underlain by gneiss, which weathered to depths of 20 m, was severe, and was attributed to man-accelerated soil erosion as a result of cultivation following clearance (Brunsden *et al.* 1981).

Caine and Mool (1982) investigated mass movements in the Kathmandu-Kakani area as part of the United Nations University Hazard Mapping Project (see Ives and Messerli 1981). Their analysis of slide morphometry and slope material properties led them to emphasize the importance of material controls on the landslides in their study area, particularly the brittle behaviour of the weathered, untransported bedrock. The high incidence of catastrophic landsliding was further explained by relief, seasonally high water tables, and recent deforestation. Rainfall was thought to be of comparatively minor importance. They gave an estimated rate of surface lowering by landsliding of 12 mm/yr.[21]

1.5.2.2 *Anthropic influences: deforestation, terracing, and construction*

There is considerable evidence from non-Himalayan environments that anthropic disturbance of the land surface can increase rates of mass wasting. Such disturbances may be divided into two categories: changes in land use, principally the removal of forest cover, terracing and irrigation; and construction activities, principally roads and canals. These are discussed below with respect to the Middle Hills of Nepal.

Deforestation. Although one author has implicated *reforestation* in increasing slide

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[20] "Elongate or lobate masses of weathered debris which move in well defined tracks bounded by steeply inclined lateral and basal shear surfaces." (Brunsden *et al.* 1981, p. 45). See also 3.3.1.
[21] Recalculation of their data gives 11.3 mm/yr (author).

incidence through encouraging soil formation and so reducing between-failure periods (Shimokawa 1984), increases in rates of mass wasting following *deforestation* have been recorded from many parts of the world, including for example British Columbia (Schwab 1983), Oregon (Swanson and Dyrness 1975), and New Zealand (Trustrum *et al.* 1984). The reasons for the increase are generally stated as being due to decreased root reinforcement of regoliths as roots die and decay (O'Loughlin 1972, Wu *et al.* 1979, Ziemer 1981), and/or increases in pore water pressure due to reduced evapotranspiration and so higher groundwater levels. The ways in which forest cover can influence slope stability and erosion have been summarized by O'Loughlin and Ziemer (1982). Positive influences depend upon:

* modification of soil moisture distribution and soil pore water pressures caused by forest evapotranspiration;
* accumulation of an organic forest floor layer;
* mechanical reinforcement of the soil by tree roots.

Negative influences result from:

* root wedging and windthrow;
* surcharge due to weight of the tree crop.

The accumulation of the litter layer is beneficial both in preventing rainsplash, and in improving infiltration and ground-water recharge through keeping open the entrances to macropores in the mineral soil. It could be argued that the resulting higher water tables will decrease slope stability, but this must be balanced against the increased moisture storage available due to lower water tables caused by forest transpiration. On balance the net influence of forests on slope stability is positive, with the major factor being root reinforcement (O'Loughlin 1984a). There is thus a presumption that removal of the forest cover will affect slope stability to some degree.

However, in Nepal, observations have not invariably supported this presumption.

For example, Upadhyay (1977) quotes Hunting Technical Services (1975)[22]:

> "Areas with the most numerous and most spectacular land slides (apart from those associated with roads) were observed to be under forest cover and appeared to be more closely associated with structure and landform rather than land use" (Hunting Technical Services 1975, cited in Upadhyay 1977, p. 31).

Furthermore, although all the papers on mass wasting in Nepal reviewed in the preceding section (1.5.2.1) concur on the importance of geological factors in precipitating landslides, none of the authors except Starkel found any clear relationship between forest clearance and mass movement activity.

One of the difficulties in obtaining numerical data with which to examine this question is that in the Middle Mountains of Nepal remaining areas of forest tend to be on slopes too steep for terracing and cultivation, which by definition have a greater tendency towards mass wasting than areas which have been cleared. Thus, any study of the relative frequency of landslides on forested and non-forested slopes immediately runs into the problem of locating undisturbed control sites. On the basis of visual observations alone, it is reasonable to suggest that geophysical considerations such as relief, faulting, undercutting, and heavy precipitation, are likely to have more effect on slope stability than forest influences such as root reinforcement and lowered water tables. An exception to this general rule may be the small, shallow, translational failures ubiquitous in the Middle Hills of Nepal. These are usually located in mid or upper slope positions, often recently cleared of forest, and involve material within the rooting depth of trees and shrubs.

The persistence of the public association of rapid mass failures with deforestation in Nepal can be attributed to four factors; firstly, the existence of predisposing evidence such as that of Wilson (1973), who found that on an international scale land use outweighed both precipitation and relief as the single most important factor

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[22] Not listed in Upadhyay's bibliography.

affecting sediment yield; secondly, the transposition of erosion models developed elsewhere which demonstrate such a link; thirdly, the undoubted effect of deforestation on *surface* erosion and gullying in the hills, as opposed to mass wasting (see 1.5.3 below); fourthly, the credibility afforded to the link by institutions,[23] the media, and "experts", e.g. Kollmansperger, who regards mass wasting in the Midlands, the Mahabharat and Siwaliks "as being a man-made erosion process on an exclusive basis" (Kollmansperger 1978/79, p. 19).

Terracing. Terracing *per se* is not a direct cause of mass wasting, and indeed in some areas may make a positive contribution to slope stability through facilitating the rapid reclamation of failed sites which might otherwise expand (see Kienholz, Hafner and Schnieder 1984). Although the addition of irrigation water to level terraces can cause slope failure by increasing regolith mass and decreasing cohesion and shear resistance, the length and intensity of human occupancy of the mountains means that areas liable to slide due to irrigation have probably already done so (B. Carson, in press). Existing irrigated terraces (Nep. *khet*) are generally stable, and small slumps and collapsed terrace risers are quickly repaired[24]. The perception of landslide hazard also sometimes leads farmers to shift to lower intensity land uses, such as from irrigated to rain-fed cropping (Johnson *et al.* 1982).

Construction activities. The category of construction activities includes dams, canals, quarrying and road building. Dam building has been implicated in mass wasting in Sri Lanka through saturation of materials at the toe of shallow angle deposits, causing slumping (Russell 1981), but in Nepal is primarily associated with problems along

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[23] See e.g. Asian Development Bank (1982); Brown *et al.* (1984).
[24] See Green (1978) and L.R.M.P. (1983) for a full discussion of terracing practices in Nepal.

access roads and around borrow pits, as at Kulekhani south of Kathmandu. The interruption of fluvial sediment transport by dams and reservoirs may also cause new erosion downstream, since the rivers will have greater erosive power without their original sediment load, and will seek to regain equilibrium.

Canals in the hills, both large and small, are frequently associated with slope failure due to both the removal of toe support from slopes and to saturation of the regolith by seepage and overflow. The maintenance of the irrigation water distribution system is a major burden on rural inhabitants. Quarrying can also cause slope failures by removing basal support, but these are usually small-scale events.

A much larger problem in Nepal is the impact on slopes of road construction. Although much of the difficulty is due to poor or non-existent design studies, poor alignments, and poor construction techniques (see e.g. Kojan 1978), the Himalayan environment is extremely hostile to road building. Problems centre on road cuts, which destabilize slopes through the removal of toe support and weight, fills, which overload slopes already near critical angles, and drainage, principally the concentration of water which was previously dispersed or able to drain away. Even when extensive engineering geology investigations have been undertaken prior to construction formidable problems remain. The Dharan-Dhankhuta road (the subject of Brunsden *et al.*'s field studies) is a case in point. Road maintenance constitutes a severe drain on government resources.

1.5.3 SURFACE EROSION AND GULLYING

1.5.3.1 *Measured data.*

Measured rates of surface erosion in Nepal are only available in four publications: Chatra Research Centre[25] (1976), Laban (1978), Mulder (1978b), and Impat

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[25] An Indian aid project associated with studies of the Sapta Kosi river. Variously referred to in the literature as Chatra Research Centre, Chatra Forest Research Centre, Chatra Experimental Station, and Soil Conservation Research, Demonstration and

(1981). All four sources report on runoff plot experiments, and Laban's paper also includes a literature review and original data on erosion determined by silt accumulation behind gully check dams.

Four runoff plot installations are known to have existed in Nepal: at Chatra in East Nepal (Chatra Research Centre 1976); at Gagretal near Surkhet in the West (Laban 1978); and in the Phewa watershed near Pokhara in Central Nepal (Mulder 1978b; Impat 1981). The fourth installation was observed on the Shivapuri watershed immediately north of Kathmandu but was in a state of disrepair (1983), and no results from it are known to have been published.

Rates of surface erosion reported from the first three installations are shown in Table 2. It should be noted that all the data are short-term, site-specific, and under no circumstances should be generalized over large areas. For example, Mulder's results were based on only 4 individual measurements made following rain events between 29 June and 5 July 1978 (Mulder 1978b), and the small plot size (10 m^2) is hardly representative of a longer slope. However, the figures do serve to illustrate both the high absolute rates of surface erosion under some circumstances (Gagretal), and the relative differences between different land use types, e.g. overgrazed pasture (9.85 t/ha from 11 June to 15 Oct. 1979), protected pasture (1.01 t/ha for the same period), and forest (0.43 t/ha between 01 July and 07 Oct. 1979) at Banpale and Tamagi in the Phewa watershed near Pokhara (Impat 1981). Of particular interest is Impat's (1981) finding that, although precipitation peaked in August, soil loss was greatest at the beginning of the measurement period, in June (Appendix 2). This is most likely to be related to an increase in the vigour of the grass cover during the monsoon, and to date is the only quantitative evidence of the importance of vegetation in reducing surface erosion in the Middle Mountains of Nepal.

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[25](cont'd) Training Centre, Chatra. For further information contact: Central Soil and Water Conservation Research and Training Institute, Dehra Dun 248 195, India.

Table 2. *Surface erosion rates reported from runoff plot studies in Nepal*

Location and plot data	Land use	Erosion rate	Source
Siwaliks: Chatra, east Nepal; south aspect, sandstone; period of measurement and number of plots not given.	Various, forest to grazing.	7.8–36.8 t/ha/yr [1]	Chatra Research Centre, in Laban 1978
Siwaliks: Gagretal, near Surkhet, west Nepal; south aspect, sandstone, average slope 60%; period of measurement and number of plots not given.	Severely degraded heavily grazed forest on intensively gullied badlands.	200 t/ha/yr [1]	Sakya, pers. comm., in Laban 1978
Middle Mountains: Banpale, Phewa watershed, near Pokhara, central Nepal; south aspect, grey phyllitic schist; soils 40–70 cm clay loam, moderately well drained; one 10 m^2 plot on each land use type; four individual measurements 29 June to 5 July 1978.	Fenced/unfenced grazing land.	9.4/34.7 t/ha/yr [1]	Mulder 1978b
Middle Mountains: identical location to Mulder 1978; two 10 m^2 plots each land use type; K-value[2] of surface soil given as 0.35; daily measurements 11 June – 15 Oct. 1979.	Protected pasture mixed with forest/overgrazed land.[3]	1.01/9.85 t/ha/period of measurement	Impat 1981
Middle Mountains: Tamagi, Phewa watershed, near Pokhara; north east aspect, elevation 1800 m; one 10 m^2 plot; well drained clay loam derived from grey schist and quartzite schist; 11 composite measurements 01 July to 07 Oct. 1979.	Dense forest.	0.43 t/ha/period of measurement	Impat 1981

[1] Values given as tons(*sic*)/ha/yr in original publications.
[2] Soil erodibility (Wischmeier *et al.* 1971).
[3] Same fenced pasture as in Mulder's study; trees were seedlings at the time (author).

Laban's method for determining soil loss from silt accumulated behind check dams included the use of sediment delivery ratio and trap efficiency curves developed for use in other environments such as the United States (probably based on the work of Brune (1948, 1953)), as well as assumptions on gully shape and sediment contribution from gully-wall slumping. Consequently, his figures should be treated with caution. Other soil loss figures reported by Laban are based on a preliminary exercise in stream sediment sampling in the Kathmandu Valley undertaken by Kandel (1978). Sampling was carried out once or twice weekly, and the results extrapolated to give annual soil loss figures. Therefore the same caution again applies.

Data on soil loss from cultivated land in Nepal are not available. Sastry and Narayana (1984) reported markedly reduced runoff and erosion from bunded areas compared to rates under forest in the Doon Valley near Dehra Dun in India, but this work has limited application away from similar environments such as the Chitawan valley in Nepal.

1.5.3.2 *Estimates.*

A number of observers have tried to estimate surface erosion for specific areas in Nepal rather than to measure it, either by making "informed guesses" using the published figures noted above (e.g. Junor (1981), for the Bagmati catchment; Carson, in press), or else by attempting to use the universal soil loss equation of Wischmeier and Smith (1978) (e.g. Fetzer and Jung 1978/79; Jahn *et al.* 1979; Shakya 1982), despite the paucity of input data for the equation[26] and the pitfalls involved in use of the

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[26] Rainfall erosivity (R) has been calculated by Fetzer and Jung (1978/79) for Kathmandu Airport, and by Impat (1981) for one season in the Phewa valley near Pokhara. At Kathmandu Airport erosivity calculated by the KE >25 mm/hr method (Hudson 1971) for the period 1971-1976 had a mean annual value of 72, which is moderately low. However at Banpale in the Phewa watershed erosivity in 1979, calculated by the same method, was 432. Erosivity has been calculated for other stations in Nepal such as Pakhribas Agriculture Centre but the results have not been widely circulated. It is generally agreed that precipitation intensity decreases with altitude in Nepal (see e.g. Brunsden *et al.* 1981; L.R.M.P. 1983).

model outside the area where it was developed (for a discussion of these see Wischmeier 1976, 1984; Elwell 1984).

1.5.3.3 *Surface erosion, gullying and forest clearance.*

The effect of forest clearance on soil erodibility has been studied by Chakrabarti (1971), who investigated water-stable aggregates in soils in eastern Nepal, and established that forest soils there were considerably less erodible than soils exposed by deforestation. Other effects of forest clearance on soils include compaction due to trampling by livestock, reduced infiltration capacity, and consequently higher surface runoff. Burning also exposes soils to erosion. In India, Dwivedi (1980), quoting Dalal *et al.* (1961), reported increases in splash erosion of up to 4000% in forests of *Shorea robusta* subject to annual leaf litter burning. No comparable data on the effect of fire are available for Nepal, but Impat's (1981) figures for runoff from the erosion plots in the Phewa catchment demonstrate the influence of overgrazing and trampling on runoff (Appendix 2). Mean monthly runoff on protected pasture varied from 5.5% to 17% of total precipitation, but runoff on overgrazed land ranged from 11% to 53% (Impat 1981). This high rate of runoff causes sheetwash, rilling, and eventually, gullying, which has been noted to be severe in many parts of Nepal (Laban 1978; Brunsden *et al.* 1981; Caine and Mool 1982), and which is intimately associated with communal grazing areas and marginal agricultural land[27].

The effect of surface erosion and gullying is to reduce the productive capacity of the land affected, both by removing nutrients and degrading soil physical properties (most importantly texture and depth), and by altering the topography. Additionally,

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[27] The variability of the Himalayan environment is well illustrated by comparing Impat's runoff figures with those found by Pandey *et al.* (1983) in a study in the Kumaun Himalaya near Naini Tal. Average seasonal overland flow and soil loss in very small catchments varied from 0.44% of total incident rainfall and 0.025 t/ha respectively under dense forest, to only 0.60% and 0.081 t/ha on a site with "soil deposition" (Pandey *et al.* 1983, p. 25). The authors concluded that they were dealing with subsurface flow systems.

downstream effects can be severe, with sediment deposition affecting cultivated lands. In India, Champion and Seth (1968, p. 397) have described these consequences:

> "The damage done to cultivation below the eroded slopes by the unchecked run-off, floods, deposition of sand, gravel and boulders is immense and notorious in the Siwaliks of the Punjab, Himachal Pradesh and Jammu."

Although some control is necessary, a total cessation of all erosion in Nepal would probably have a negative effect on agricultural output in the hills. This is due to the dependence of lowland terrace production on the nutrients brought in by irrigation water (see 2.8 for a description of the agroecosystem).

The marginal agricultural areas responsible for much of the soil loss make a minimal contribution to the rural system. In India, Whyte (1957) has described the main functions of the grossly overgrazed public pastures as being an "exercise place" for livestock, and the same description has been applied in Nepal (Y.Khatiwada, pers. comm.). In central Nepal, demand for grazing on these areas peaks during the dry season, and again after the monsoon before crops are harvested (Fox 1982, 1983). The grazing is most important to households with little private land. Equally, it is these same poorer households which are most dependent on public lands for fodder and firewood. The lack of local control or participation in management of these areas results in a classic pattern of over-exploitation close to settlements and under-use at greater distances. Unable to withstand the pressure, the forests retreat.

Physically, the processes involved in forest degradation and clearance include repeated lopping and consequent reduction in vigour, felling, the removal of the litter layer which inhibits regeneration, browsing and trampling by livestock, and fire, both accidental and purposely set to stimulate a flush of grass. Most of these processes are, directly or indirectly, related to the maintenance of livestock. Studies of the energetics of a Himalayan agroecosystem immediately to the west of Nepal (Pandey and Singh 1984a, 1984b; Singh *et al.* 1984) have emphasized the very high energy subsidy supplied by the forest to cultivated areas, and a large part of this subsidy is in the form of fodder for livestock[28]. Wyatt-Smith (1982) has analysed data on land use and livestock populations in the Middle Mountains, largely from Tansen and Pokhara in central Nepal, and determined that, to sustain current activity, the average family of 5-6 persons, with an average farm holding of 1.25 ha, requires 0.4 ha of land for timber, 0.3-0.6 ha for fuel, and 3.5 ha of land for fodder. Thus, rather than the search for fuel or the encroachment of cultivation being required to explain deforestation (see Bajracharya 1981, 1983), it is possible to argue that the process can be ascribed largely to the demands caused by livestock.

This view is supported by the presence, in many parts of the hills, of fallow or abandoned rainfed terraces (Gilmour 1984). These can be explained as being due to a fertility limitation, which has acted to reduce the area under cultivation rather than expand it (L.R.M.P. 1983). Insufficient compost is available from remaining woodland to maintain yields on the total cultivated acreage, and so resources are concentrated on the most productive fields and marginal areas abandoned. On the basis of this evidence it is possible to propose the following sequence[29]: increasing population and static agricultural technology cause food shortages; attempts are made to expand and intensify agricultural production, with associated increases in the livestock population. The demand placed on the forest by the larger herd initiates a decline in forest area. The reduced forest area is unable provide sufficient nutrients to support an increase in the cultivated area, and this remains static. Further decreases in forest cover result in the abandonment of marginal fields, and the only land use type to expand is the overgrazed and barren *charan*. Thus, far from hunger resulting in an increase in the cultivated area, it may serve, indirectly, to reduce it. The unmanaged, communally

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[28] For an analysis of the energy budget of slash and burn agriculture, *jhum*, in north-eastern India, see Toky and Ramakrishnan (1982).

[29] A similar sequence was first presented in L.R.M.P. (1983).

grazed areas become the focus for surface erosion.

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The following three chapters describe a case study of erosion processes in the Phewa valley near Pokhara in central Nepal.

Chapter 2

THE STUDY AREA: THE PHEWA VALLEY

2.1 LOCATION

The study area is located in the Middle Mountains of Nepal (Figure 2) immediately to the south of the Annapurna massif, which rises to some 8078 m 35 km north of Pokhara. It comprises the catchment of the Andheri Khola and Sidane Khola (*khola* Nep. river or stream) which feed Phewa Tal (*tal* Nep. lake), Nepal's most prominent lake (Figure 3). Estimates of the area of the watershed above the Pardi Dam at the outlet of the lake vary from 113 km^2 (Fleming 1978) to 126 km^2 (Anon. 1980). Planimetry of a topographic map of the watershed at a scale of 1:25,000 (I.W.M. 1979) gave a value of 121.8 km^2. The Phewa valley is situated at the western end of the Pokhara valley, an intra-montane basin drained by the Seti Khola ("White River")[30] and its tributaries, and famous in Nepal for its impressive river terraces through which the Seti Khola has cut a spectacular gorge.

2.2 THE GEOLOGICAL CONTEXT

2.2.1 THE POKHARA BASIN

The Pokhara Basin (Gansser 1964) extends for nearly 42 km from Barbhure in the north-west to Dobhan in the south-east (Fort and Freytet 1982), and is bounded to the south by the Barsami Ridge (Figure 4), a fault-scarp ridge which forms the northernmost expression of the Mahabharat Lekh (*lekh* Nep. range). This boundary is comparatively straight and runs parallel to the Main Central Thrust zone to the north. The thrust zone separates the Himalayan Meta-sediments (mostly meta-sandstone,

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[30] So-called due to its milky colour caused by a suspended load of fine calcareous particles transported from high on the Annapurna massif.

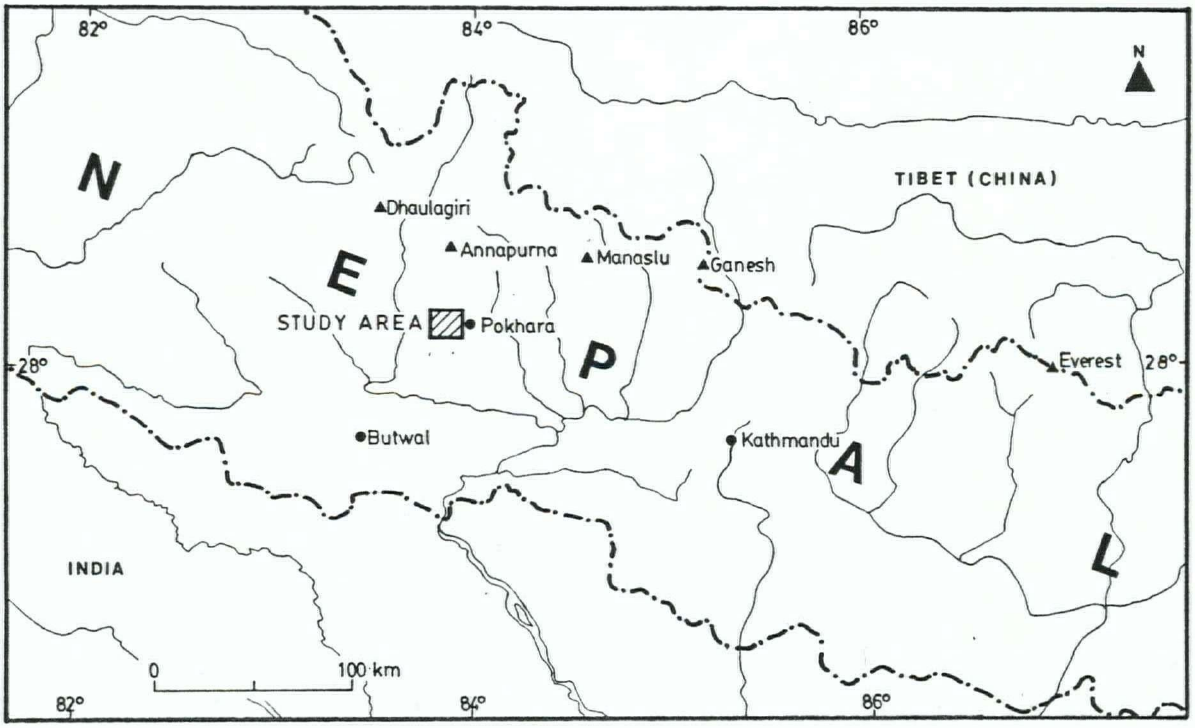

Figure 2. Location of the study area.

Figure 3. Phewa Tal: view from the west towards Pokhara and the Pokhara Basin.

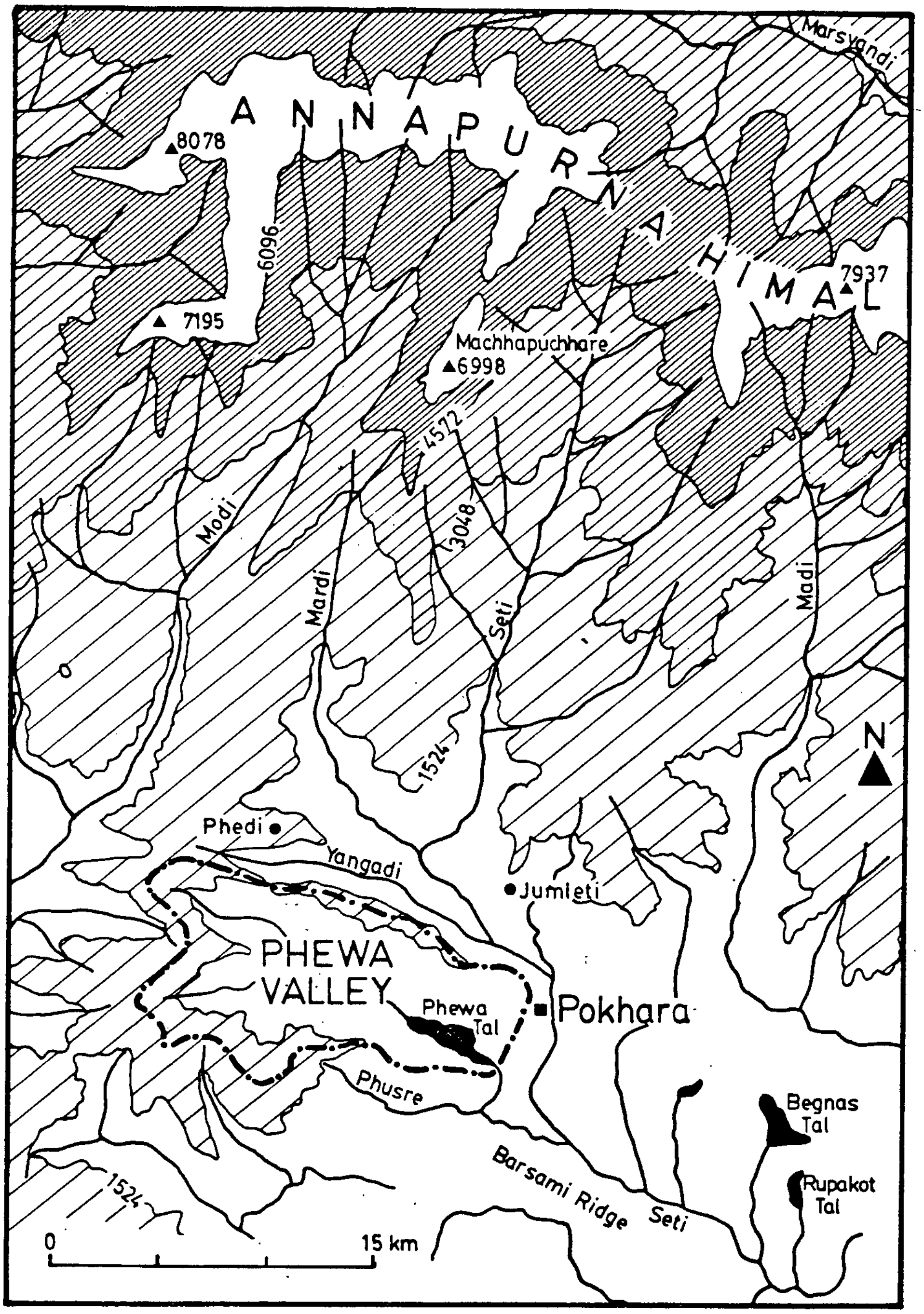

Figure 4. The study area: sketch map of the local environment.

quartzite, chlorite–sericite schist, and crystalline schist) which make up the hills surrounding the basin from the Himalayan Gneiss of the Annapurna Range, and is one of the major tectonic lines in the Himalaya (Yamanaka *et al.* 1982). A possible sequence for the genesis and tectonic development of the Pokhara Basin is described and illustrated in Yamanaka *et al.* (1982, pp. 132–133), and the consensus is that the Basin is a a depression of tectonic origin (Fort and Freytet 1982), situated along a northwest–southeast anticline depressed along its axis (Sharma 1975, Pecher 1978). It is apparent that the Seti Khola is an antecedent river whose current course is controlled by the general WNW–ESE structural trend of the Himalayan Range.

2.2.1.1 *Quaternary deposits*

Because the Middle Hills of Nepal form a zone of subsidence relative to the Great Himalaya and the Mahabharat Range (Yamanaka 1982), Quaternary deposits are found preferentially in this region (for example in the Pokhara Basin; in the Kathmandu Valley; in the Kusma Basin of the Kali Gandaki (Fort and Freytet 1982); in the valley of the Marsyangdi Khola (Yamanaka 1982); along the Buri Gandaki and Ankhu Khola in the Arughat Basin (Thouret 1977)). The Pokhara Basin is filled with detrital material (pebbles, gravels, sands, and muds), mainly calcareous (marbles) and with a minor percentage of sedimentary rocks (gneiss, micaschists) (Fort and Freytet 1982). This filling has been interpreted variously as the result of lacustrine sedimentation (Akiba 1980), secondary deposition of morainal material (Hagen 1969), glacial, fluvioglacial and partly lacustrine deposition (Sharma 1975; Sharma *et al.* 1978), fluvial and fluvioglacial deposition (Gurung 1970; Dollfus and Usselman 1971; Hormann 1974; Yamanaka *et al.* 1982), and colluvial, alluvial and fluvioglacial action (Fort and Freyet 1979, 1982). Relative stratigraphies for the deposits have been proposed by Dollfus and Usselman (1971), Hormann (1974), Sharma (1975), Fort and Freytet (1979, 1982), Akiba (1980), and Yamanaka *et al.* (1982), and maps are presented in Gurung

(1970), Dollfuss and Usselman (1971), Sharma *et al.* (1978), Fort and Freytet (1982), and Yamanaka *et al.* (1982).

The calcareous gravelly conglomerates which form the majority of the basin deposits have a well defined geological origin (mainly Nilgiri and Larjung limestones (Fort and Freytet 1982) which presently crop out at the summit of Annapurna Himal (Bordet *et al.* 1971). Two deposits, the Pokhara and Ghachok Formations, have volumes estimated to be 5.5 km^3 and >8.7 km^3 respectively (Yamanaka *et al.* 1982). It is generally agreed that they were transported to the basin by intense and rapid re-working of morainic materials, possibly associated with the failure of a glacial or landslide dam (B. Carson, pers. comm.). The rapidity of the aggradation process resulted in the damming of valleys adjacent to the basin (Gurung 1970), causing the development of small lakes (Phewa Tal, Begnas Tal, Rupakot Tal). This may have occurred at least twice during the late to middle Quaternary (Yamanaka *et al.* 1982). The most recent aggradation, which created the Pokhara Formation, is thought to be Holocene, and radiocarbon dating indicates ages of 1100 to 500 years B.P. (Yamanaka 1982; M. Fort pers. comm.). Such a recent event is within the reach of oral history, and a local guidebook does indeed recall a "lost city" under Phewa Tal (B. Carson, pers. comm.). Currently the Seti Khola is in an erosional phase and has cut a channel to bedrock in some locations in the Pokhara valley. There is evidence of continued tectonic movement, with the whole basin tilting to the south (Yamanaka *et al.* 1982).

2.2.2 THE PHEWA VALLEY

The geology of the Phewa valley has been described briefly by Mulder (1978a) and Fleming (1978). Fleming's account is largely based on the work of Remy (1975) who mapped the geology of western Nepal at a scale of 1:506,880. The watershed area has been mapped more recently by the Land Resource Mapping Project (L.R.M.P.) at a scale of 1:125,000 and appears on geology sheet No. 62 P–D (Topographical Survey Branch 1984a).

The Phewa catchment (Figure 5) is underlain by two lithologic units with a general east–west strike and a moderate (15^0 – 30^0) dip to the southwest. The northern part of the catchment is formed in grey phyllitic schist or phyllite consisting mainly of micas and chlorites which form the high ground of the Kaski ridge. The phyllites are weakly bedded, low grade metamorphic rocks which dip to the south at approximately the same angle as the topography. The southern part of the catchment consists of talc–rich, red phyllitic schist (Mulder 1978a) and quartzose or carbonaceous schist of a higher metamorphic grade (biotite) than that to the north (Fleming 1978). Bedding structures are moderately strong, and dip is again generally to the southwest and into the slope. Quartzite schist crops out at the western end of the watershed, forming cliffs. Soft grey talc schist appears in several locations including the saddle of the Kaski ridge at Naudanda and in the valley of the Andheri Khola between Pamdur and Deorali. It consists of very small, weak platelets and is associated with active slope failures. A major fault (probably a continuation of the fault on the southern side of the Pokhara valley) runs through the centre of the watershed. In common with the rest of Nepal, numerous minor faults and local deformation are imposed on this macro–structure, causing zones of weakness which have been exploited by erosive forces such as the Andheri Khola (Figure 5).

2.3 TOPOGRAPHY

The elevation of the watershed varies from 790 m at Pardi Dam at the outlet to Phewa Tal lake to 2520 m at Panchase some 17 km away at the western end of

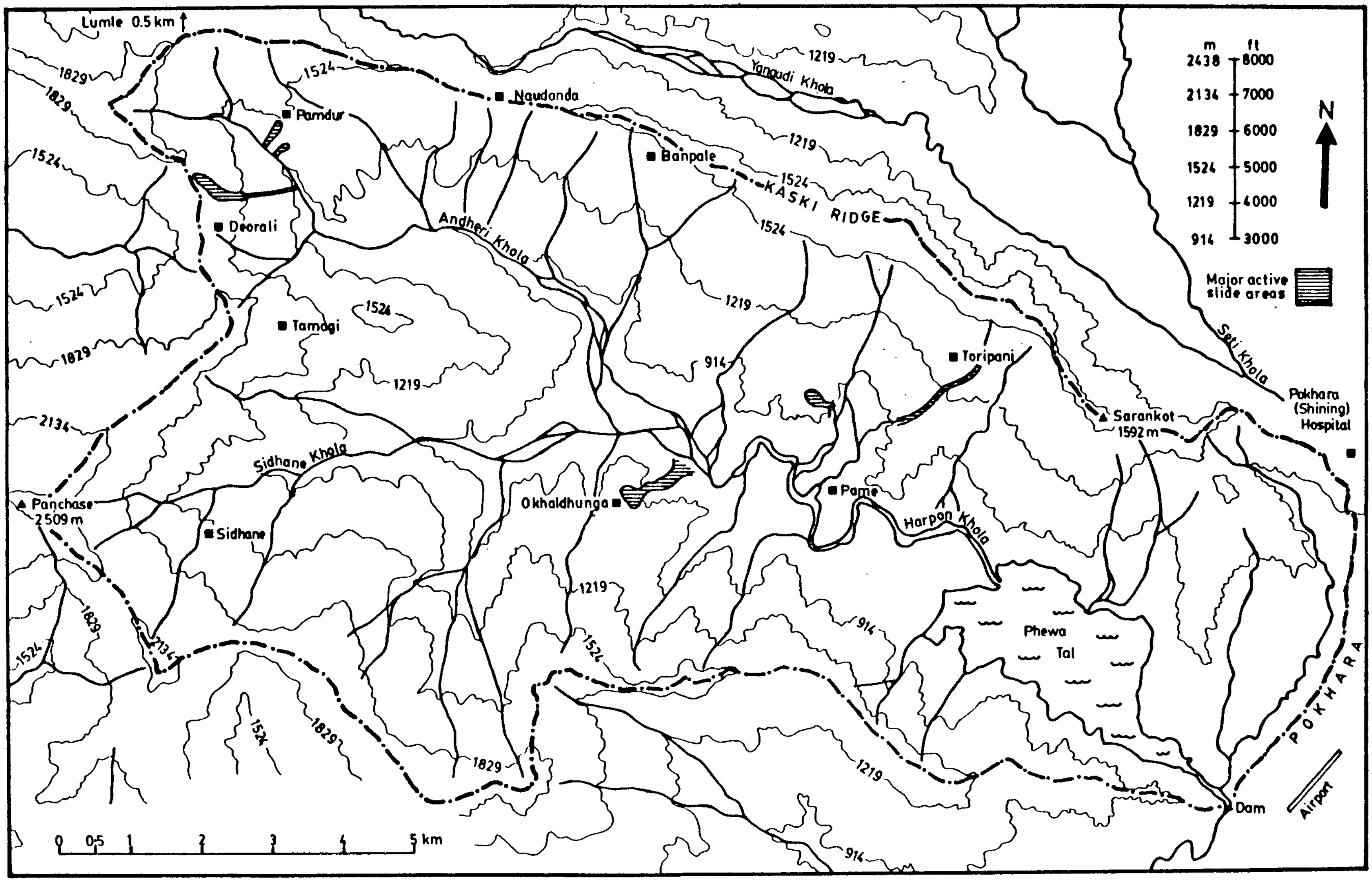

Figure 5. The Phewa Valley: sketch map showing places mentioned in the text.

the watershed. Slopes are generally steep to very steep, but with a virtually flat valley floor caused by sedimentation above the lake (Figure 6). Above this level of debris accumulation the tributary valleys are V-shaped with gentler slopes above, indicating rejuvenation. The topography is illustrated in Figure 7, a schematic cross-section of the central part of the watershed, and is readily visible in Figure 8, a stereopair of the same area. A summary description of the major landforms is given below (after Impat 1980):

(1) Scarp slopes: north aspect, gradients 60-120%, mainly forested, generally stable, little mass wasting.

(2) Toe slopes and spur ridges: mainly north aspect, gradients 30-100%, 60% forested, 20% cultivated, 20% grazing, some large landslides.

(3) Dip slopes: south aspect, generally plane surface conforming to bedrock dip but with marked erosion ampitheatres, gradients 30-60%, mostly cultivated, some grazing, forest on steeper slopes, high level or erosional activity including gullying, slumping and debris avalanches.

(4) Toe slopes: south aspect, gradients 30-60%, dissected slopes above colluvial accumulations, 60% cultivated, 30% grazing, 10% forest.

(5) Bottom lands: decrease in width towards headwaters, coalescing fan component radiating from side drainages at gradients of 5-10%, riverplain gradient 1-3%, all cultivated and subject to damage by meandering and sediment deposition.

A slope categories map is presented in Fleming (1978), and indicates that 60% of the watershed has slopes of between 11° and 31°, with an average of 22°. Slope categories are shown in Table 3.

2.4 CLIMATE

The climate of the study area is humid sub-tropical to humid temperate, with a dry season in the winter. Rainfall seasonality is due to the monsoonal conditions of the Indian sub-continent. Mean daily temperatures vary between 12.6° C in January and 25.1-25.2° C in July and August in Pokhara (elevation 827 m), and between 8.6° C in January and 19.8° C in July and August at Lumle (elevation 1675 m) (Figure

Figure 6. Phewa Valley: Harpon Khola near Pame. View to the south from Chankapur, pre-monsoon. Note intensive use of valley floor for rice cultivation.

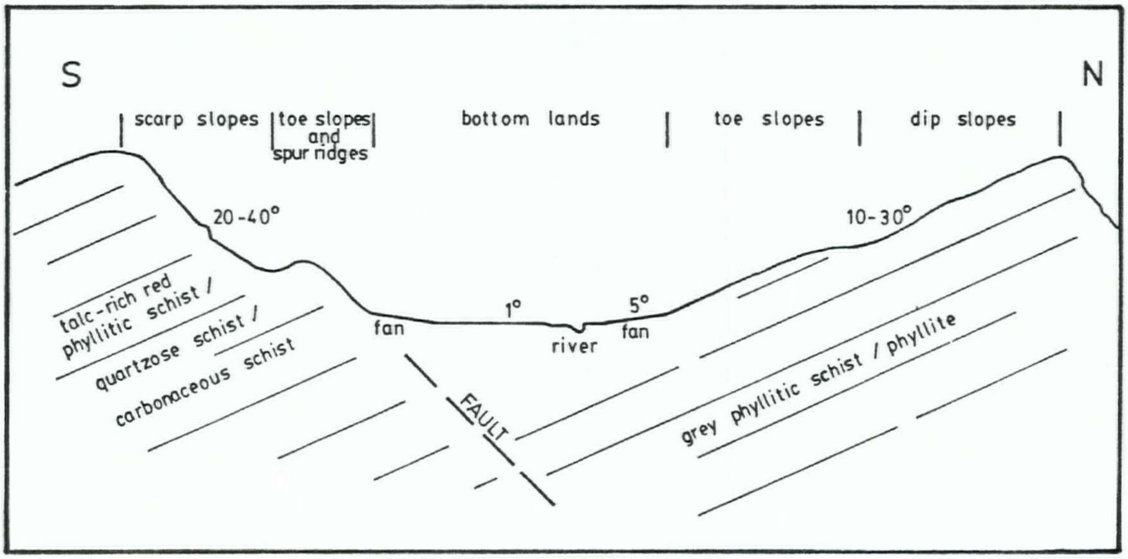

Figure 7. Schematic cross-section of Phewa Valley near Pame.

Figure 8. Stereogram of central part of the Phewa Valley. North at top.
Note:
(1) Steepness of topography: gullying at top.
(2) Mass movement catchments (arrowed).
(3) Valley floor; braided channel at left and meandering channel near lake.
(4) Delta growth in lake.
(5) Remaining forests on steeper slopes.

Table 3. *Slope categories of the Phewa Tal catchment*[1].

Slope (%)	(degrees)	Area (% of total)
< 10	< 6	10.7
10–20	6–11	9.3
20–40	11–22	31.4
40–60	22–31	29.8
60–80	31–39	9.9
80–100	39–45	5.0
> 100	> 45	0.2
Lake		3.7

[1] Modified from: Fleming 1978, Fig. 2.3

9).[31] Some 85% of annual precipitation falls during the four monsoon months (June–September, Figure 9). Mean monthly rainfall for seven stations in the locality is shown in Table 4. Mean annual precipitation is elevation-dependent and varies from 3724 mm at Pokhara Airport to 5140 mm at Lumle (13 years record both stations). A regression of mean annual precipitation on elevation for the 7 stations gave the following relationship, significant at the 95% level (Figure 10):

$$\text{precipitation (mm)} = 2176 + 1.64 \text{ elevation (m)} \qquad (r=0.847)$$

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[31] Meteorological stations in the area are Pokhara Airport (No. 0804) and Lumle (No. 0814), both operated by the Department of Irrigation, Hydrology and Meteorology. Additionally, rainfall data is available for Pokhara Hospital (the Shining Hospital, not the new Gandaki Zonal Hospital), from 1967 to 1976 (no data for 1969, 1975); from Pokhara Agricultural Farm for 1978 and 1979; and from three stations in the Phewa watershed operated by the Department of Soil Conservation and Watershed Management: Toripani (elevation 1340 m) from 1977: daily gauge; Banpale (elevation 1405 m) from 1978: daily gauge and weekly recording gauge; and Tamagi (elevation 1615 m) from 1978: daily gauge and weekly recording gauge, moved to Sidane (elevation 1560 m) in 1982. In general raw meteorological data in the area is unreliable and requires interpretation and smoothing before analysis.

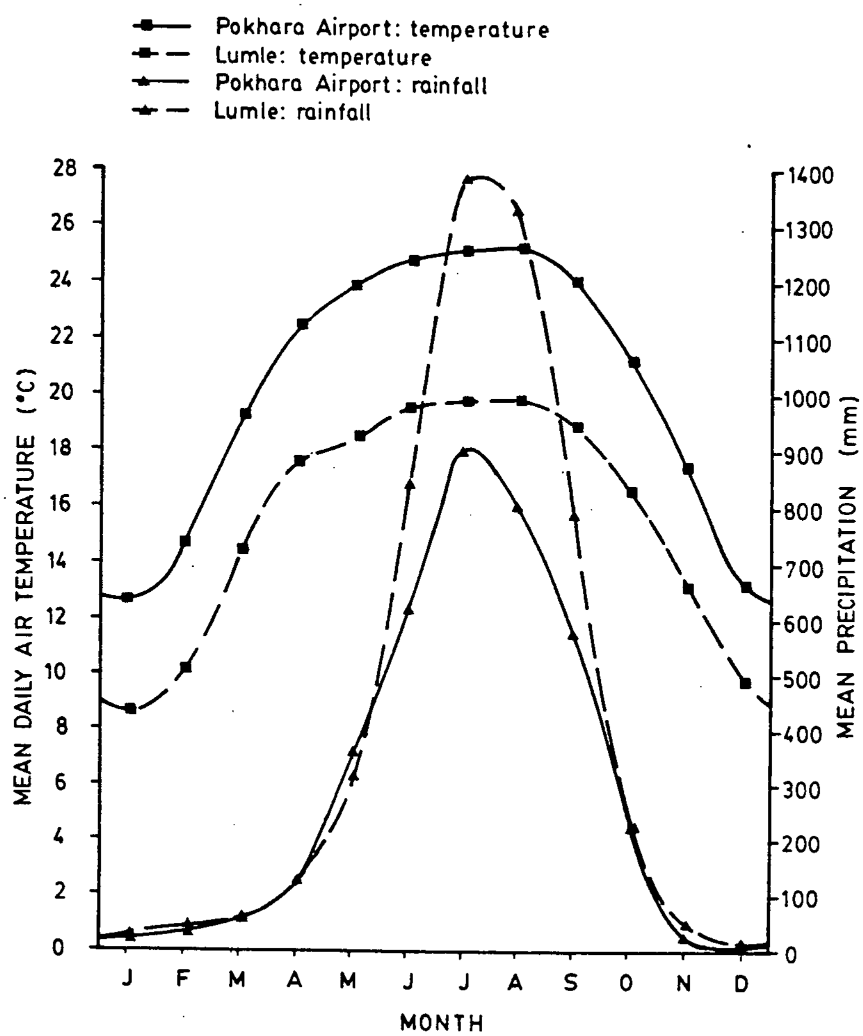

Figure 9. Temperature and rainfall regimes at Pokhara Airport and Lumle. Data from Department of Irrigation, Hydrology and Meteorology records.

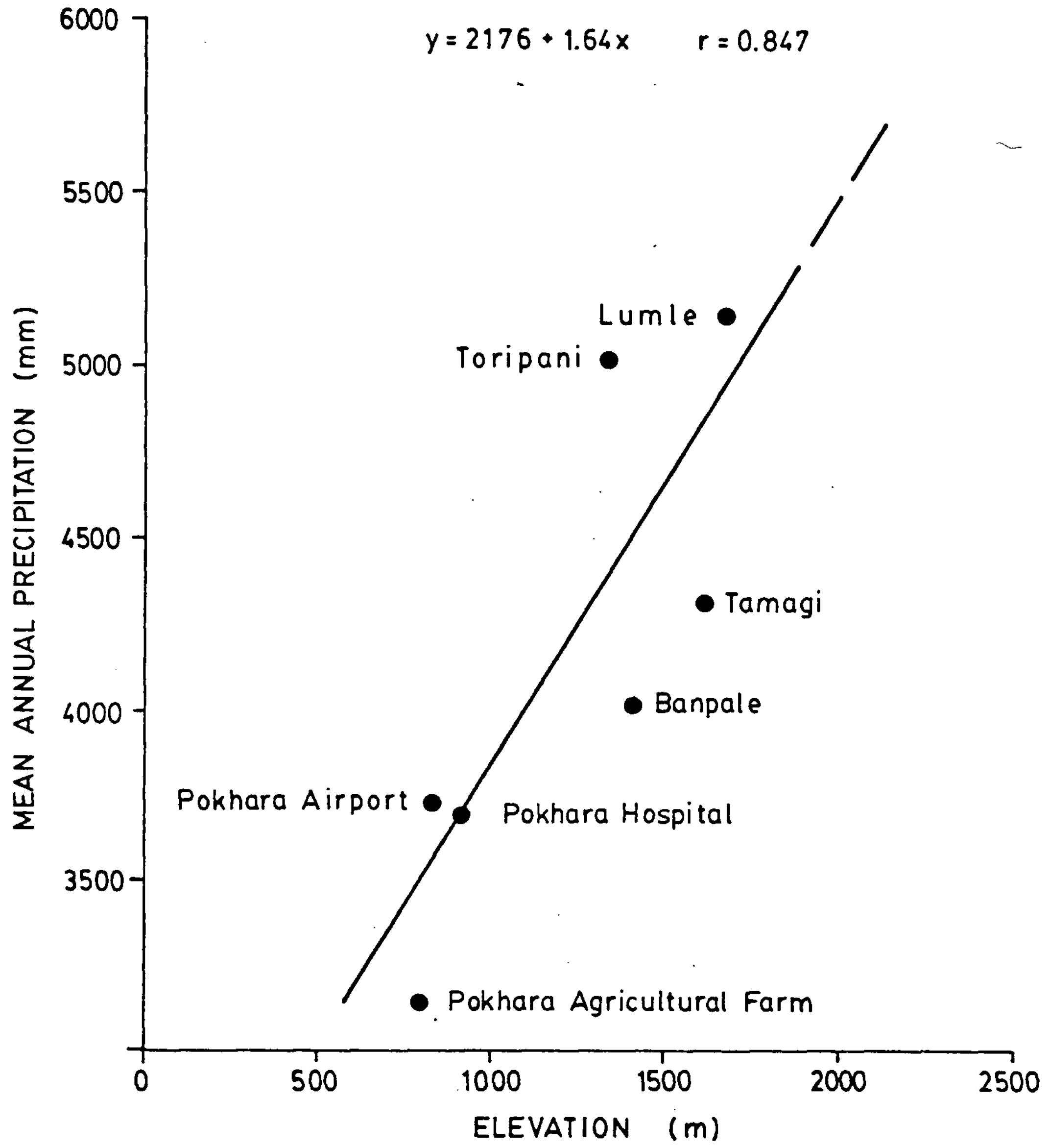

Figure 10. Regression of mean annual precipitation on elevation for 7 stations in and near the Phewa Watershed. Data from Table 4.

The mean annual precipitation for the whole watershed, calculated from this regression and a hypsometric curve[32], is 4202 mm. The area is one of the wettest in the country, with Lumle having the highest annual rainfall of any station in Nepal. This is probably due to the generally low elevation of the Middle Mountains lying between Pokhara, at the base of the Annapurna massif, and the Terai, thus allowing monsoonal air-masses to approach the High Himal unimpeded (Stainton 1972). The region does not appear to be affected by the winter (west) monsoon. All precipitation falls as rain, and frost is only recorded above about 1500 m.

The absolute maximum 24 hr precipitation officially recorded in the area is 278 mm at Pokhara Airport in August 1979, although there is a less reliable report of 279 mm in July 1980 from a daily gauge at Tamagi (elevation 1340 m) operated by the Department of Soil Conservation and Watershed Management. It is also reported that 233 mm fell in one and a half hours at Lumle in July 1974 (Wormald 1976a). A preliminary set of intensity-duration-frequency curves for Pokhara Airport based on 7-10 years of weekly recording gauge data is presented in Figure 11. The curves indicate 1 hour rainfall intensities of 64 mm, 78 mm, and 91 mm for, respectively, return periods of 2, 5, and 10 years. The 24 hour intensities are 168 mm, 234 mm, and 276 mm for the same return periods, with a tentative 312 mm suggested for the 25 year period. It is not known whether rainfall intensities increase with elevation in the locality, but, if they are related to the increase in annual precipitation with elevation, some very high intensity events can be expected in the upper parts of the catchment. The reported and predicted rainfall figures may be compared with the highest recorded 24 hour precipitation in Nepal, 505 mm at Gumthang, east-north-east of Kathmandu, on 25 August 1968 (Nayava 1974).

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[32] Plot of area against elevation. See Strahler (1952) for an application of hypsometric analysis to erosional topography.

Table 4. ***Mean monthly rainfall for 7 stations in the Pokhara area***

Station	Pokhara Agric. Farm[1]	Pokhara Airport[2]	Pokhara Hospital[3]	Toripani[4]	Banpale[5]	Tamagi[6]	Lumle[7]
Elevation (m)	792	827	918	1340	1405	1615	1675
Station Number		0804	0803				0814
Month							
Jan.	6	20	22	36	36	26	29
Feb.	33	31	25	60	47	20	42
Mar.	33	55	60	76	145	54	52
Apr.	119	116	106	124	68	107	121
May	295	352	306	352	307	394	293
June	364	620	764	704	679	638	830
July	590	908	955	1190	953	1442	1383
Aug.	1233	797	772	1365	883	981	1325
Sep.	236	573	588	761	588	446	784
Oct.	195	217	212	258	213	173	223
Nov.	7	23	21	39	76	19	50
Dec.	32	12	3	44	21	7	8
TOTAL	3143	3724	3834 (3578, 3689)[8]	5009	4016	4307	5140

[1] Pokhara Agricultural Farm: 2 years record: 1978–1979.

[2] Pokhara Airport: 13 years record: 1968–1980.

[3] Pokhara Hospital (the Shining Hospital): 8 years record: 1967–1976 (no data for 1969, 1975).

[4] Toripani: 5 to 6 years record: 1977–1983.

[5] Banpale: 1 to 5 years record: 1978–1983.

[6] Tamagi: 3 to 5 years record: 1978–1982.

[7] Lumle: 13 years record: 1970–1982 (Note: Data supplied directly from Lumle Agriculture Centre does not correspond with data for Lumle supplied by the Dept. of Irrigation, Hydrology and Meteorology in all months).

[8] Pokhara Hospital: mean annual rainfall given as 3578 mm based on 18 years record (Water and Energy Commission 1982), and 3689 mm based on 19 years record from 1958–1976, but with 1966, 1969 and 1975 missing (Impat, pers. comm.). This last figure was chosen for the regression analysis of elevation and precipitation (Figure 8).

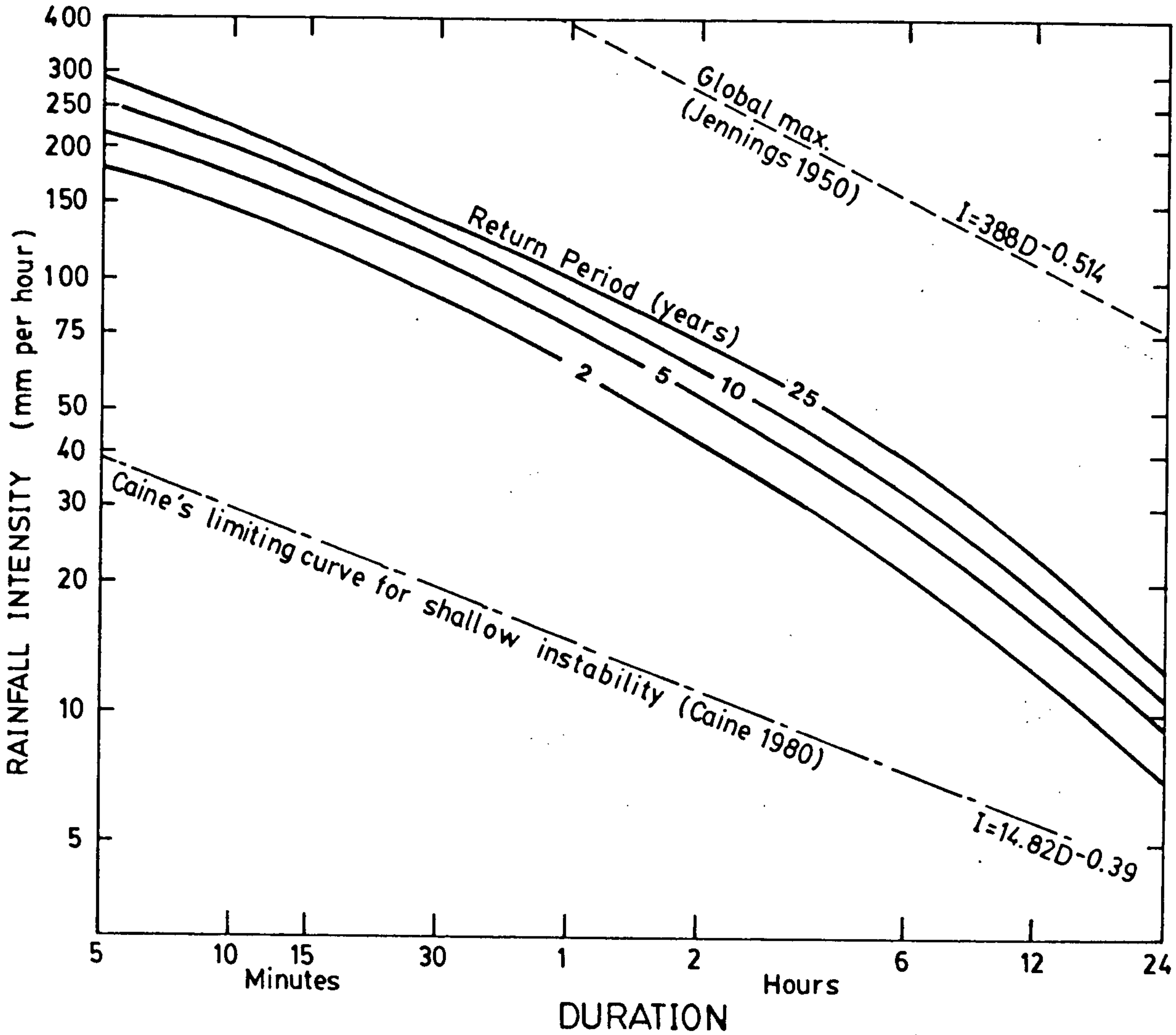

Figure 11. Preliminary intensity–duration–frequency curves for Pokhara Airport based on 7–10 years of data.

Relative humidity, sunshine duration, and Class A pan evaporation data are available for both Pokhara and Lumle, but many observations are missing. Shah (1980) presented figures on solar radiation and "equilibrium potential evaporation" for Pokhara. Potential evaporation exceeds precipitation from November to March and under natural conditions very little moisture is available for plant growth (Shah 1980). Wind run is recorded at Lumle.

2.5 WEATHERING AND SOILS

The climate of the Phewa Valley puts it well into the zone of "intense chemical weathering" described by the Land Resource Mapping Project (L.R.M.P. 1983, after Peltier 1950). The underlying phyllites tend to weather rapidly where water can penetrate joints and bedding planes, forming fine-textured saprolite with a high proportion of illite clays (Brian Carson, pers. comm.). Soils developed on phyllites tend to be reddish, have strong clay accumulation in the subsoil, are mildly acidic, moderately fine-textured, and non-stony (L.R.M.P. 1983). The quartzites and schists tend to be more resistant and result in coarser debris and shallower soils. The rapid removal of weathering products by solution and erosion allows weathering to proceed uninhibited (Ollier 1984)[33].

The intensity of erosional processes means that soil development is largely an expression of stability and position in the landscape with horizonation and structure developing best in the most stable locations. Untransported regolith thicknesses are generally less than 3m, but may be much more locally, especially around faults. Colluvial deposits can exceed 15 m in depth, as at the entrance to the mass movement catchment near Pame, and it is possible that "wedges" or hollows in the bedrock filled with colluvium may be present. Such wedges have been implicated in

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[33] Strakhov's (1967) concept of erosion suppressing weathering does not seem appropriate in this environment.

slope failure in mid-latitude environments such as the west coast of North America (see, e.g., Dietrich *et al.* 1982).

The soils in the valley have been surveyed and described at 1:50,000 by Mulder (1978a) and the Land Resource Mapping Project (Topographic Survey Branch 1984b), and at 1:25,000 by Impat (1980)[34]. The majority of the watershed falls into the bedrock controlled unit (no. 12) of the L.R.M.P.: steeply to very steeply sloping mountainous terrain with dominant slopes >30°, loamy skeletal texture[35], well drained, and <50 cm to bedrock (Figure 12). Soil development is better expressed in unit 11, mainly found on the more stable upper slopes on the north side of the valley: moderately to steeply sloping mountainous terrain, dominant slopes <30°, loamy skeletal texture, moderately well to well drained, and 50 cm to 1 m to bedrock. The alluvial valley floor and fans with slopes of <5° (unit 9) tend to be extremely stony with dominant textures varying from fragmental sandy to loamy/bouldery (L.R.M.P. 1983).

Soil pH is generally low, about 5.1–5.5 (Impat 1980[36]), decreasing to 4 on the valley floor where ammonium-sulphate fertilizers have been used (Shah 1980, citing Van de Putte 1979). This is sufficiently low to reduce nutrient availability, although under the anaerobic conditions of paddy rice production pH may rise to 6.5, obviating any availability problem (L.R.M.P. 1983). Although the cation exchange capacities of soil minerals in the area can be appreciable (e.g. illite, which may have values of 10–40 meq/100 g), cation exchange capacities in the soil are also low, approximately 10 meq/100 g. The low organic matter content of cultivated soils, typically 1.5–2% in

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[34] Mulder (1978a) carried out a reconnaissance survey of the northern part of the catchment; Impat (1980) extended Mulder's survey to include the southern part of the watershed. His map shows soil units differentiated by parent material, depth class, slope class, and runoff class, rather than by soil series or subgroup. The recent L.R.M.P. survey covered most the country. Recognizing the extreme spatial variability of soils in Nepal their legend (Figure 12) is based on repeating landscape units.

[35] Rock fragments make up 35% or more by volume; enough fine earth to fill interstices >1 mm; the fraction finer than 2 mm is loamy as defined for the loamy particle size class (Soil Survey Staff 1975).

[36] pH measurement method not stated.

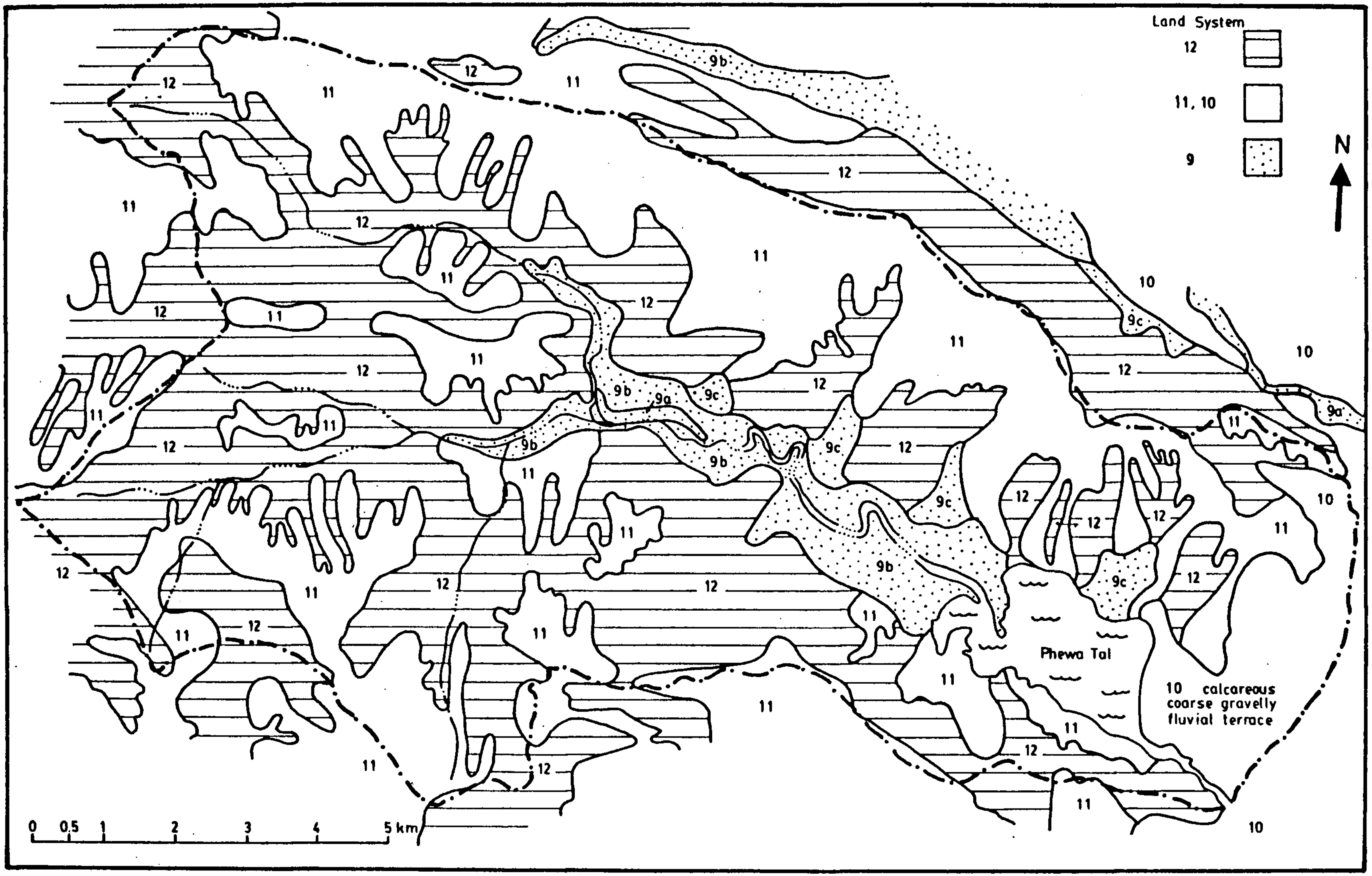

Figure 12. Land systems of the Phewa Valley. Legend overleaf. After: Topographical Survey Branch (1984b).

Land Systems Legend

MIDDLE MOUNTAIN REGION	Precambrian to Eocene phyllites, quartzites, schists, limestones, and gneisses, generally deeply weathered. Subtropical to Warm Temperate.						
Land System	Landform	Land Unit	Dominant Soils	Dominant Slopes (deg)	Dominant Texture	Seasonal Range of Depth to Watertable	Drainage
9	Alluvial Plains and Fans (depositional)	9a river channel	Psamments Ustorthents	<1	Fragmental Sandy	0-2 m	variable
		9b alluvial plains	Ustifluvents Fluvaquents Ustachrepts	<1	Loamy/ Bouldery	0-2 m	well
		9c alluvial fans	Ustachrepts Haplustalfs	1-5	Loamy/ Bouldery	1-15 m	well
10	Ancient lake and River Terraces (Tars)		Typic & Rhodic Haplustalfs Ustochrepts	0-5	Loamy	>2 m	well
11	Moderately to Steeply Sloping Mountainous Terrain		Typic, Rhodic Udic, Anthropic Subgroups of Ustochrepts Dystrochrepts Haplumbrepts	<30	Loamy/ Skeletal	>50cm to bedrock	moderately well to well
12	Steeply to Very Steeply Sloping Mountainous Terrain		Lithic Subgroups of Il and Ustorthents	>30	Loamy/ Skeletal	<50cm to bedrock	well

the plough layer, and the presence of large amounts of coarse material, reduces the contribution to overall cation exchange capacity which these minerals can make (S. Burton, pers. comm.). Organic matter content reflects land use, decreasing rapidly following forest clearance.

2.6 VEGETATION

The vegetation associations of the country south of Annapurna and Himal Chuli have been described by Stainton (1972, pp. 32–34), and a climax or potential vegetation map of the area at a scale of 1:250,000 has been produced by Dobremez and Jest (1974). Although now much modified by man, remnants of the original forest cover of the Phewa valley remain, and indicate that from 850 to 1500 m elevation (most of the catchment) a subtropical wet forest composed of *Schima wallichii* (Nep. *chilaune*) and *Castanopsis indica* (Nep. *katus*) would have predominated, with Sal (*Shorea robusta*) on dry southern exposures at low elevations; above 1500 m a lower temperate mixed broadleaved association including *Michelia–Lauraceae–Lithocarpus* would have existed with *Quercus* associations above about 2000 m. Alder, (*Alnus nepalensis*), is common on moist, disturbed sites. An annotated checklist of plants in the area has been provided by Wormald (1976b).

Within the watershed the most detailed observations of forest characteristics have been made by Levenson (1979), in the course of a study on fuelwood utilization. One of Levenson's most interesting comments is that many of today's dominant species were components of the understorey when Stainton made his observations in the 1950's and 1960's.[37] Both Stainton (1972) and Dobremez and Jest (1974) emphasize the *Schima wallichii/Castanopsis indica* forest as being the climax in the area, but Levenson (1979) postulated a "disturbance secondary type species association" comprised mainly of

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[37] In this area, 1954, 1963, 1966, 1967 (Stainton 1972).

Daphnephyllum himalayense (Nep. *chandan*) and *Symplocos ramosissima*. The gradual degradation of the forest in the valley has recently been confirmed by the Land Resource Mapping Project: although a large proportion of the watershed is shown as being forested (Figure 13), the legend of the L.R.M.P. maps indicates that virtually all stands are composed of "immature or small size timber material", with crown densities of 40%–70% (Topographical Survey Branch 1984c). Most forest stands are surrounded by a leech-infested belt of lopped trees, shrubs, and scrub. It is possible that the forests on the Kaski ridge were burnt for military purposes several centuries ago (J.B. McDonald, pers. comm.).

Forest biomass production in the area has been estimated at 12.5 m^3/yr in Bhadaure panchayat[38] by Levenson, based on plot measurements and taking into account species composition, differences in wood specific gravity (averaged at 0.517 g/cm^3), stocking rate, and village preference for fuelwood species, and assuming that all species follow a growth pattern similar to that of *Daphne himalayense* (linear after 14.3 years of age) (Levenson 1979). Wormald (1976c) estimated that the mean annual increment for presently unmanaged woodland around Lumle Agriculture Centre was 15–20 m^3/yr, and could be raised to 25–30 m^3/yr by management. Yields of leaf material for use as fodder are uncertain. Farm surveys indicate approximately 39–150 kg/tree/yr (fresh weight) according to species (Shah 1980)[39]. Preferred fodder trees are *Artocarpus lakoocha* (Nep. *badhar*), *Ficus nemoralis* (Nep. *dudhilo*), and *Ficus glaberrima* (Nep. *pakhuri*), although some 35 other species are also used (Shah 1980).

Indigenous grass species are mainly subtropical, and include *Chrysopogon articulatus, Dicanthium* spp., *Bothriochloa intermedia, B. pertusa, Themedia anathera, Chrysopogon montanus, Andropogon pumilus, Imperata orlindrica, Sporobolus* spp., *Setaria*

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[38] Administrative area at western end of the Phewa watershed with a population of between 4000 and 5000 and an area of approximately 2000 ha.

[39] Fodder tree utilization and management are discussed extensively in Shah (1980), and in the annual reports of Lumle Agriculture Centre.

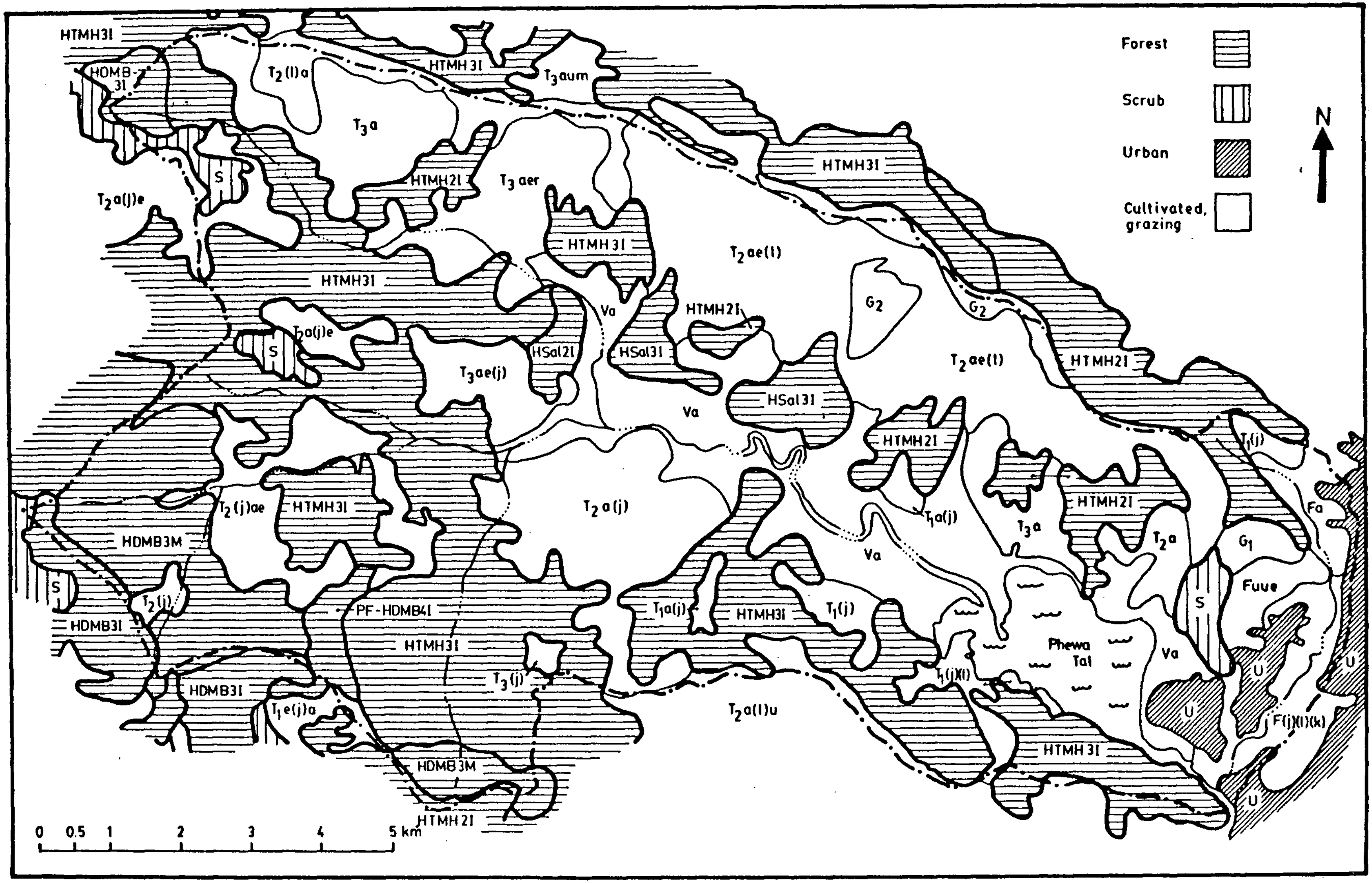

Figure 13. Forest cover and land use in the Phewa Valley. Legend overleaf. After: Topographical Survey Branch (1984c).

Forestry Legend

COVER TYPE

H Hardwood - 75% or more of tree species are hardwoods

S Shrub; shrub vegetation which may include hardwood regeneration

SPECIES TYPE

Tropical Types	Temperate Type
Sal - Shorea robusta	DMB - Deciduous mixed broad leaved
TMH - Tropical mixed hardwoods	

CONDITION TYPE

PF - Protection Forest - forests with management problems due to site fragility

CROWN DENSITY

Expressed as a percentage of the area covered

2. 10-40%
3. 40-70%
4. >70%

MATURITY CLASS

M - Mature to overmature trees have reached at least estimated rotation age or saw timber size

I - Immature or small timber size material

TYPE LEGEND SAMPLE

HTMH3I - Hardwood
Tropical mixed hardwoods
40-70% crown density
Immature

Land Use Legend

VALLEY CULTIVATION

Valley Floors including Tars, Footslopes and/or Alluvial Fans which are too small to map	V
Tars, Alluvial Fans and/or Lower Footslopes	F

GRAZING LANDS		G	NON AGRICULTURAL LANDS	
Sub-Tropical Zone	<1000m	1	Lake	L
Warm Temperate Zone	1000m - 2000m	2	Urban	U

DOMINANT CROPPING PATTERNS

MONSOON SEASON	WINTER/DRY SEASON	
Rice	Fallow	a
Rice	Cereal	e
Maize-Rice	Fallow	u
Maize-Rice	Winter crop	r
Maize or Millet	Fallow	j
Maize	Mustard	k
Maize	Cereal	l
Mixed		m

Double monsoon crop in brackets (.)

TYPE LEGEND SAMPLE

T2ae(r) Level terraces
50-75% cultivated
Rice/Fallow, Rice/Cereal, Maize/Rice
double cropped before winter crop

HILLSLOPE CULTIVATION

Level Terraces		T
Intense:	75-100% cultivated	3
Medium:	50-75% cultivated	2
Light:	25-50% cultivated	1

glauca, Heteropogon contortus, Digitaria spp., *Axonopus affinis,* and *Paspalum* spp. (Shah 1980). Legumes are rare, although some species of *Desmodium* occur in moister areas.

The botanical composition and productivity of the sward are severely affected by grazing pressure. In protected areas bunch type grasses such as *Andropogon, Themeda* and the *Chrysopogon* group survive, but in heavily grazed areas *Imperata* and *Artemisia* spp. are spreading (Shah 1980), with bracken, *Pteridium aquilinum,* increasing in areas of scrub. The effect of enclosure on pasture productivity is marked. Several areas of overgrazed land in the watershed have been fenced off for trials by the Department of Soil Conservation and Watershed Management, and in these paddocks pasture yields are estimated to have increased from 1.2 t/ha/yr to 4.1 t/ha/yr (fresh weight) (Shah 1980), simply due to the exclusion of livestock.

2.7 LAND USE

In the Kathmandu area Nepalis recognize six major land use types: *khet* (irrigated terrace); *bari* and *pakho-bari* (rainfed terrace); *bhir* (land too steep, rocky or barren to be cultivated); *charan* (grazing land); *ban* (forest); and *gaun* (settlement) (Johnson *et al.* 1982; B. Carson, pers. comm.). Land utilization in the Phewa watershed follows much the same pattern, with the inclusion of *kharbari,* privately owned fenced pasture used mainly for thatching grass. Land use in the watershed has been mapped several times[40], and use categories as interpreted by Fleming (1978) are shown in Table 5. Land use interpreted from the same photos by the Land Resource Mapping Project is shown in Figure 13. It should be noted that this drawing gives an inadequate impression of the extent of grazing land in the catchment, which is largely

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[40] By J. Kraayenhagen and co-workers, based on 1:15,000 scale air photos taken in 1972 and on cadastral maps, and reported in Section 5.5 of the Management Plan for the Integrated Development of Phewa Tal Watershed (Anon. 1980); by Impat (1980), based on 1:25,000 scale air photos taken in 1978 for Lumle Agriculture centre; and by Fleming (1978) and the Land Resource Mapping Project (Topographical Survey Branch 1984c) from 1:50,000 scale air photos also taken in 1978.

Table 5. *Land use categories in the Phewa Tal catchment*[1]

Land use	Area (ha)	% total area
Forest	2935	25.9
Scrub	1070	9.4
Cultivated	5410	47.7
Open grazing	1193	10.5
Enclosed pasture	71	0.6
Water	428	3.8
Gullies/landslides	73	0.7
Townsite	156	1.4
Total	11,336	100

[1] Source: Fleming 1978

in parcels too small to be included in the generalized L.R.M.P. map. Fleming's figures indicate that just under half the watershed is cultivated, about a quarter is still in forest[41], and scrub and open grazing[42] account for most of the remainder. Agriculture predominates on the south-aspect slopes on the north side of the valley. The remaining forest is largely on the southern side of the watershed where slopes are too steep to allow successful terracing. Most of the grazing land is in the northern and western parts of the watershed on slopes averaging 22° (Fleming 1978).

2.8 THE AGROECOSYSTEM

The Middle Mountains of Nepal support a mixed farming system with settled agriculture predominating between 1000 and 2000 m. Livestock are crucial to this system, providing manure, draught power (cattle), food for domestic consumption (buffalo milk, meat from sheep, goats, pigs, poultry), products for off-farm sales

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[41] Forest names are given in Levenson (1979, Fig. 1).
[42] Names of grazing areas are given in Shah (1980, Table 5.10).

(mainly *ghee*, clarified buffalo butter), and are also essential for some religious ceremonies. The principal crops are paddy rice (*Oryza sativa* var. *indica*), wheat (*Triticum vulgare*), maize (*Zea mays*), and finger millet (*Eleusine coracana*). At lower elevations high temperatures and irrigation allow double cropping, but at higher elevations this is limited by lower temperatures, greater cloudiness, and water shortages. A simplified schematic model of a Nepalese hill farming agroecosystem showing the main energy and nutrient pathways is presented in Figure 14.

Agriculture in the Phewa valley has been the subject of intensive scrutiny by the Hill Agriculture Development Project (Ministry of Agriculture/FAO/UNDP), and an introduction is available in Van de Putte (1979), Scoullar (1980), and Shah (1980). The total population of the valley is about 35,000, increasing at approximately 2% p.a. Family size is typically 5–6. Population density and landholding per household average 288 inhabitants/km^2 and <1 ha, respectively (Shah 1980), but are not evenly distributed. Poulation density in Dhikur Pokhari panchayat on the Kaski ridge is given as 364/km^2 in Fleming (1978), and only 13% of the farmers own 48% of the *khet* (Scoullar 1980). About 19,000 large ruminants (cattle and buffalo) subsist on some 2000 ha of scrub and grazing land, but their productivity is low, with a pronounced negative trend in production parameters (Shah 1980). Forage cultivation is non-existent, largely due to shortcomings in the extension system - farmers do not know about forage cultivation possibilities (Shah 1980). They are generally aware of the practice of double-cropping *khet* with winter wheat, but enumerate constraints such as lack of irrigation water, uncontrolled grazing, and (most importantly), a shortage of compost for the crop and consequently a possible adverse effect on subsequent rice yields.

Despite the grazing problem, farmers in the valley sometimes cite insufficient livestock as being a primary constraint preventing increases in agricultural production, as in Pumdi Bhumdi Panchayat, Phewa watershed (Shah 1980). This is related to the

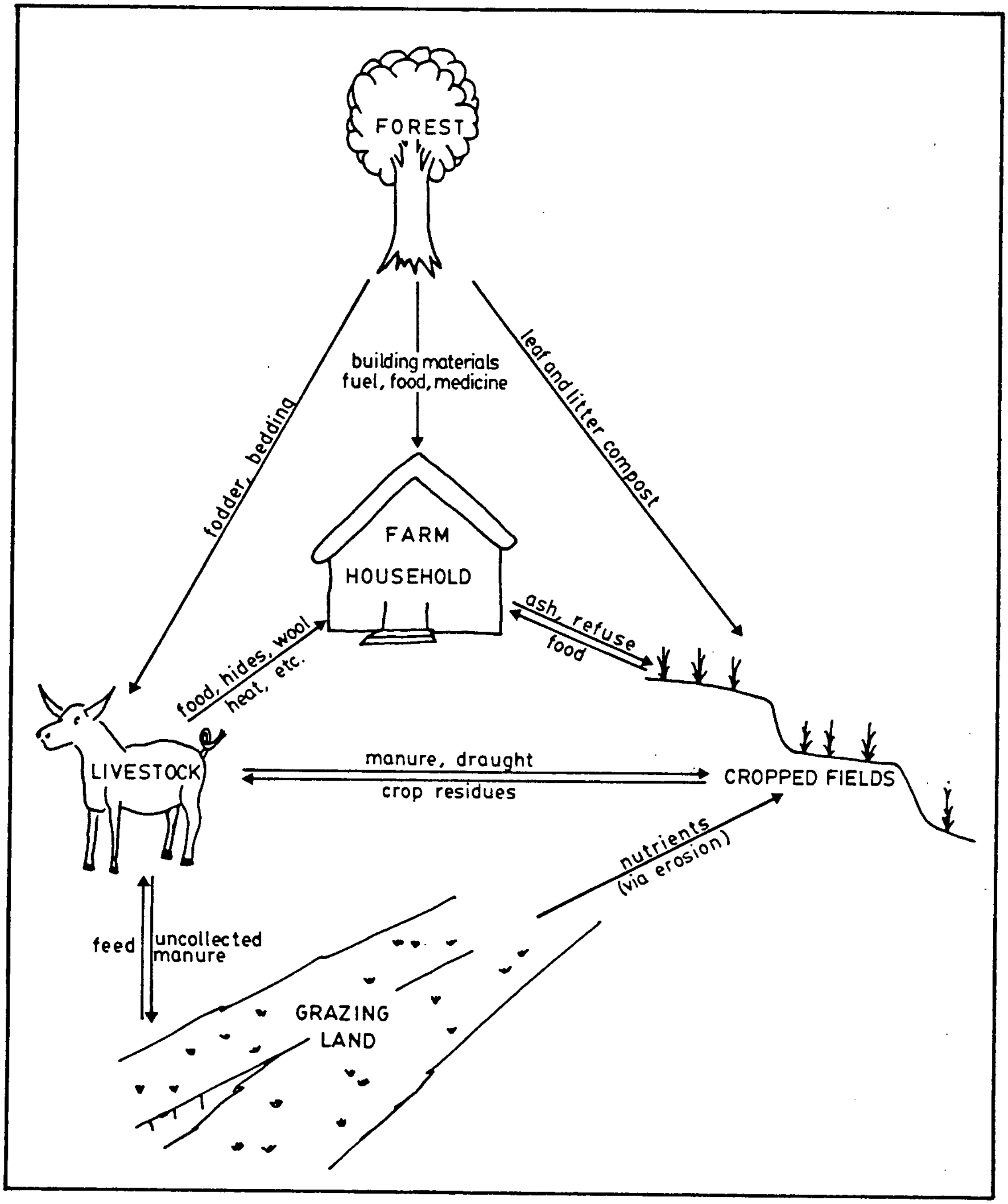

Figure 14. Simplified schematic model of a Nepalese hill farming system. Modified from: L.R.M.P. (1983).

gross inadequacy of fodder resources (crop residues, weeds, grasses from terrace risers, fodder trees, leaves and litter from the forest, and least importantly, communal grazing areas), graphically described by Shah (1980, p. 45): livestock "are in a semi-starved condition for 6 months (November-April)". In the Phewa valley crop residues now provide 73% of total feed (Shah 1980), but this does not lessen the pressure on the forests caused by fodder collection and grazing.

The watershed is unusual in some respects, with the town of Pokhara nearby providing a market for commodities such as milk (some 500 t/yr (Shah 1980)), and tourism injecting cash to hoteliers and tea-shop owners in villages along the trekking routes. Another form of cash subsidy is the remittances of mercenaries recruited from amongst the Gurung communities at the western end of the valley. Although often spent on "luxury" consumption (weddings, furniture, travel etc.), such capital does allow its beneficiaries to experiment with new farming techniques and commercial ventures, risks which the majority of the population cannot afford to take in case they fail. The effect of population pressure and socio-economic differentiation can be seen in Figure 15, which shows a hillside near Tamagi at the western end of the watershed. Here, a low-caste community is forced to live on a slope acknowledged to be liable to catastrophic failure at some unknown date; there is nowhere else for them to go if they are to maintain a settled existence with some guarantee of family unity and economic survival. A penetrating study of rural life in the area is available in MacFarlane (1976), and a sobering analysis of the interaction of economic and political forces in Nepal, and their consequences for the individual, has been made by Blaikie *et al.* (1980).[43]

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[43] For further anthropological studies of communities in central Nepal see, e.g., Jones and Jones (1976); Messerschmidt (1976); Hitchcock (1980); Coburn (1982). A description of historical and political trends in Nepal can be found in Rose and Scholz (1980).

Figure 15. Hillside near Tamagi, Phewa Valley.
Note:
(1) Reclamation of old landslide scar to *bari.*
(2) Human occupancy of failure-prone slope in background by low-caste community.
(3) Degradation of forest to scrub on hilltop.

Physically, this agroecosystem is totally dependent on indigenous sources of energy and nutrients. As elsewhere in the country, chemical fertilizers have yet to become a major source of inputs to the farming system in the watershed, and so gains are limited to nitrogen fixation, weathering, inputs in runoff and irrigation water from upslope, and inputs in precipitation and through the trapping of wind-borne dust, aerosols and gases on plant surfaces (the "filtering effect")[44]. Losses include soil erosion, leaching, volatilization from manure and compost, and export in cash crops. The role of the forest is largely that of a nutrient capture facility, with nutrients "cascading" from the forests on the upper slopes through farm households and out onto *bari* terraces as compost, from where runoff carries them down to the *khet* below. This link was implicitly recognized as long ago as 1823–24 by Bishop Reginald Heber, who travelled through northern India and observed:

> "Great devastations are generally made in these woods, partly by the increase of population, building, and agriculture, partly by the wasteful habits of travellers, who cut down multitudes of young trees to make temporary huts, and for fuel, while the cattle and goats which browse on the mountains prevent a great part of the seedlings from rising. Unless some precautions are taken the inhabited parts of Kemaoon will soon be wretchedly bare of wood, and the country, already too arid, will not only lose its beauty, but its small space of fertility." (Heber 1849).

To date no quantitative study of this nutrient pathway has appeared in the literature on Nepal, although fertility management is discussed in L.R.M.P. (1983).

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[44] Recent studies from middle and northern latitudes have indicated that precipitation and airborne nutrient capture can together supply forests with their total nutrient requirement over a rotation (see e.g. Tamm 1979, Miller 1984 for discussion). It is interesting to speculate on the relative importance of these sources in the sub-tropics where weathering is faster. An introduction to biogeochemical cycling in tropical forest ecosystems can be found in Anon. (1978).

Chapter 3

MASS MOVEMENT IN THE PHEWA VALLEY

3.1 INTRODUCTION

Owing to the importance of Phewa Tal as a tourist attraction, and to the relative accessibility of the northern part of the watershed at the start of a major Himalayan trade and recreational route[45], the Phewa valley has been the subject of considerable attention by national and international development agencies. The principal objective of this attention has been to reduce the rate of environmental degradation in the catchment through integrated development, and thereby to protect Phewa Tal from siltation and eutrophication. As is common in many development projects the government and aid technicians involved have tended to become enmeshed in the welter of detail of project design and implementation, and so have not been able to devote much time to strategic studies of the natural processes which they are trying to modify. Chief amongst these processes is erosion. Despite being a major stated concern of many of the agencies involved, rates of erosion and sedimentation in the catchment have not been systematically surveyed. Current knowledge of erosion processes and rates in the watershed is based on:

(i) the erosion plot studies of Mulder (1978) and Impat (1981) discussed in Chapter 2;

(ii) suspended sediment sampling of the Harpon Khola near Pame above Phewa Tal in 1979 (Impat 1981), discussed in Chapter 4;

(iii) bathymetric surveys of the lake carried out in 1976 and 1979, again discussed in Chapter 4;

(iv) an assumed correspondence between erosion rates and a simplified mass balance analysis of the phosphorus dynamics of the lake and watershed made by Fleming (1978, republished as Fleming 1983); see Chapter 4.

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[45] Trans-Himalayan trade along the Kali Gandaki valley, and trekking routes round the Annapurna massif.

The presence of the lake, which acts as a sediment trap, makes the Phewa valley one of the few sites in Nepal where estimates of erosional activity on the hillslopes can be verified by comparison with sediment deposition downstream. Despite this advantage, no work has been done on either mass wasting or fluvial activity in the watershed. As well as being highly visible sources of sediment input to the valley bottom fluvial system (Figure 8), these processes are also hazards well known to the inhabitants of the area.

In May 1983 a reconnaissance survey of mass movement activity in the watershed was carried out, with the objective of identifying the dominant hillslope processes and their controlling mechanisms. Several of the larger failures had been investigated informally during the previous year in connection with erosion control activities in the watershed.

3.2 METHODS

3.2.1 AERIAL PHOTOGRAPHY

Aerial photography is important in allowing the rapid assessment of erosional landforms and, if sequential cover is available, facilitates the investigation of landscape change over time. Vertical air-photo coverage of the Phewa Valley exists from:

(i) January 1958: full cover, 1:40,000, flown for the Survey of India as a base for the 1:63,360 maps series;

(ii) post-monsoon 1972: partial cover (Figure 15), approx. 1:15,000, probably flown by the Air Map Company of Italy for Pokhara Town Planning Department;

(iii) March 1978: full cover, 1:50,000, flown for the Land Resource Mapping Project and available from the Topographical Survey Department, Kathmandu;

(iv) November/December 1978: partial cover (Figure 16), approx. 1:25,000, flown by Huntings Surveys for Lumle Agriculture Centre; negatives now with Topographical Survey Branch, Kathmandu.

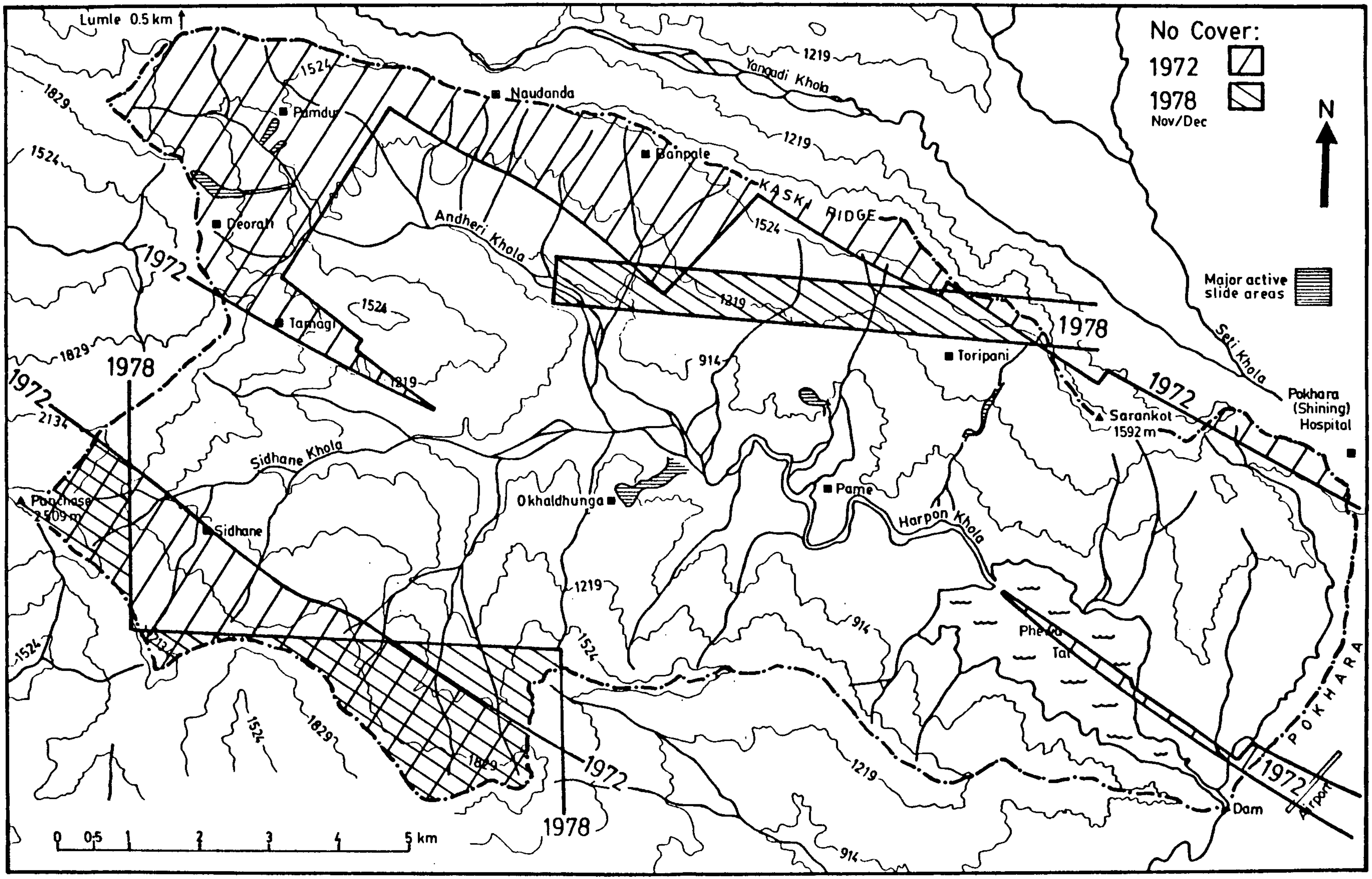

Figure 16. Phewa Valley: air–photo coverage in 1972 and 1978.

In addition, Mulder (1978a, p. 9) mentions full coverage of the watershed by air-photos at 1:64,000. These may have been flown for the Department of Forestry, but, together with the 1958 Indian photography and the March 1978 photography, were not available for this study.

Mass movement sites in the watershed were identified by interpretation of the 1972 and November/December 1978 air-photos, and marked onto a 1:25,000 topographic base map (I.W.M. 1980) produced from the March 1978 photos. Failure locations are shown in Figure 17. A number of sites outside the watershed were also identified, and were marked onto 1:50,000 scale topographic maps (photographic enlargements of the Indian One-Inch series).

3.2.2 FIELD DATA COLLECTION

In May 1983, 50 suspected mass movement sites identified by air-photo interpretation in the Phewa watershed and surrounding area were visited on foot. Morphometric and other characteristics of 22 of these slides in the Phewa watershed, and 4 outside, were determined (Table 6). Slope angles were determined by clinometer, and morphometric measurements by hand-held tape for smaller slides, by pacing for larger ones, and, for extremely large failures, by measurements from air-photos. Slide age was estimated from a combination of scar freshness and degree of recovery through vegetation establishment, local interviews, and existence and relative size on the 1958 topographic maps and the 1972 and post-monsoon 1978 air-photos.

Other characteristics recorded in the field were the nature of the failure surface, the nature of the failed material (soil, untransported regolith, colluvium, bedrock), soil texture, structure, horizonation, and drainage, root penetration of the regolith, bedrock geology (including lithology, bedding, dip, jointing, faults, and competence), surface and subsurface moisture regimes, topography, connections to the drainage net, debris delivery

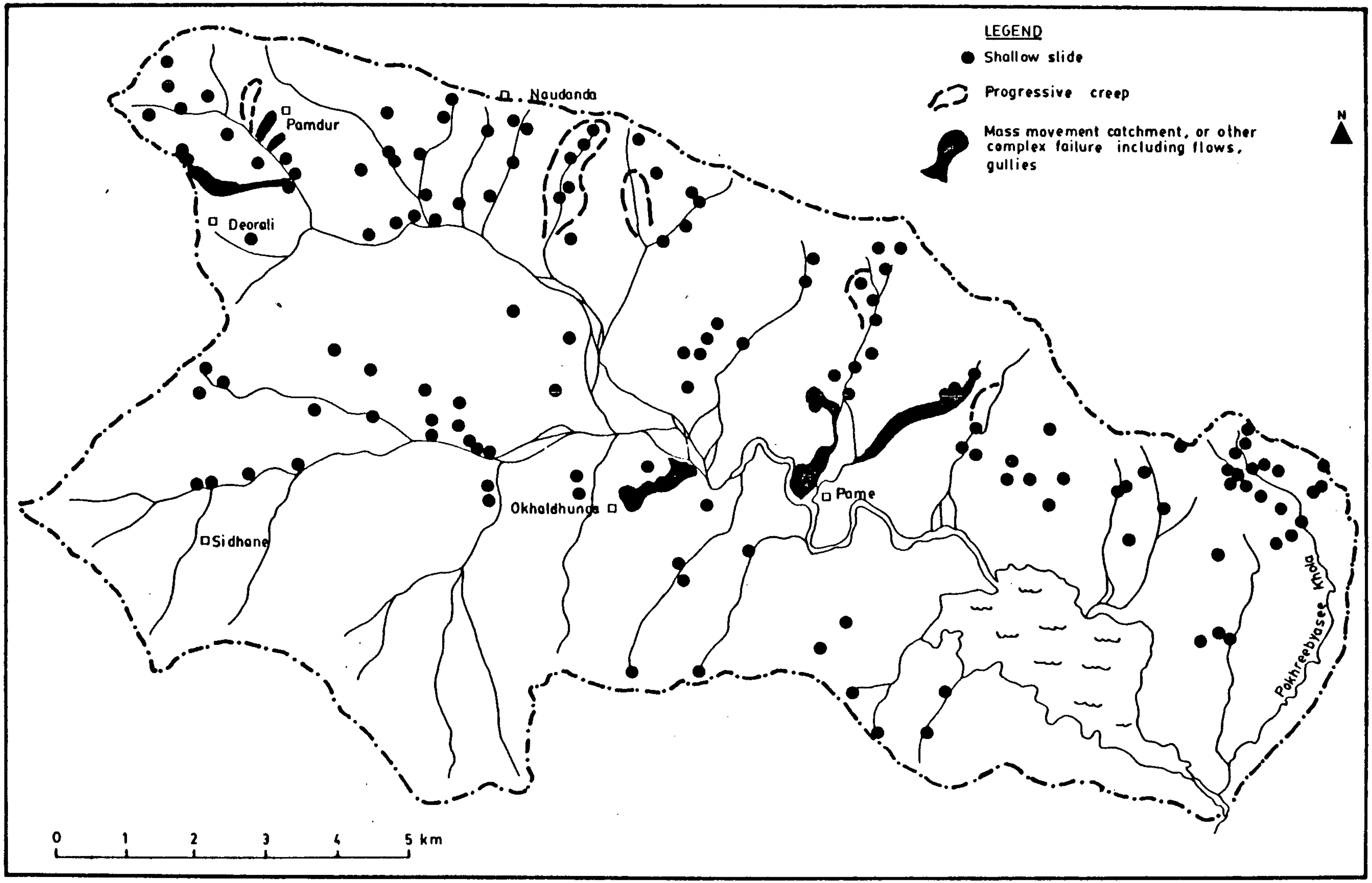

Figure 17. Phewa Valley: mass movement activity identified from 1972 and 1978 aerial photography and 1983 field survey.

Table 6. *Pokhara area: landslide morphometry*

SLIDE IDENTIFICATION	TYPE	APPROX. AGE (years)	SLOPE OF FAILURE SURFACE (degrees)	LENGTH OF SCAR Lc (m)	LENGTH OF DEBRIS Lm (m)	OVERALL LENGTH L (m)	WIDTH OF SCAR MAX. W (m)	WIDTH OF SCAR MEAN (m)	DEPTH OF SCAR MAX. D (m)	DEPTH OF SCAR MEAN (m)	AREA OF FAILURE SCAR (sq. m)	TOTAL AREA AFFECTED (sq. m)	VOLUME (cu. m)	INDICES: SHAPE W/D	INDICES: PROCESS D/L (%)	INDICES: TENUITY Lm/Lc
30	Rockfall	2	90	10	10	20	10	10	2	1	100	200	100	5.0	10.0	1.00
13	D. slide, undercut	10-12	40	33.8	N/A	33.8	58	58	1.2	0.85	1960	1960	1666	48.33	3.6	N/A
33	D. slide, undercut	1	24	60	N/A	60	60	40	7	>5	3600	3600	18000	8.57	11.7	N/A
29	D. slide, micaceous	5-6	27	24	35	59	17	15	5	2	360	885	720	3.4	8.5	1.46
Pame 11	" in talus	2	29	45	80	125	20	14	2	0.75	630	1750	473	10.0	1.6	1.78
1	Debris slide	5-10	39	10.7	20	31	7.6	7.6	1.1	1.1	81	130	89	6.91	3.5	1.87
5	"	1-2	44	17.6	120	138	11.3	8	1.4	1.1	141	1104	155	8.07	1.0	6.82
11	"	10-15	45	30	90	120	19	15	2	1.5	450	1800	675	9.5	1.7	3.00
15	"	5	39	14	30	34	20	12	1	1	168	408	168	20.0	2.9	2.14
20	"	1	42	9.5	25	35	8	7	1.2	0.9	67	245	60	6.67	3.4	2.63
28	"	15-20	45	40	35	75	15	9	4.5	2	360	675	720	3.33	6.0	0.88
31	"	1	42	14.2	50	64	11.3	7	2.5	1.8	99	448	179	4.52	3.9	3.52
39	"	5-7	36	15	80	95	10	8	1.5	1	120	760	120	6.67	1.6	5.33
40	"	5-7	36	10	60	70	10	8	1.5	1	80	560	80	6.67	2.1	6.00
Ohophare	"	1	38	45	50	95	19	8	3	2	360	760	720	6.33	3.2	1.11
Kaskikot	"	1	37	30	80	110	30	25	2	1.3	750	2750	975	15.0	1.8	2.67
23	D. avalanche	10-15	53	125	100	225	35	30	3	1.5	3750	6750	5625	11.67	1.3	0.80
Damaidanda	Shallow rotational	2-4	39	19.8	230	250	14.5	10	2.3	1.5	198	2500	297	6.30	0.9	11.62
Deorali	Complex, including flow	>26	18-30	1220	400	1620	134	100	10	6	122000	132000	730000	13.4	0.6	0.33
Pamdur	"	10-15	5-35	420	420	840	125	60	<10	5	25200	42000	126000	12.5	1.2	1.00
Pame	"	26-30	34	500	1400	1900	150	90	60	20	45000	368000	900000	2.5	3.2	2.80
Okhaldhunga	"	>26	>27	500	1125	1625	550	325	60	25	162500	400000	4060000	9.17	3.7	2.25
OUTSIDE PHEWA WATERSHED																
Phulwari	Debris slide	2	40	15	45	60	12	9	2	1.2	135	540	162	6.0	3.3	3.00
Lamachaur	Rockslide	5-10	>50	70	100	170	35	30	12	8	2100	5100	16800	2.92	7.1	1.43
Jumleti	Complex, including flow	<26	35	150	180 (fan)	330	75	40	40	25	6000	36000	150000	3.0	12.1	1.20
Bijaipur	"	<26	23	320	310	630	75	36	13.5	7	11520	22680	80650	5.56	2.1	0.97

See text for definition of terms.

to channels, land use, elevation, aspect, association with other failures, and possible causal mechanisms and triggers.

Angle of failure surface and approximate age were obtained for a further 11 slides (Table 7). The relatively homogeneous bedrock types in the Phewa valley precluded any assessment of failure variation between lithologies, and insufficient data were collected to examine the effect on failure of slope age.

3.3 RESULTS AND DISCUSSION

3.3.1 DESCRIPTION OF SLOPE MOVEMENT TYPES AND PROCESSES

3.3.1.1 *Landslide classification*

Caine and Mool (1982) describe the Nepali word for "landslide" (*pahiro*) as an all-embracing term for all forms of catastrophic slope failure including the fluvial gullies which often develop from failure scars. Since many different types of process are involved in slope failure, and "improvements in technical communication require a deliberate and sustained effort to increase the precision associated with the use of words" (Varnes 1978), it is essential to break down the overall concept of *pahiro* into process-related categories.

The classification of landslides and other forms of mass movement is a topic which has exercised specialists ever since Penck (1894) first distinguished between mass movement and mass transport. *Mass movement* describes movement under the influence of gravity alone, whilst *mass transport* allows material to be carried in a moving medium such as water, air or ice (Fairbridge 1968). Although helpful as an analytical concept, in reality these two categories merge as the content of the transporting medium in the failed material increases. At every level of classification similar problems of "where to draw the line" abound, and the ideal system has yet to be

Table 7. *Phewa watershed: age and angle of failure surface for eleven shallow translational failures*

Slide identification	Type	Approx. age (years)	Slope of failure surface (degrees)
17	Debris slide	>10	47
37	"	4–8	40
38	"	"	40
45	"	"	48
46	"	"	60
48	"	"	45
49	"	"	40
50	"	"	40
51	"	"	40
52	"	"	40
55	"	"	52

proposed.

Currently, landslide classifications are predominantly descriptive tools based on the three fundamental processes of planar sliding (translation), rotation, and flow, which are well described in a number of texts including, for example, Skempton and Hutchinson (1969). Characteristically, rotational slides occur in homogeneous materials and have a curved surface of failure. Where a heterogeneity is present within the slope (e.g. a weak soil layer or boundary between weathered and unweathered material), it can determine the surface of failure and prevent the development of a simple rotational slide; an element of translation is introduced. In general, the smaller the depth to the heterogeneity, the greater the translational element will be. Compound slides reflect the combination of a variety of curved and planar failure surfaces, generally at moderate depth, and usually involve severe distortion and shearing with corresponding disturbance in the slide mass (Skempton and Hutchinson 1969). Flows usually have a high water content, involve viscous deformation with inter-granular movements predominating over shear, and straddle the boundary between mass movement and mass transport (Hansen 1984).

Recent descriptive classification schemes include those of Hutchinson (1968), Coates (1977), and Varnes (1978), and have been reviewed by Hansen (1984). Descriptive systems have proved extremely useful in providing simple grouping methods, and some authors are now attempting to refine them through the use of morphological indices (see Section 3.3.3.2). However, it is likely that future classification work will concentrate on the use of geotechnical data rather than on morphology, owing to its greater propensity for use in slope failure prediction.

For this study Varnes' slope movement classification scheme was used (Figure 18). First proposed in 1958 (Varnes 1958), and widely recognized and favoured in South Asia by, e.g., the Central Road Research Institute of India (Mehra and Natarajan 1966), Varnes' system is partially quantified and clearly illustrated. However, it still requires some modification for Himalayan conditions, particularly with regard to complex failure events, flows, and high-angle fluvial transport systems.

3.3.1.2 *Hillslope processes*

As noted by Brunsden *et al.* (1981) in eastern Nepal, air-photo interpretation revealed failure scars to be so widespread that mass wasting should be regarded as the norm in this landscape rather than the exception. Following Varnes' classification five main categories of mass movement were identified: rockfalls, rockslides, debris slides, rotational slides, and deep and shallow flows. Shallow translational debris slides were by far the most numerous. Mass movement features ranged in scale from these small isolated slides through flows to large areas of complex movements ("mass movement catchments", Brunsden *et al.* 1981). Removal of displaced material often involved both viscous deformation and fluvial transport in steep channels which were transitional between slide debris tracks and gullies. The material involved was usually

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Few Units	Rock slump	Debris slump	Earth slump
	TRANSLATIONAL		Rock block slide	Debris block slide	Earth block slide
		Many Units	Rock slide	Debris slide	Earth slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow (deep creep)	Debris flow	Earth flow
				(soil creep)	
COMPLEX	Combination of two or more principal types of movement				

Figure 18. Varne's abbreviated classification of slope movements. Source: Varnes (1978). Note: this classification should be used in conjunction with the original reference, which specifies and illustrates the categories in detail.

Figure 19. Rockslide at Phedi, north of Naudanda. Debris travelled a further approx. 1 km downslope in a ravine to the Yangadi Khola (not shown).

untransported, weathered bedrock, but in some cases colluvial material was entrained. The various categories are described in greater detail below.

a) *Rockfalls.* These were infrequent and occurred almost exclusively on cliffs and bluffs developed in the quartzose schist in the western and southern part of the watershed. Elsewhere the weaker grey phyllitic schist and phyllites were unable to support slopes sufficiently steep to allow rockfall, except along active fault lines. The cliffs and bluffs were generally associated with the middle and upper reaches of stream channels, themselves often exploiting lines of structural weakness.

b) *Rockslides.* Rockslides, involving displacement of fractured rock along joints or bedding planes, occurred preferentially in two locations: on the outside of meanders where streams undermine rock outcrops, and on the steep faces of fault-induced mass-movement catchments. Occasional examples were noted on the quartzose schist outcrops on the south side of the watershed.

Mention should be made here of two large rockslides outside the watershed but still in the Pokhara area. One of these at Phedi, north of Naudanda, involved approximately 30,000 m^3 of material and was responsible for the loss of 7 lives (Figure 19). A rock outcrop some 100 m high failed without warning towards the end of the monsoon in 1982. Part of the debris spread out on the shallower slopes below the cliff, forming a fan, and part fluidised and travelled for approximately 1 km as a torrent down a pre-existing stream channel to the Yangadi Khola, some 300m lower. The site of the failure lay close to a fault identified by Remy (1975). The second large rockslide was a fault-induced failure at Jumleti, north of Pokhara (Figure 4), where rockfalls and rockslides from the steep sides of the failure provided a continuous supply of debris, which was then transported by fluvial action to a fan covering terraces on the low-angle alluvial slopes below. This site was active during the dry season, with small size material ravelling from the scarp, and seeps lubricating small flows in the centre of the scar.

c) *Debris slides.* The most common forms of mass movement in the Phewa watershed were shallow translational failures or "debris slides" (Figure 20). These slides could be divided into three categories: (1) failures on slopes of $<36^0$ in unusually weak or disturbed material, often micaceous (e.g. 29, Pame 11, in Table 6); (2) failures on stream and river banks due to undercutting (13, 33, in Table 6); and (3), the most common category: failures on undisturbed regolith with sufficient runout to a channel to allow the formation of flows in the displaced material.

Slides in the first category were often associated with other forms of mass movement due to the general weakness of slope materials in the vicinity. Slides due to undercutting had a much larger width-length ratio than those in non-fluvial locations. The preferred location of the slides on undisturbed regolith was interfluves, where factors such as jointing and local convergence of subsurface flow nets contributed to instability. Characteristically these slides were small, involved less than 1,000 m^3 of material (mean volume was 331 m^3), and occurred in regolith on slopes of 36^0–45^0, although one failure was noted at 60^0 (Tables 6, 7). Site features indicated that at failure, a shallow (1–3 m deep) mass of soil and weathered bedrock moved downslope with the material invariably disintegrating, and sometimes becoming fluid and travelling as a debris flow to cover the undisturbed surface below the failure site. Failure surfaces were usually the bedrock/regolith interface. No seepage was visible at any of these shallow sites at the time of the survey, in May (pre-monsoon). At some locations roots of up to 2 cm diameter protruded from undisturbed material above the primary scarp, and appeared to have broken in tension. Root penetration of bedrock at

Figure 20. Debris slide, Phewa Valley.

Figure 21. Slow debris flow at Pamdur, Phewa Valley. Rubble to front and side of debris lobe has been washed clean of fines by rain and fluvial action.

the failed sites was not observed. Although occurring in both forested and non-forested locations, these shallow slides were particularly common throughout the watershed in areas of scrub.

d) *Slow debris flow/earthflow.* In some locations in the area debris generated by slope failures accumulated and moved downslope as an elongate mass of disintegrated debris of all sizes (Figure 21). Movement was by sliding over steep lateral and basal shear surfaces with viscous deformation in the centre of the mass. Velocities were not measured, but comments by local farmers indicated movement in Varne's "slow" to "rapid" categories (between 1.5 m/yr and 0.3 m/min; Varnes 1978).

In the Phewa valley these flows occurred in four locations (Deorali, Pamdur, Pame, Okhaldhunga) associated with either very weak micaceous schist (Pamdur and Deorali), or deeply weathered phyllitic schist (Pame, Okhaldhunga). Morphometric details are available in Table 6. This category of mass movement equates to the "mudslides" of Brunsden *et al.* (1981), and the "flowslides" of Caine and Mool (1982). The very large flow at Deorali (*circa* 7.3 x 10^5 m^3) also bears comparison to the earthflows in the California Coast Range described by Kelsey (1978), with a hummocky surface, undrained depressions, and well-developed lateral margins defined by shear planes. These movements are here called slow debris flows to continue the utilisation of Varne's classification, although such a category is implied rather than described in his system. In the Pokhara area the coarse nature of the material involved generally excluded such slides from the otherwise appropriate "earthflow" and "mudflow" categories used by Varnes, which require more than 50% fines (Varnes 1978, p. 18).

Evidence for the location of these flows in groundwater discharge zones was considerable. All the flow sites were observed to be moist at the time of the survey, in May, with evidence of recent movement such as torn roots and dying vegetation

(Figure 21). At two sites seepage was sufficiently reliable for the local inhabitants to regard the springs as sources of dry season drinking water. At Pamdur retrogressive slumping had eaten back to a rockshelf from the base of which a steady flow of water emerged to lubricate the head of the failure. All the flows were noted to be active during the monsoon season of 1982, with activity decreasing during the subsequent dry season as, presumably, pore-water pressures declined. In some cases, during the monsoon rain generated sufficient runoff on these flows to allow the formation of fluvial channels cutting across the surface. Evidence such as scoured stretches of debris track suggested that, on some slopes, the flows may have become thixotropic on failure and fluidised, resulting in rapid flow, a phenomenon similar to the debris torrents of Japan and the Pacific Coast of North America.

Although few in number the scale of these flows and their transport efficiency meant that they were responsible for a high proportion of overall sediment movement and input to valley bottom river systems. The four slow debris flows were all associated with "mass movement catchments" and are discussed further below (f).

e) *Rotational slides.* Rotational slides were not common features in the study area owing to the generally low cohesiveness of regolith materials and the intensity of slope processes, resulting in shallow regoliths. They were confined to two locations: the upper end of mass movement catchments where retrogressive slumping supplied material to the debris transport system (Figure 22), and much larger, deeper slumps in the deep regolith which occurs in some re-entrants on the southward-facing slopes of the Kaski ridge. Here failure was due to erosion nickpoints moving slowly upslope in "slope failure ampitheatres" (Brunsden *et al.* 1981), thereby removing support from material above. Both types of rotational slide rapidly developed a more translational form as the blocks disintegrated and slid on the planar surface of the underlying

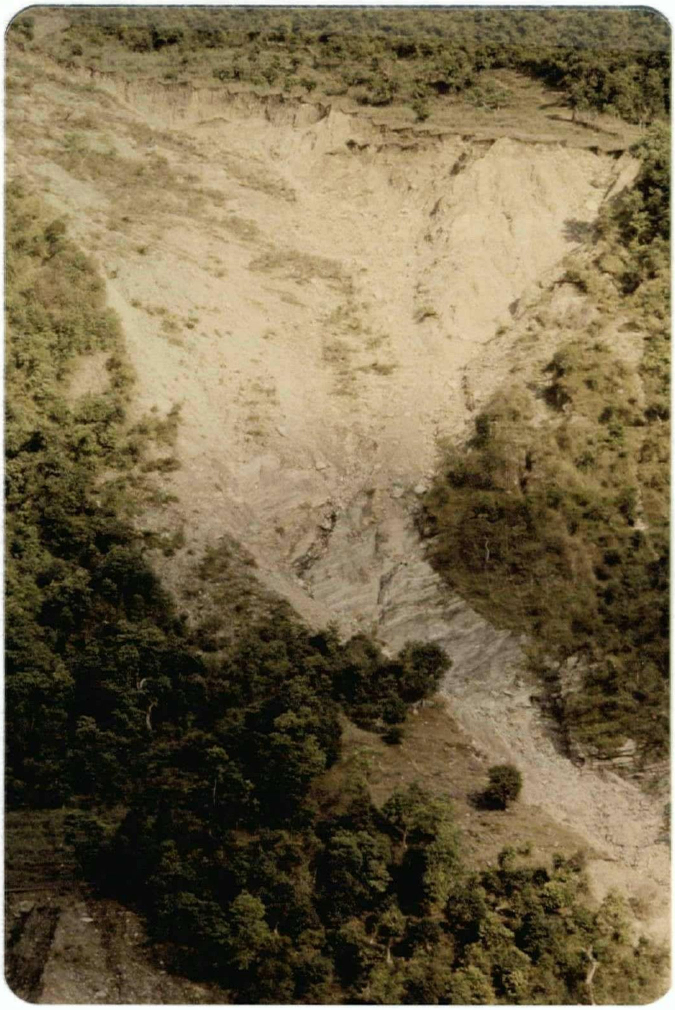

Figure 22. Retrogressive slumping supplying mass movement catchment, Bijaipur, near Pokhara. Fault runs up centre of gully. Stepped appearance of main scarp is caused by terracing (*bari*).

outward-dipping phyllites.

f) *Mass movement catchments.* In four locations in the watershed (see (d) above) debris flows were fed by complex failures in a rapidly eroding catchment above (Figures 8, 23). Failure types included rockslides, debris topples, debris slides, debris and earth slumps, and dry ravel. At a fifth location near Pamdur, debris from a mass movement catchment moved directly into a stream channel. Debris from the Pame and Okhaldhunga failures had formed large fans spreading out onto the valley floor, with concave profiles gradually increasing from 1^0 on the valley floor to about 14^0 at the base of the failures. These fans had encroached on the channel of the Harpon Khola. During the monsoon intense activity was noted in these catchments, with rapid expansion at the head by retrogressive slumping. Activity continued at a lower level for the remainder of the year, with talus slides and ravel supplying coarse debris from the steeply sloping failure scarps. At all these sites seepage was observed during the dry season, At this time of year, waves of coarse sediment moved by flow and viscous deformation in lobes some 1-3 m deep along the bed of the failures, but these were largely washed away by runoff processes generated within the catchment during the monsoon.

Distinction should be made between these discrete, extremely actives sites and the larger erosion ampitheatres on the north side of the watershed (Figure 8). These ampitheatres, were some 800 m in length, and although dissected by vigorous ephemeral streams and gullies, were sufficiently stable to allow cultivation of the majority of their area. The streams and gullies provided rapid removal of any material reaching their channels, depositing it in fans where the streams debouch on the valley floor (see profile of ephemeral stream in Figure 33).

Figure 23. Mass movement catchment at Pame, Phewa Valley.
Fault runs up centre of failure.
Note:
(1) Fluvial action in bed of catchment.
(2) Fresh failures at top left.
(3) Displacement at top indicating deep movement.

g) *Progressive creep.* This phenomenon was detected in a number of the erosion ampitheatres on the north side of the valley. The whole mantle was moving downslope at a rate of 1–5 m/yr by means of both shallow creep and deeper viscous deformation, creating an undulating profile with occasional tension cracks. The process has been described in the Kathmandu–Kakani area of Nepal by Kienholz *et al.* (1983), who termed it "slow mass movement", and is synonymous with the "depth creep" of Ter–Stepanian (1965). Geomorphological interpretation of the landscape and local oral history suggest that eventually catastrophic failure of these moving masses occurs, and very large masses of material are transported to the valley floor, possibly triggered by extreme precipitation events and/or seismicity.

h) *Gullies.* The slopes on the south side of the Kaski ridge were dissected by ephemeral streams, some of which had eroded down to bedrock and were relatively stable, but others of which were extremely active. Material was supplied to them by rills, dry ravel, shallow planar slides, topples from the banks, and slumping at the headcut. These features were distinguished from the slow debris flows by having an obvious fluvial form, and a bedload consisting of sorted material rather than the varied particle sizes of the flows.

The various hillslope processes identified are illustrated in Figure 24, a composite landscape based on the north side of the Phewa watershed.

3.3.2 MASS WASTING RATES IN THE PHEWA VALLEY

3.3.2.1 *Landslide density and area affected*

Overall landslide density in the Phewa watershed was 1.6 slides/km^2. 95% of these sites were small shallow failures. The figure includes all recent active mass

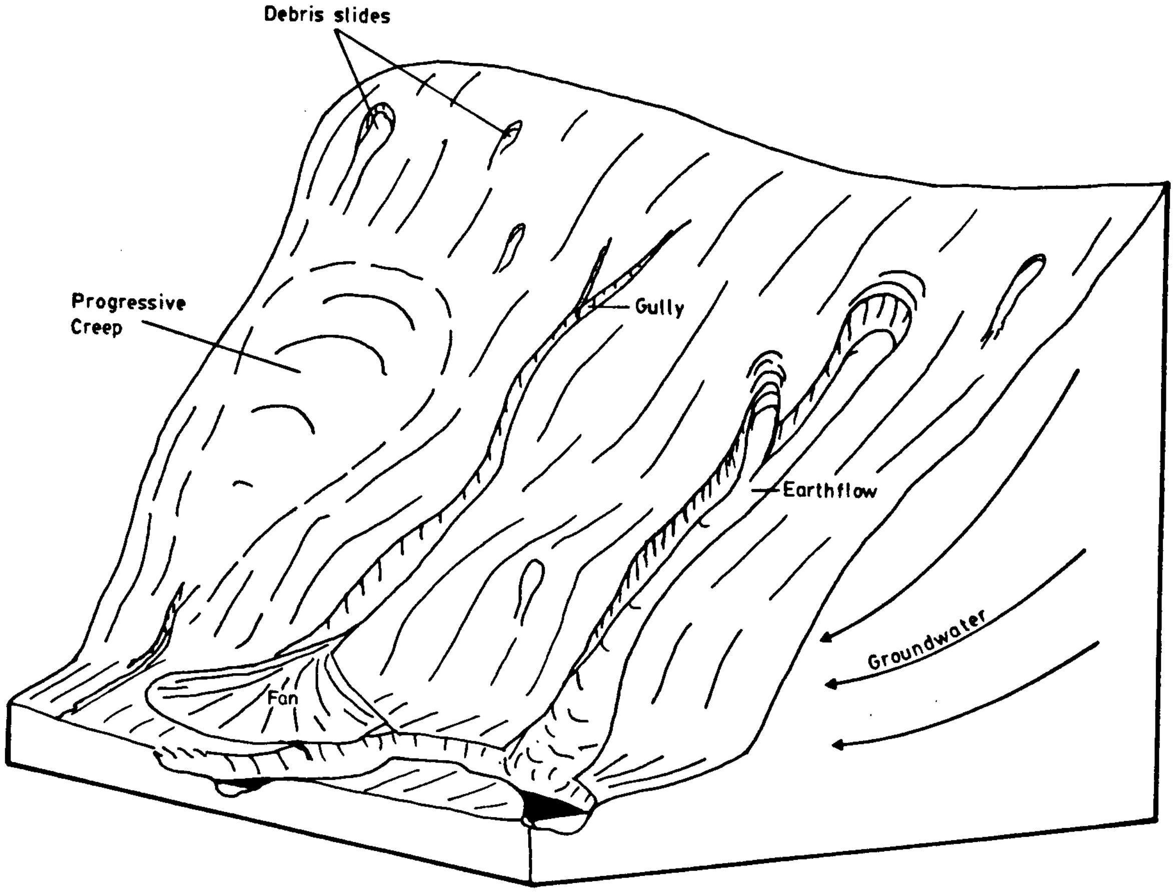

Figure 24. Schematic diagram of part of the Kaski ridge, showing four types of slope process.

movements identified on the 1972 and 1978 air photos and by the 1983 field survey (190 separate sites in all). The aerial photography covered only 74% (1972) and 90% (1978) of the watershed (Figure 15), and therefore the density figure should be regarded as conservative.[46]

Excluding "slow earth flow" the total *area* of active and unhealed failures was 0.7 km^2, or 0.5% of the basin area. The total area directly affected by landslides includes the area of debris as well as that of the failure itself and so was considerably larger, at 3.25 km^2, or 2.7% of the watershed. Of this, a very large proportion (90%) was due to debris fans resulting from activity in mass movement catchments.

3.3.2.2 *Landslide growth and recovery*

As Caine and Mool (1982) noted for their study area northwest of Kathmandu, true sliding failures were much smaller and shallower than those involving slow flow and gully development. Based on a plot of age against area, they hypothesized a linear expansion of their slides at about 60 m^2/yr from an initial failure area of, typically, about 600 m^2. However, this model cannot be supported in the Pokhara area. Although a regression of area of failure scar on estimated age for all sites gave a positive relationship significant at the 99% level:

$$\text{Area } (m^2) = 2599 \text{ Age (yrs)} - 10176 \qquad (r=0.626,\ n=26)$$

many of the shallower debris slides were observed to be healing, rather than expanding with time. This was confirmed by a plot of shallow debris slide area against age (Figure 25), which failed to show any obvious trend of size with time

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[46] In addition no allowance was made for slides not visible on the photos due to e.g. forest cover; equally no adjustment was made for false positive identification of slide sites on the photos beyond those excluded during fieldwork. Of the 46 sites visited in the watershed, 12 (26%) were false identifications due to reflectance of light tones from barren areas, and rocks. However, at the same time, four previously unidentified failures were located.

($r=0.150$). The tendency of these shallow failures to cluster below an age of eight years suggests that, typically, they may heal and so no longer be identifiable within a decade. In the Kathmandu-Kakani area Caine and Mool (1982) also found their debris slides to be of very recent age, less than five years. These figures may be compared with the observations of Zollinger (1979b), who reported revegetation times for new landslides on "very steep slopes" in the Mahabharat Lekh and Midlands to be, sometimes, as little as 1-5 years; Dutt, who found that slides in Siwalik formation near Darjeeling caused by the 1934 earthquake were revegetated by 1955 (although slides in phyllite continued to grow) (Dutt 1966), and Simonett, who estimated an approximate revegetation time of 30 years for "non-contiguous landslides", and 40 years for "large isolated debris avalanche or composite gully slides", all on granitic terrain in New Guinea (Simonett 1967).

In contrast to the shallow failures, the future of the mass movement catchments in the Pokhara area (which are largely responsible for the high correlation between age and area in the regression) may well involve further growth. Brunsden *et al.* (1981) have described a mechanism whereby mass movement catchments could be maintained in an active condition by runoff processes: where the area of bare unstable ground becomes so extensive in relation to total catchment area that runoff cannot be dissipated by remaining vegetation, runoff will increase, resulting in further instability and erosion; an "autocatalytic" condition exists. The authors suggest that this condition can be maintained because the recovery time of the vegetation and soils is longer than the reaction time of the system to monsoon events. Stability will not return until the failure is sufficiently large to permit the development of slopes at a stable angle. The major failures in the Pokhara area may well be in an autocatalytic condition, and the time required for them to stabilize is not known. Phewa watershed.

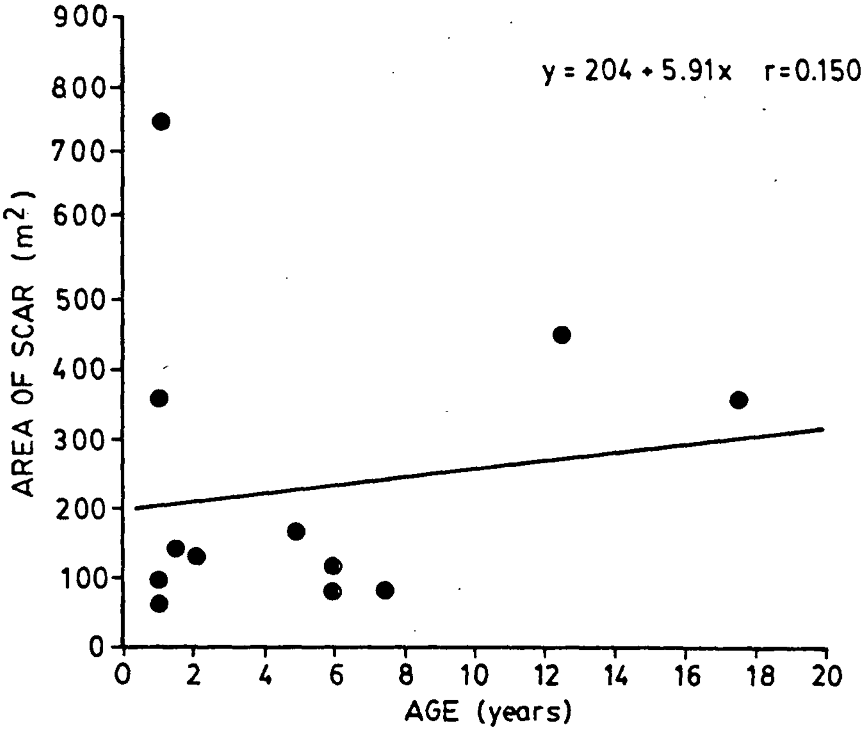

Figure 25. Plot of area of failure scar on estimated age for 12 debris slides in the Pokhara area. Data from Table 6.

3.3.2.3 *Volume and area*

The survey results revealed wide variability in mass movement types in the Pokhara area. Slide volume varied from 60 m^3 to over 4 x 10^6 m^3, although this last figure represents material moved by a succession of incidents in a single mass movement catchment, rather than a single failure event. In the Phewa watershed the largest volume of material currently moving as a unit is probably the Deorali slow debris flow, *circa* 7.3 x 10^5 m^3, although progressive creep in the erosion ampitheatres on the north side of the valley may involve up to 5 x 10^6 m^3.

3.3.2.4 *Failure frequency and surface lowering by landsliding*

Estimates of the average rate of slope retreat by landsliding can be obtained by combining the volumes of debris for individual mass movements with their spatial distribution (landslide density), and then finding some way of estimating their frequency of occurrence (Saunders and Young 1983). For the Phewa watershed mean volumes of material displaced by each type of slide were calculated from the morphometric measurements (Table 6), and their spatial distribution determined for the year 1978, a date chosen owing to the high proportion of air photo coverage of the catchment that year (90%, Figure 16).

Frequency of occurrence can be estimated in two ways: firstly, from the average age of slides, and secondly, from sequential counts of actual slides on the ground. In this study the first method gave values of failure age of 24 years for mass movement catchments, and 5.5 years for all other slides (in 1983) (Table 6). Multiplying these ages by the landslide density figure of 1.6 slides/km^2 (section 3.3.2.1) gave a frequency of about 0.3 slides/km^2/yr. These figures are very approximate owing to lack of precise dating, and a small and unrepresentative sample.

The second method of frequency estimation should be more reliable: excluding the mass movement catchments, 81 slope failure sites were identified on the 1978 air photos in the area of overlap with the 1972 photos. Of these, 25 sites were common to both sets of photographs; *ergo*, in this area, 56 new mass movements occurred in the six years between 1972 and 1978. The area of overlap is 84.88 km^2, or 70% of the catchment. This gives a slide frequency of 0.11 slides/km^2/yr, or, *pro rata*, 13.3 slides/yr for the whole catchment.[47]

These failures were largely shallow translational slides, with a high proportion caused by undercutting. By adding an average volume for these slides (5000 m^3, an approximate weighted mean volume of debris slides in both undercut and open slope situations), to that of the annual output of the mass movement catchments (volume divided by age), it was possible to make a crude estimate[48] of the average annual volume of material mobilized by mass movements in the catchment: 3.1 x 10^5 m^3/yr. This is equivalent to a rate of surface lowering by landsliding of about 2.5 mm/yr.

To determine a denudation rate from this estimate it is necessary to add the contributions from other erosion processes (soil creep, sheetwash, rilling and gullying, solution), and to adjust the total by a sediment delivery ratio to account for material redeposited within the catchment. Values for surface erosion can be estimated from Impat's (1981) runoff data: assuming a bulk density of 1.6 g/cm^3 for undisturbed material, Impat's soil loss data from dense forest, protected pasture, and overgrazed pasture in 1979 (Table 2) convert to approximately 0.7 mm/yr, 1.6 mm/yr, and 5.6 mm/yr, respectively. These figures could, cautiously, be extrapolated to the remainder of the watershed, except that nearly half of the area is under cultivation (see 2.7). Erosion rates on the *bari* and *khet* have not been measured, and neither have the

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[47] Both frequency estimates suffer from the methodological problems common to all frequency assessments such as the assumptions of climatic and slope strength constancy (see Crozier (1984) for discussion).

[48] Calculation: (1) 13.3 slides/yr x 5000 m^3 = 66,500 m^3; (2) 5.8 x 10^6 m^3 (total volume of complex failures in Phewa watershed from Table 6) divided by age (24 years) = 2.4 x 10^5 m^3; (3) Sum = 3.1 x 10^5 m^3; (4) Sum divided by area of watershed (122 km^2) = surface lowering (2.5 mm/yr).

contributions of creep, gullying, and solution. In addition, the sediment delivery ratio remains unknown (see 4.3.3), and the overall uncertainty makes it unwise to propose a denudation rate for the catchment at the present time.

3.3.3 MORPHOMETRIC ANALYSIS

3.3.3.1 *Volume/area relationships*

Empirical relationships between landslide volume and area have proved useful in mass movement and sediment studies through allowing the extrapolation of limited field data over a wider area by air-photo interpretation. For example, in southern California Rice *et al.* (1969) determined a power relationship between volume and area of:

$$\text{volume} = 0.234 \ \text{area}^{1.11}$$

and in New Guinea Simonett (1967) established a very high correlation between slide volume and slide area:

$$\log \text{volume (ft}^3) = 1.368 \log \text{surface area (ft}^2) - 0.6885 \qquad (r=0.98)$$

based on a sample of 201 failures containing a "wide variety of landslide types".

In the Pokhara area linear regression of volume on area for all failures gave a relationship of:

$$\text{volume (m}^3) = 18.4 \ \text{area of failure (m}^2) - 34669 \qquad (r=0.888,\ n=26)$$

significant at the 99% level. However, as with the area/age regression, this curve is strongly affected by the very large mass movement catchments, with the intercept giving the unrealistic value for area of nearly 2000 m^2 at zero volume. It is more appropriate to investigate the relationship within process groups, and analysis of the large failures on their own gave a regression of:

$$\text{volume} = 19.7 \ \text{area of failure} - 194270 \qquad (r=0.841,\ n=6)$$

The regression for all shallow failures (Figure 26) was:

$$\text{volume} = 1.5 \ \text{area of failure} - 23 \qquad (r=0.993,\ n=16)$$

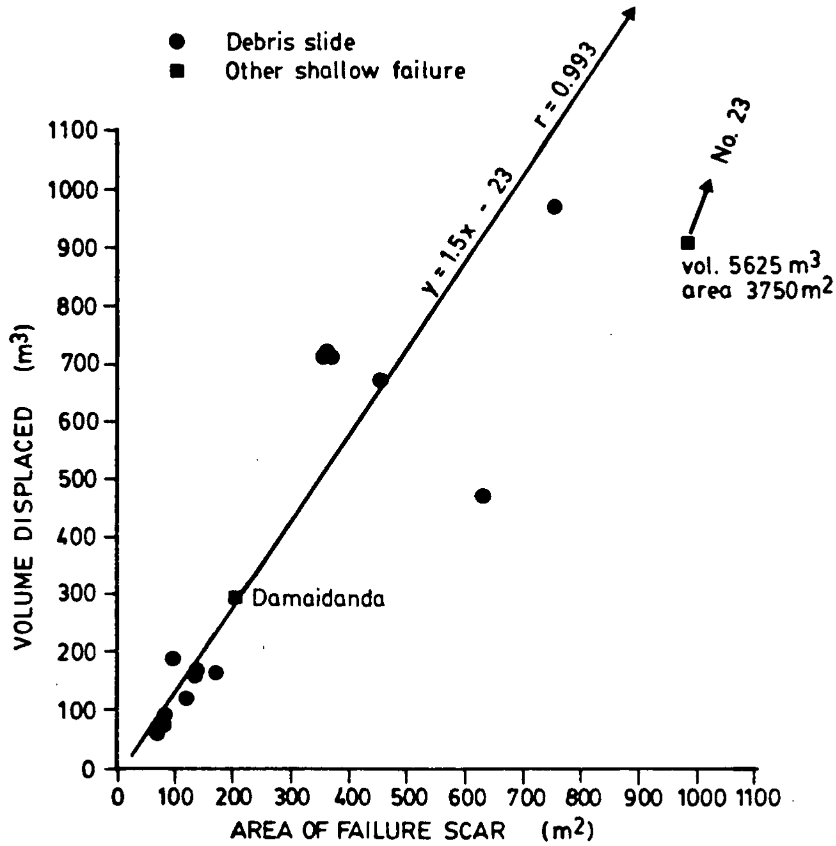

Figure 26. Regression of estimated volume on area for shallow slope failures. Data from Table 6.

significant at the 99% level. Volume and area are not, of course, independent variables, but the correlation coefficients do indicate some linearity in their relationship. In the case of the Pokhara area debris slides the high correlation coefficient suggests that similar processes and material properties may be involved throughout this category of failures. It should be emphasized that these regression are based on very small samples and should not be taken out of context.

3.3.3.2 *Shape indices*

Although Blong (1973) found multivariate analysis of morphometric attributes to be unsuccessful in distinguishing between slide, avalanche and flow-type failures, other workers (Skempton 1953, McLean and Davidson 1968, Crozier 1973, Caine and Mool 1982) have suggested that morphometric measurements of landslide scars can help to illuminate conditions on the slope at the time of failure. The hypothesis under consideration when using morphometric analysis is that the morphology of a particular slide is closely related to its dominant genetic processes (Crozier 1973). For any one study verification of the process/morphometric index relationship can only be based on a subjective assessment of the the dominant process as diagnosed in the field after the event, and the usefulness of morphometric analysis as a diagnostic tool should not be overemphasized. However, the use of quantitative shape indices does facilitate comparisons with other results in the literature, and a brief exercise in morphometric analysis is carried out here. Relevant terms in landslide morphology are illustrated in Figure 27[49].

Three shape indices were applied to the Pokhara landslide data: a cross-sectional shape index, a process index (Skempton 1953), and the tenuity index (Crozier 1973).

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[49] Detailed morphometric definitions for landslides are available in Brunsden (1973) and Hansen (1984).

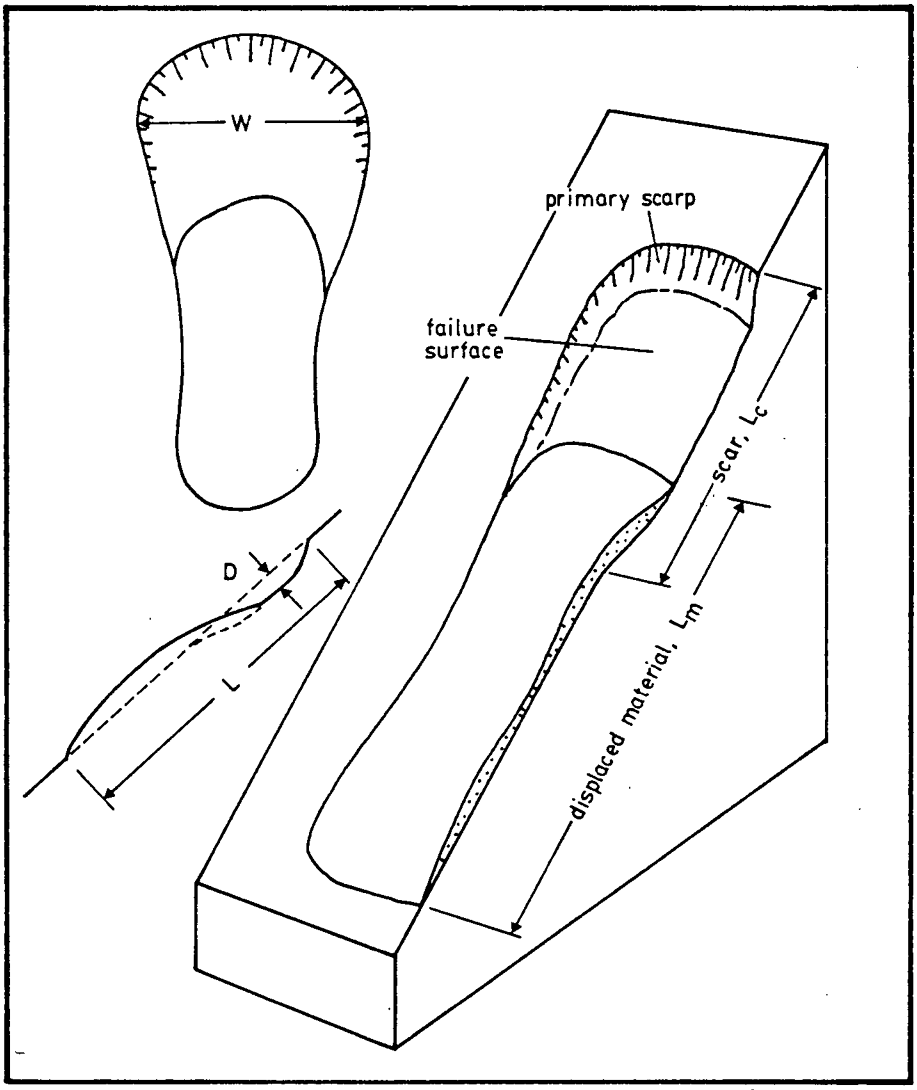


Figure 27. Terms in landslide morphology.

The *cross-sectional shape index* (width of failure scar over maximum depth of failure scar, W/D) was highly variable. Values ranged from 3.33 to 20.0 for slides of less than 1,000 m^3 (mean=8.03, st. dev.=4.15, n=18), with a modal value of 6 to 7, to 2.5 to 48.33 for larger failures (Table 6). These ratios indicate that cross-sectional form is not constant and is controlled by site-specific factors rather than being purely a function of process.

The *process index* is so-called because, in his study of landslips in boulder clay in north-east England Skempton found this index useful as a means of distinguishing between "surface slips", "deep rotational slips", and "slumps" (Skempton 1953). As defined by Crozier the process index, or D/L value, is

> "the ratio of the maximum depth of the displaced mass, prior to its displacement (true depth), to the maximum length measured up the slope, expressed as a percentage." (Crozier 1973).

The "maximum length measured up the slope", has also been described by Skempton and Hutchinson (1969) as the "maximum initial downslope extent", and is taken to mean the distance from the primary scarp to the tip of the displaced material (see Fig. 27).

Since Skempton's original paper in 1953, several workers have found D/L ratios to be extremely useful as an indicator of failure mechanisms and consequently in classification studies (Davidson 1965, Selby 1967, Davidson and McLean 1968, Crozier 1973, Caine and Mool 1982). The average value of the process index for the 12 debris slides surveyed in the Pokhara area, expressed as a percentage, was 2.87. This value is very low compared to figures for planar slides reported by other workers (Table 8), even though the debris from many failures debouched into stream channels, and longer run-outs (and therefore even lower D/L values) would have resulted on longer slopes. However, it is above values for flows, which range from 0.83 to 2.40 (Table 8). The workers quoted in the table were working in areas of deeper regolith

Table 8. *Average values for the D/L ratio or Process Index for planar slides and flows*

D/L Ratio (%)		Author
Planar slides	Flows	
8.00		Skempton 1953, West Durham, U.K.
7.66	2.40	Crozier 1973, Eastern Otago, nr. Dunedin, N.Z.
6.63		Caine and Mool 1982, Kathmandu-Kakani, Nepal
6.00	1.50	Davidson 1965, nr. Gisborne, E. Coast N. Island, N.Z.
5.00	0.83	Extracted from the literature by Davidson, 1965
5.00		Selby 1967, Waikato, N.Z.
2.87		This study

and generally less intense rainfall, and their higher D/L values indicate more coherence in the failed materials. The value of D/L for the Phewa debris slides is consistent with failure with a high water content and consequent viscous deformation or flow of the displaced material to produce long downslope extensions of debris. It therefore appears reasonable to support Crozier's supposition that areas with shallower regoliths and higher and more intense rainfall will have slides with lower D/L values (Crozier 1973).

A plot of D/L for both open slope debris slides and mass movement catchments against age (Figure 28) was not significant ($r=0.231$, $n=20$). This suggests that either slides undergo no expansion whatsoever with time (i.e. they heal), or that any enlargement is allometric[50], i.e. extension increases in proportion to depth. This may be an artefact of the regression, since it appears unlikely that shallow translational failures

[50] Allometry: when two processes change rate but retain the same ratio to each other. See e.g. Fairbridge (1968); Bull (1975).

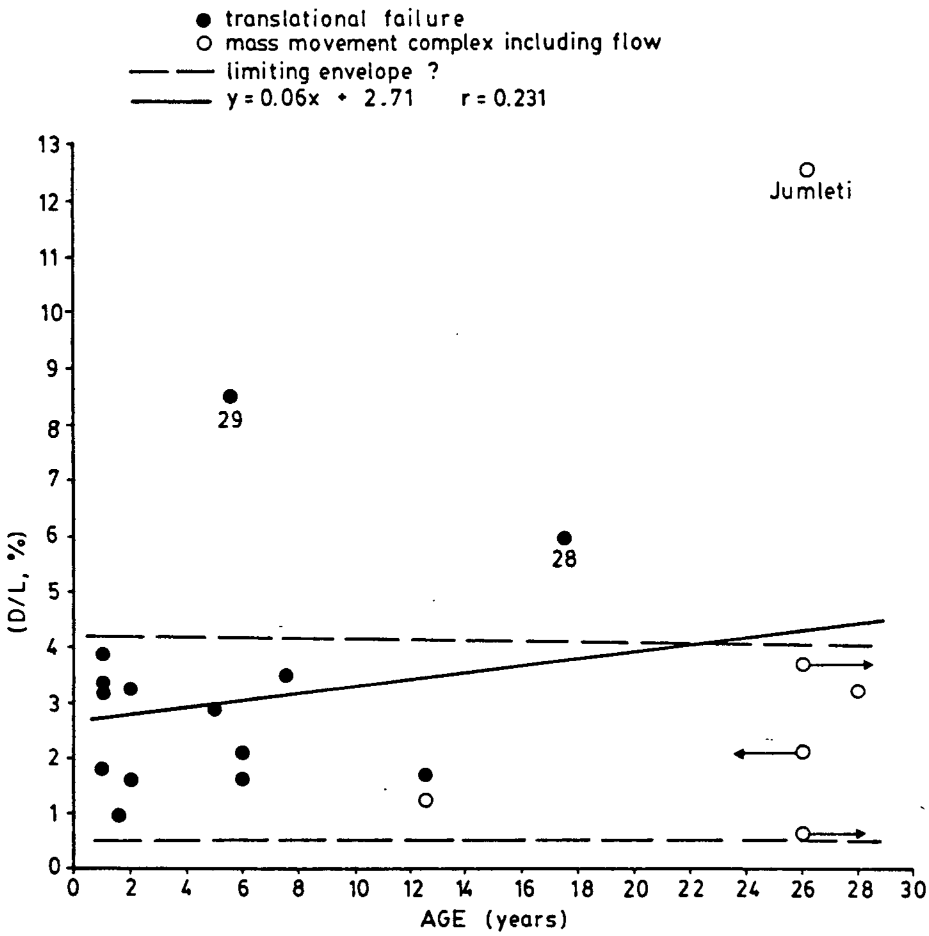
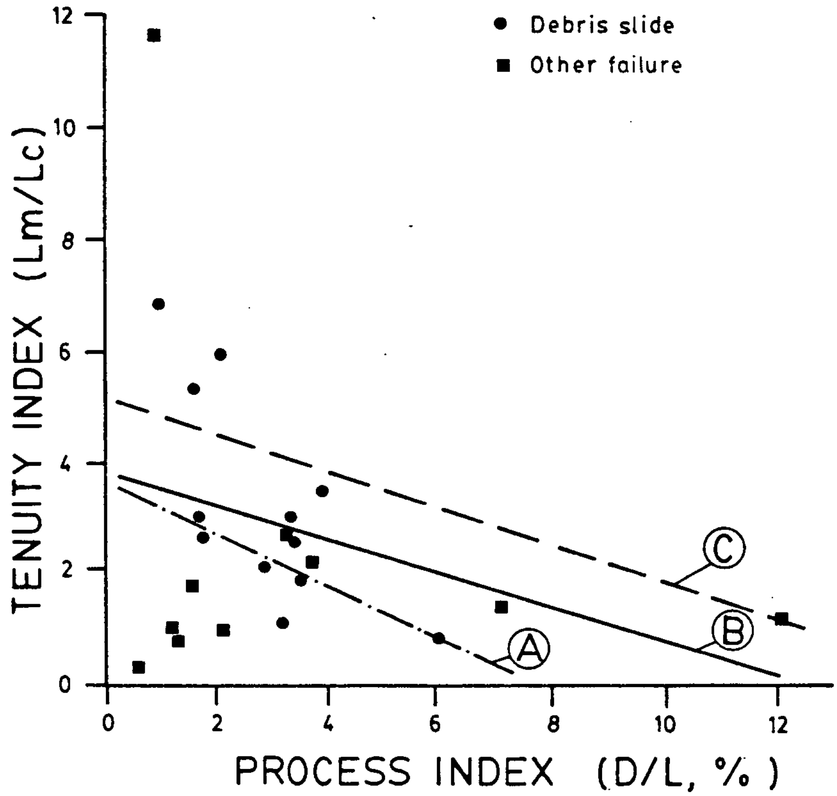


Figure 28. Regression of process index on age for debris slides and mass movement catchments. Data from Table 6.

will deepen if their original slip surface was bedrock. The plot also suggests a limiting envelope for D/L values of between 0.5 and 4.0 for the majority of failures. Events with D/L values >4 were generally either rockslides and rockfalls, or planar slides on streambanks with much reduced or non-existent runout paths.

Crozier's *tenuity index*, the length of the displaced material over the failure scar (Lm/Lc: Figure 27), reflects the tenuity of the displaced mass in relation to its original size, and so gives an indication of fluidity. However it is not a true measure of fluidity because it does not take into account lateral spreading or the effect of slope inclination (Crozier 1973). The mean tenuity index value for all the debris slides in the Pokhara area (mean=3.25, st. dev.=1.88, n=12), was similar to the tenuity value for "fluid flow" failures found by Crozier (1973) in New Zealand (3.33). The tenuity value for the mass movement catchments (mean=1.43, st. dev.=0.92, n=6) was similar to Crozier's figure for "viscous flow" (1.71). As with the process index, these figures may indicate a high water content and/or low cohesion in displaced material immediately after failure. In Nepal, Caine and Mool (1982) obtained a similar range of tenuity index values for failures in their study area near Kathmandu. However, in contrast to the Kathmandu area, Lm/Lc for the Phewa slides showed no reliable trend when regressed against slope angle (r=0.252). If genuine, this may indicate the importance of site specific factors other than slope angle in determining degree of runout.

Of greater interest is the relationship between D/L and Lm/Lc (Figure 29). Although weak (r=0.313), the regression line of tenuity on process for all failures in the Pokhara area (except for rockslides and falls and undercut debris slides) is approximately parallel to the regressions determined by Caine and Mool (1982) for 15 slides and flows in the Kolpu Khola watershed near Kathmandu, and by Crozier (1973) for flows in New Zealand (Figure 29). The plot for the Pokhara debris flows



A	y = -0.47x + 3.65	r = 0.83	Crozier 1973
B	y = -0.30x + 3.82	r = 0.313	This study
C	y = -0.33x + 5.17	r = 0.551	Caine and Mool 1982

Figure 29. Regression on tenuity index on process index for all slope failures in the Pokhara area, except for rockfalls, rockslides, and undercut debris slides.

alone was steeper ($y=-0.98x+6.07$, $r=0.706$, $n=12$), and significant at the 95% level. The implication of these inverse relationships between tenuity and process is that shallower failures are more tenuous, i.e. fluid, than deeper ones. As with the process index results, this may indicate a higher water content in the shallower slides.

3.3.4 MATERIAL PROPERTIES AND SLOPE STABILITY

Mass movement occurs when the stress applied to material on a slope equals or exceeds the strength of the material along a failure surface, with consequent movement by fracture or plastic deformation. The shear strength, *s*, of a soil was first defined, empirically, by Coulomb in 1776, in terms of cohesion and intergranular friction:

$$s = c + \sigma \tan\phi \qquad (1)$$

where s is shear strength mobilized at failure, c is cohesion, σ is the stress normal to the shear plane, and ϕ is the angle of internal friction[51] (Coulomb 1776). s varies with σ due to the effect of increasing normal stress which increases the friction between moving particles.

In engineering terms soils can be divided into two broad classes with regard to slope stability: coarse grained cohesionless sands and gravels in which, by definition, the angle of repose when dry is equal to the angle of internal friction ($\theta = \phi$), and in which failure surfaces are essentially planar; and soils which possess cohesion and in which failure surfaces are generally curved if the material is homogeneous (Graham 1984).

Failures in the Pokhara area were usually translational. Because of this it is possible to use the concept of infinite slope analysis as an approach to a discussion of slope stability[52]. Natural slopes will rarely display the ideal conditions assumed by the infinite slope model, but it is a useful approximation when, as in the Pokhara area,

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[51] Also termed the angle of shearing resistance.
[52] For a recent review of slope stability analysis see Graham (1984).

the thickness of the unstable mantle is small compared to the length of the slope in question (O'Loughlin 1972). The assumptions of an "infinite slope"[53] and isotropic soil conditions permit the analysis of a typical slice of material above a hypothetical failure surface (Figure 30).

From considerations of continuity the forces on both sides of the slice must be equal, opposite, and colinear. For a slice of unit width and vertical thickness z (Figure 30), the vertical force across the base of the slice must equal its weight W, and can be resolved into normal (N), and tangential (W), components:

$$W = \gamma \; z; \qquad N = \gamma \; z \; \cos\theta; \qquad T = \gamma \; z \; \sin\theta \qquad (2)$$

where γ is density. Since the length of the slide surface is $1/\cos\theta$, the normal and shear stresses (σ and τ) are:

$$\sigma = \gamma \; z \; \cos^2\theta; \qquad \tau = \gamma \; z \; \sin\theta \; \cos\theta \qquad (3)$$

For stability, the downslope shear stress τ must not exceed the mobilized shear strength, s, of the material. Thus, for a cohesionless mass, the factor of safety against sliding (F) can be defined by the ratio s/τ, or:

$$F = \frac{c' + (\gamma \; z \; \cos^2\theta - u) \; \tan\phi'}{\gamma \; z \; \sin\theta \; \cos\theta} \qquad (4)$$

where c' and ϕ' are the effective cohesion and effective angle of internal friction[54].

With the free water surface at a height of mz above the failure surface (Figure 30), and seepage parallel to the slope, the pore water pressure, u, is equal to γ_W mz $\cos^2\theta$, where γ_W is the density of water. Substitution into (4) gives:

$$F = \frac{c' + (\gamma - \gamma_W \; m) \; z \; \cos^2\theta \; \tan\phi'}{\gamma \; z \; \sin\theta \; \cos\theta} \qquad (5)$$

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[53] "... a constant slope of unlimited extent which has constant conditions and constant soil properties at any given distance below the surface of the slope." (Taylor 1948).
[54] "Effective" strength parameters are those determined for the drained state, rather than for the undrained state used in short-term (total stress) analysis, where s = c.

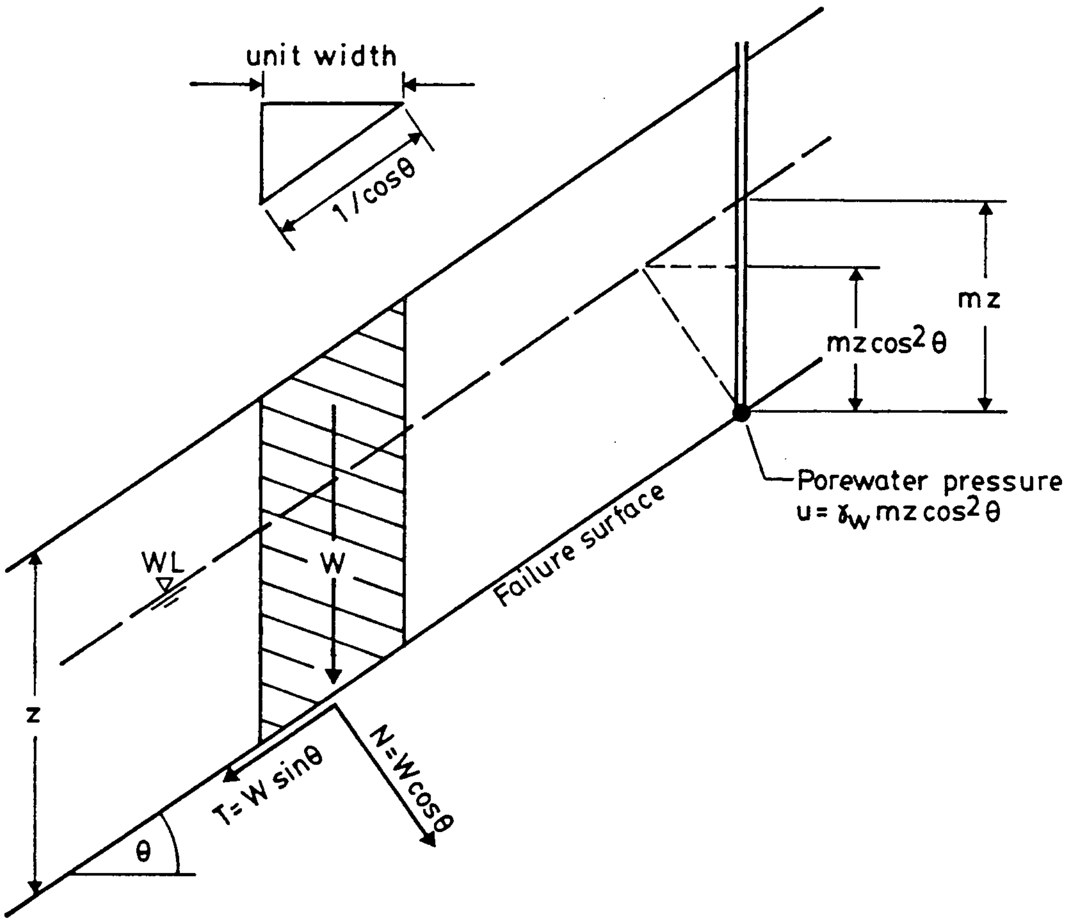

Figure 30. Diagram to illustrate the infinite slope approach to shallow slide stability analysis. See text for definition of terms and symbols.

The types of material involved in the Pokhara failures varied from untransported weathered bedrock to colluvial debris and talus to surface soils. The taluvial materials[55] included deposits of very recent origin, as within mass movement catchments, and much older deposits now being reworked. Generally these slope materials consisted of non-plastic sands and silts with a variable proportion of gravel, boulders and bedrock corestones. It is reasonable to assume that these materials had a low or non-existent cohesion, and that any strength was imparted by frictional properties. The assumption of non-cohesiveness is supported by evidence that most natural materials in slopes do not exhibit tensile strength properties at the macroscopic level (Kenney 1975), and that over time the cohesive component of strength in materials near the ground surface is lost due to unloading and weathering (Carson 1976). It has also been validated empirically through successful application of the infinite slope approach to the analysis of slope failure problems.

Under the assumption that $c'=0$, the angle at which stability can be maintained or *threshold slope angle* (Carson 1975) becomes a function of the angle of internal friction of the material comprising the failure zone (ϕ'), the maximum pore-water pressure (u) on the failure plane, and the unit weight of the mass (Carson 1976).

Brunsden *et al.* (1981) suggested that typical values of ϕ' for taluvial materials might be between 33° and 45°, based on a review of measurements in the literature. In Nepal, Caine and Mool (1982) found values of ϕ_p[56] of between 20.4° and 47.0° in untransported, *in situ* debris developed on phyllites in the Kathmandu-Kakani area. Back calculation using the infinite slope model gave threshold slope angles for this material of 32.8° when drained, and 18.5° when saturated. In the Pokhara area the mean failure surface angle of shallow translational failures was 38.5° (st. dev.=5°, n=15), which is very similar to the mean slope angle of undercut slopes in phyllite

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[55] Mixed talus and colluvium.
[56] Peak friction coefficient, equals angle of internal friction.

in eastern Nepal (39.2°) determined by Brunsden *et al.* (1982) from profile data. Brunsden *et al.* found that their debris slides generally occurred in the range of 35° to 43°, which prompted them to suggest they may be controlled by full frictional strength rather than being dependent on saturated regoliths and high pore water pressure conditions. Sufficient data to carry out a realistic assessment of slope material properties in the Phewa watershed are not available.

In other forested environments sensitivity analysis of the infinite slope model indicates that, whilst the factor of safety may be relatively insensitive to changes in ϕ' and density, it responds rapidly to changes in θ, z and c, and also to piezometric pressure at high groundwater elevations (O'Loughlin 1972; Wu *et al.* 1979; Gray and Megahan 1981). In many of the cases analysed the contribution of roots was critical to stability, increasing cohesion both through root tensile strength and by soil arching or buttressing between trunks and root systems. For example, in Alaska, Wu *et al.* (1979) found a shear strength value provided by roots of only 5.9 kPa to be critical in preventing failure, and O'Loughlin (1984a) found values of artificial cohesion due to roots of 1.0 kPa to as much as 20 kPa reported in the literature.

Most of these studies were carried out in areas of coarse–textured soils. In the Pokhara area the underlying phyllitic rocks weather rapidly to clays, and this might supply some cohesion. Alternatively, shear strength could be increased by the frictional component supplied by interactions between coarse particles in the debris and roughnesses in the underlying bedrock. The argument for cohesion can be supported by the morphometric analysis which indicated saturation and high pore water pressures on failure, and so high resistances to movement in pre–failure material. Two direct shear tests carried out by Caine and Mool (1982) in the Kathmandu area indicated an almost total loss of cohesive strength in remoulded materials developed on granite and augen gneiss, and penetrometer tests in the same area indicated that debris derived from phyllitic rock was appreciably weaker than that from other lithologies. The significance of this loss of strength on remoulding is that the

> "entire rheological character of a mass may change from quasi-plastic to viscous if amounts of pore fluid are large enough" (Carson 1976)

with a resulting extension of downslope travel.

3.3.5 LANDSLIDE INCEPTION

3.3.5.1 *Geological: undercutting, faulting, oversteepening*

The survey of mass movement characteristics in the Pokhara area suggests three categories of slope failure with fundamentally different causes. These are:

(1) failure due to the removal of basal support by undercutting, usually by fluvial action but occasionally by construction activities;

(2) failure on or near structural discontinuities;

(3) failure by shallow sliding and rotation on non-undercut slopes, or by deeper creep and eventual failure of large masses of material in areas of deeper regolith;

The first category of failures is important as a direct source of sediment for fluvial transport. In the Phewa watershed the second category, fault-induced mass wasting, was responsible for a very large proportion of all material displaced (see section 3.3.2). The prevalence of large, active failures close to structural discontinuities was probably due to movement along active faults, and to the presence of shattered rock which allowed the penetration of water and consequently deep weathering and loss of cohesion. Dip and bedding also contributed to instability, and it is interesting to note that according to Karunakaran (1975), the joints along which stress release failure takes place in many Himalayan river valleys are completely independent of structural and lithological boundaries. These "valley joints" (Karunakaran 1975) or "deep tension cracks" (Carson 1971) generally run parallel to the surface of the slope. They are a result of *unloading*, the reduction in pressure caused by the removal of overlying material by denudation, and the consequent volume expansion or *deconsolidation* (Carson 1976). Strength reduction by deconsolidation affects both cohesion, by promoting fractures, and friction, by reducing interlocking between the resulting blocks.

In the area around Pokhara, it was possible to confirm the presence of faults by drawing lines between mass movement clusters marked on 1:50,000 topographic maps and then visiting the sites in the field. An excellent example of this was the fault line running north west from Bijaipur near Pokhara to Dandagaon and Jumleti[57], traceable on maps numbers 62 P/16 and 71 D/4.

The third category of failures is a response to oversteepening, and can be viewed as an attempt by the slope to retreat to a stable angle. The grouping of shallow debris slides around 38.5^0 and the presence of apparently stable slopes at lower angles is confirmation of Brunsden *et al.*'s (1981, p. 49) suggestion that, as in eastern Nepal,

> "a significant control on the distribution of mass movement is likely to be the intensity of lateral and vertical erosion or stream incision which maintains steep slopes, promotes basal removal of debris, and prevents the free degradation of the slopes to a stable angle."

Oversteepening, weathering and deconsolidation are all long term causes of slope failure, either increasing shear stress or decreasing shear strength. Shorter-term causes include loss of root reinforcement following deforestation, high pore water pressures during the monsoon, and vibration or shock caused by seismicity[58].

3.3.5.2 *Anthropic: effects of forest clearance*

In the Phewa catchment a large number of shallow translational slides were observed in the small, recently deforested catchment of the Pokhreebyasee Khola immediately west of Pokhara (Figure 5). Rapid destruction of the forest in this catchment commenced with the nationalisation of forest resources in 1957, and was

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[57] Not shown on the recent 1:125,000 L.R.M.P. geological maps.
[58] Also by explosions, thunder, sonic booms and traffic.

complete by the early 1970's (Y. Khatiwada, pers. comm.). The slides all occurred between 1972 and 1978, and it is interesting to speculate that they could be due to deterioration of root tensile strength following final deforestation. O'Loughlin (1984b) states that on clear-felled areas the landslide-susceptible period usually occurs between 2 and 8 years after harvesting, depending on tree species, slope, and climatic conditions. The Pokhreebyasee Khola catchment slides fall neatly into this period.

Elsewhere in the Phewa Valley, shallow failures were particularly numerous on the southern side of the Kaski ridge (Figure 17), but also occurred in forest. The geographical association of the majority of these shallow failures with cleared or scrub areas can be explained, in part, by increased runoff causing fluvial incision and gullying, and consequently the oversteepening of slopes. Thus, there may well have been an increase in the number of small, shallow landslides in the watershed due, both directly and indirectly, to deforestation. However, they are only minor contributors to total sediment production (see 3.3.2).

Elsewhere in Nepal it has been observed that although shallow slides are frequent on deforested slopes, larger, deeper failures are more common on forested terrain (B. Carson, in press). This is most likely to be due to the location of remaining forests on steep slopes which are intrinsically liable to major failures (see 1.5.2.2). In the Phewa watershed extensive planting of *Alnus nepalensis* in and around the mass movement catchment at Pamdur failed to prevent further sliding (Figure 21), but did provide wood and fodder from otherwise useless land.

3.3.5.3 *Extrinsic: pore water pressure*

According to Cedergren (1967), soil water lowers slope stability by:

(i) causing soil particles to migrate to escape exits, resulting in piping and erosional failures;

(ii) reducing or eliminating cohesive strength;

(iii) increasing neutral pore water pressures and thereby reducing effective stresses and shear strength;

(iv) producing horizontally inclined seepage forces which increase downslope tangential forces on soil masses and the possibility of failure;

(v) lubricating failure planes after small initial movements occur;

(vi) supplying an excess of fluid that becomes trapped in soil pores during earthquake or other severe shocks and promotes liquefaction failures.

In the study area overland flow was a common sight during rainstorms. Although this may have been due in part to precipitation intensities exceeding soil infiltrability, with consequent surface runoff over unsaturated soils, the length of the monsoon and the intensity and duration of individual rainfall events make it reasonable to assume that at times the piezometric surface would have risen close to or even above the ground surface. The effectiveness of high piezometric levels in affecting stability has been demonstrated by O'Loughlin (1972), who reported the maximum stable slope of a saturated, cohesionless soil mantle with downslope seepage to be approximately half that of an unsaturated mantle. He is supported by Terzaghi (1950, quoted in Thornes 1980), who noted that shallow failures may usually be accounted for by high pore water pressures causing a reduction in the shear strength of slope materials. Transient high water tables are thus prime candidates for explaining the initiation of the small, shallow debris slides in the Pokhara area.

In discussing groundwater conditions, it is essential to differentiate between two basic groundwater regimes, and two categories of failure. Groundwater can be seasonally high, as is indicated for the shallow failures which were often on interfluves and other mid or upper-slope locations, or perennially, caused by groundwater discharge. In the first case, monsoon rains will have a direct effect on stability. In the second, the constant moisture reduces any cohesive strength and lubricates failure planes, and the low-elevation position allows the build up of high piezometric pressures under confining layers of debris. Such mechanisms could be involved in the continuous activity of the slow debris flows in the Phewa valley, and their acceleration during the wet summer months.

Whilst new failures in Nepal almost invariably occur during the monsoon period (see e.g. Prasad's data in Appendix 1), and often can be related to specific storm events, as yet no study of the response of piezometric levels to rainfall has been undertaken in the country. In the Kathmandu-Kakani area, Caine and Mool (1982) suggested that water tables had to rise to within 2 m of the ground surface (i.e. into the weathered mantle) before sliding was initiated, but they noted little new geomorphic activity during a heavy rainfall in June 1980. Following Crozier and Eyles (1980), this led them to emphasize the importance of antecedent moisture conditions to slope failure.

Barring extreme events, the magnitude of rainstorms which trigger slope failures in Nepal is uncertain. Caine (1980) has proposed a limiting curve for precipitation intensity below which failure is seldom recorded (Figure 11), which suggests a threshold for slope stability of approximately 100 mm/24 hr. In the Pokhara area rainfall events with intensities above this value are a frequent occurrence (Figure 11). At Pokhara Airport 150 mm/24 hr will occur at least once a year.

Caine and Mool (1982) commented that, owing to the frequency with which precipitation exceeded Caine's general threshold, extrinsic conditions might not be the most important limiting factors affecting mass wasting in the Kathmandu area. Instead, intrinsic characteristics, i.e. topography and material properties, were put forward as the primary controls. On the other hand, Brunsden *et al.* (1982), discussing the magnitude-frequency question, emphasized the role of heavy precipitation in achieving pronounced erosion. This view is supported by oral history. For example, as reported by Carson (in press), in one area southwest of Banepa near Kathmandu the villagers acknowledged that all the landslides still visible on the surrounding slopes had occurred during two heavy rainfall events, in 1934 and 1971. The most recent event of this nature in Nepal occurred in late September 1984, when the last storm of the season deposited approximately 700 mm of rain on the Siwaliks in 36 hours, resulting in widespread slope failure on all land-use types (B. Carson, pers. comm.).

3.3.5.4 *Extrinsic: seismicity*

Seismicity has been implicated in mass wasting in a number of studies, including that of Simonett (1967), with numbers of failures tending to decrease logarithmically with distance from the epicentre. The effects and relative intensity of seismic shaking are influenced by surface slope, near-surface geology, regolith properties, groundwater and soil moisture conditions, and vegetation cover (Hewitt 1983). Rapid mass movements are a central feature of many high magnitude earthquakes, and often have devastating results (see e.g. Hansen 1965). The physical and cultural factors influencing the extent of earthquake damage have been reviewed by Hewitt (1983), and an introduction to earthquakes and their effects in the Himalayan arc is available in Chaudhury (1981). Notable earthquakes which have affected Nepal include the Assam earthquake of 1897, the Dhubri earthquake of 1930, the Bihar-Nepal earthquake of 1934 which caused extensive damage in the Kathmandu Valley, and the 1966 earthquake in the west of the country. The combination of seismic shock both with and without monsoon rain events is undoubtedly a trigger for slope failure in the region.

* * * * * * * * * * * *

The results of the survey of hillslope processes indicate that, historically, mass movement is probably the principal mechanism by which slopes have evolved in the study area. Currently, the most numerous failures are shallow, translational, and have extended runout paths. They occur on all forms of slope and under all land use types, and are not usually incorporated into the drainage net. Consequently recovery is rapid, and most sites appear to be revegetated after ten years. Volumetrically, the largest producers of sediment are "mass movement catchments" associated with structural or lithological weaknesses. These result from specific geological conditions and may have crossed some geomorphological threshold, encouraging further growth. The shallow failures are probably triggered by transient increases in pore water pressure resulting from prolonged intense rain. The large failures may be triggered in the same way, but are invariably associated with groundwater discharge, which maintains sediment transfer activity throughout the year.

Locally, surface erosion may be responsible for rates of sediment production which are twice that attributable to mass wasting. The contributions of gullying, shallow creep, and solution to surface lowering are unknown.

Sediment produced by these hillslope processes is transferred by mass movement or mass transport to the valley floor, where, owing to the perched base level caused by the presence of the lake, it accumulates. The interaction of this material with the fluvial system forms the subject of the next chapter.

Chapter 4

FLUVIAL PROCESSES IN THE PHEWA VALLEY

4.1 INTRODUCTION

In recent years increasing attention has been paid to sediment budgets and routing, i.e. the production, transport and discharge of detritus from a drainage basin[59]. The construction of a sediment budget for a catchment presumes the recognition and quantification of transport processes and storage elements, and identification of the links between them (Dietrich *et al.* 1982). Quantification of the budget requires lengthy and detailed monitoring to measure the components of the sediment balance, and the design of the monitoring network itself requires the construction of an approximate budget based on preliminary studies (Dietrich and Dunne 1978). However, where episodic events are a major contributor to landscape change even extended periods of measurement may not be sufficient to include these formative events.

Sediment movement is a continuous process extending from source areas on slopes to final deposition in sedimentary basins inland or offshore. Once delivered to channels by slope processes, sediment becomes part of the fluvial system for onward transport. In transit, particles undergo changes in size and angularity which interact with hydraulic factors to change the morphology of the channel system. Fluvial geomorphology has been studied extensively in mid-latitude areas (see e.g. Leopold *et al.* 1964; Gregory and Walling 1973; Dunne and Leopold 1978), but infrequently in tropical mountains. In Nepal, there is only one published quantitative study of basin and channel geomorphology to complement Brunsden *et al.*'s (1981) descriptive work on fluvial systems in eastern Nepal, and that is Caine and Mool's (1981) paper on two small streams in the Mountain Hazard Mapping Project study area northwest of

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[59] For a recent discussion see Swanson *et al.* (1982).

Kathmandu (Caine and Mool 1981). The authors concluded that the channels studied did not behave in an "abnormal way" compared to streams in mid-latitude areas, and that therefore

> "...models derived from mid-latitude areas can be applied with few modifications to the serious stream problems of the Middle Hills of Nepal." (Caine and Mool 1981, p. 243).

The Phewa watershed is unusual in Nepal in that, currently, base level is controlled by seasonal water levels in the lake rather than by riverbed levels downstream. Phewa Tal has formed and been drained several times during the Pleistocene (Yamanaka *et al.* 1982), and was created most recently by the catastrophic fluvial deposition of the sediments of the Pokhara Formation in the Pokhara Valley some 500–600 years B.P. (see 2.2.1.1). The existence of laminated lacustrine deposits in the vicinity of Pame, currently being eroded by the Harpon Khola, suggests that this event resulted in the formation of a stable lake surface some 2–3 m higher than at present, unless the deposits are the result of some unrecorded dam[60]. The lake acts as a sediment trap, and is useful in permitting an estimation of the sediment yield of the Harpon Khola from measurements of sediment accumulation in its delta. By comparing this to estimates of sediment production upstream it should be possible to determine a sediment delivery ratio, and hence a denudation rate for the catchment.

The recent publication of Caine and Mool's (1981) paper, the interest of the sediment yield estimation exercise, and the need to understand the fluvial component of the sediment transport system, suggested that this field should be investigated during the present study. Accordingly, a reconnaissance survey of fluvial characteristics in the

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[60] A rockfill dam was built on the Pardi Khola in 1942, followed by a masonry dam cemented with lime and *surki* (ground brick) in 1958 (Sharma 1974) or 1961 (Nippon Koei 1976a). The masonry dam failed due to piping on 2nd January 1975 (Nippon Koei 1976a), and a concrete dam was constructed to replace it. The sluices of the new dam were closed in June 1982 and, in order not to flood valuable *khet*, maintain a high water level of 793.7 m, the same as the old dam, rather than the design high water level of 794.7 m.

Phewa watershed was undertaken in order to determine:

(i) hydraulic geometry:

(ii) sediment transport and storage characteristics;

(iii) sediment yield to the lake.

4.2 METHODS

4.2.1 FLUVIAL MORPHOMETRY

Selected channel variables were determined at 15 stations along the Andheri Khola and Harpon Khola at approximately 1 km intervals (Figure 31). The variables surveyed were:

* width at estimated bankful stage;
* cross-section;
* water surface slope (estimated from channel gradient);
* roughness (as estimated Manning's *n*).

Measurements were made using a tape, level, staff, and clinometer.

The data from all 15 stations are listed in Table 9, but should be treated with caution owing to the difficulty of defining some of the hydraulic characteristics such as slope and *n*. Two further morphometric parameters, capacity (cross-sectional area below water level at bankfull stage) and hydraulic radius (capacity/wetted perimeter), were derived from these variables. Capacity was determined by planimetry from plots of the cross-sections.

4.2.2 SEDIMENT TRANSPORT

At each station the dominant particle size class by weight on the stream bed was determined by the pebble-count method of Leopold (1970). Random sampling of surface materials on gravel bars results in a bias towards larger sizes since, owing to greater surface area, these are more likely to be picked up. Leopold's method avoids

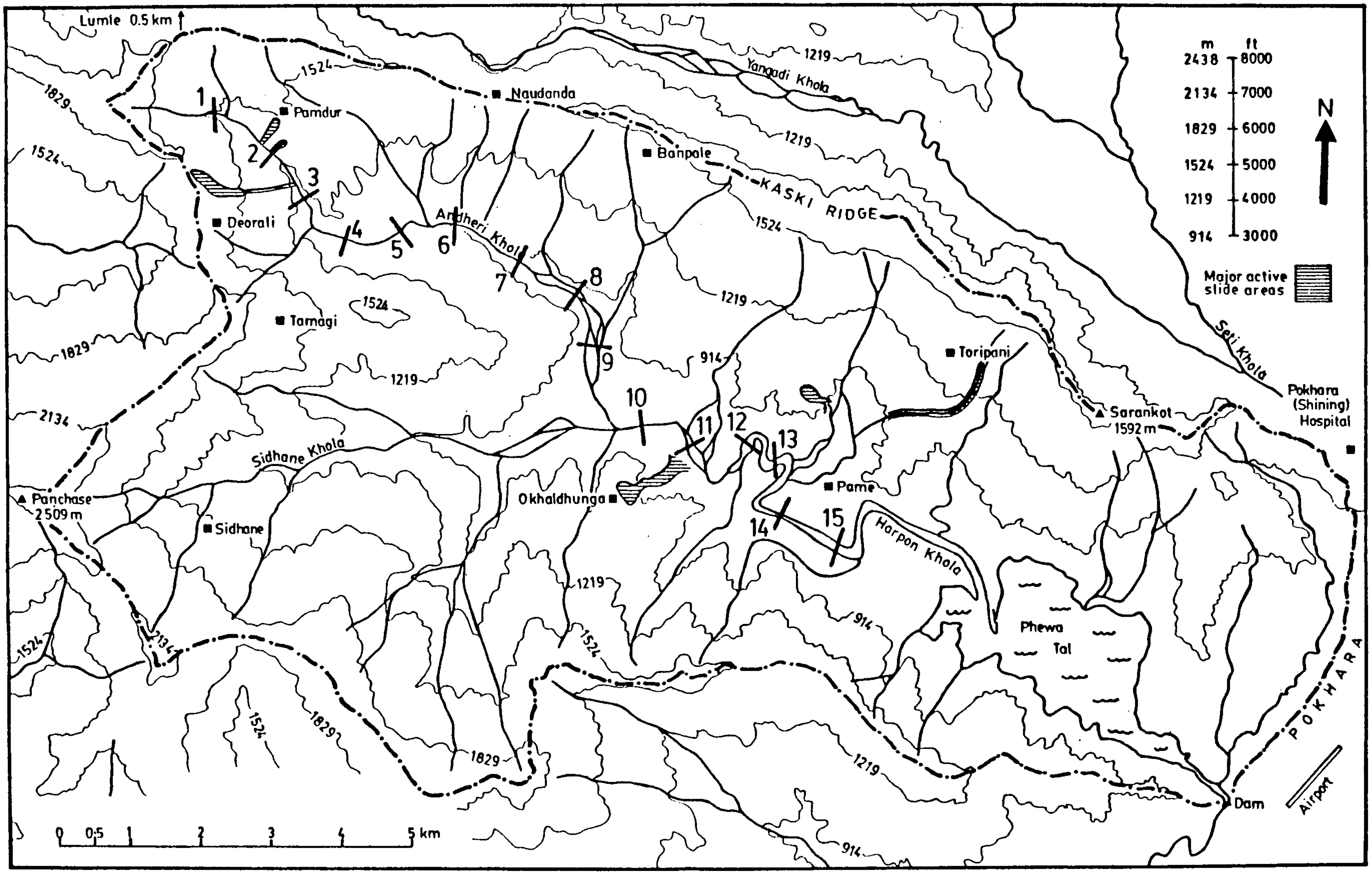

Figure 31. Phewa Valley: location of stations for channel variables survey.

Table 9. *Andheri Khola and Harpon Khola: hydraulic geometry, discharge, and dominant particle size class on channel bed*

STATION	DISTANCE D (km)	AREA DRAINED A (sq km)	WIDTH W (m)	CAPACITY C (sq m)	WETTED PERIMETER (m)	MEAN DEPTH R (m)	SHAPE W/R	SLOPE S (deg)	ROUGHNESS n	MEAN VELOCITY Vm (m/s)	DISCHARGE Q (cu m/s)	PARTICLE SIZE DOMINANT (mm)	PARTICLE SIZE SECONDARY (mm)
1	1.34	1.07	6	8.0	9	0.89	6.74	12	0.065	6.57	52.6	240+	-
2	2.24	3.03	12.5	13.0	15	0.87	14.37	12	0.065	6.47	84.2	420	-
3	3.08	4.58	8	5.4	9	0.60	13.33	13	0.065	5.26	28.5	300	? 2000+
4	4.16	7.68	15	18.9	16	1.18	12.71	4	0.060	8.94	169.3	200-470	-
5	5.34	9.65	24	28.6	29.5	0.97	24.74	4	0.060	4.32	123.6	340	1240
6	6.02	14.45	20	15.0	22	0.68	29.41	2	0.055	2.63	39.4	1200+	-
7	7.03	18.23	30	16.2	32	0.51	58.82	2.5	0.050	2.68	43.5	220-280	? 1750
8	8.04	21.49	145	62.5	150	0.42	345.2	1.5	0.043	2.10	131.2	140	440
9	8.95	26.48	350	150+	355	0.42	833.3	1.25	0.043	1.93	289.5	95	? 620
10	10.10	63.06	172	111	175	0.63	273.0	<1.25	0.040	2.40	266.4	31	-
11	10.95	65.07	245	212	250	0.85	288.2	"	0.040	2.92	619.0	46	-
12	12.73	73.57	85	109	88	1.24	68.5	"	0.040	3.76	409.8	28	-
13	13.83	74.42	58	75	60	1.25	46.4	"	0.038	3.98	298.5	<2	9
14	14.95	82.15	65	63	68	0.93	69.9	"	0.035	3.55	223.7	<2	-
15	15.65	82.69	96	102	98	1.04	92.3	"	0.035	3.82	389.6	<2	-
ERROR	5%	5%	5%	10%	5%	15%	20%	10%	25%	40%	50%		

? denotes uncertainty.
Terms are defined in the text.
Error estimates are subjective assessments of the accuracy of field measurements, proportionately increased for derived values.

this problem by correcting for area. The procedure is outlined in Appendix 3.

In addition, at each station the a, b, and c dimensions of 20 particles moved by recent flows and 10 particles not moved were measured as potential input data for equations relating grain size to velocity at the stream bed, and hence discharge (Appendix 4).

4.2.3 SEDIMENT YIELD

Sediment yield was to have been estimated by studying delta growth in Phewa Tal. However, locally available data proved to be insufficient to allow any realistic estimate of sediment delivery to be made. In case it is of interest to other workers, the methodology that was to have been adopted is noted below. The difficulties encountered with this approach are discussed in Section 4.3.3.

The growth of the delta of the Harpon Khola where it enters Phewa Tal (Figures 3, 8) has been recorded by aerial photography and, recently, satellite imagery. By superimposing outlines of the delta from sequential images it proved possible to trace the expansion of the delta (Figure 32). The 1972 and 1978 outlines shown in the figure derive from the air-photo coverage described in section 3.2.1. The 1958 outline was taken from the Indian one-inch map, which is based on 1958 aerial photography. The 1975 outline is from a false-colour LANDSAT image taken in March/April 1975. Scale correction and image transfer was achieved using a zoom transferscope.

Approximate lake contours are known from two bathymetric surveys (see 4.3.3). By measuring the areal increase of the delta over time, correcting for sediment density, bathymetry, and water level, it was thought that a unit rate of deposition could be calculated. This estimate of sediment yield could then be checked against figures for suspended sediment in the Harpon Khola in 1979 measured by Impat (1981). If

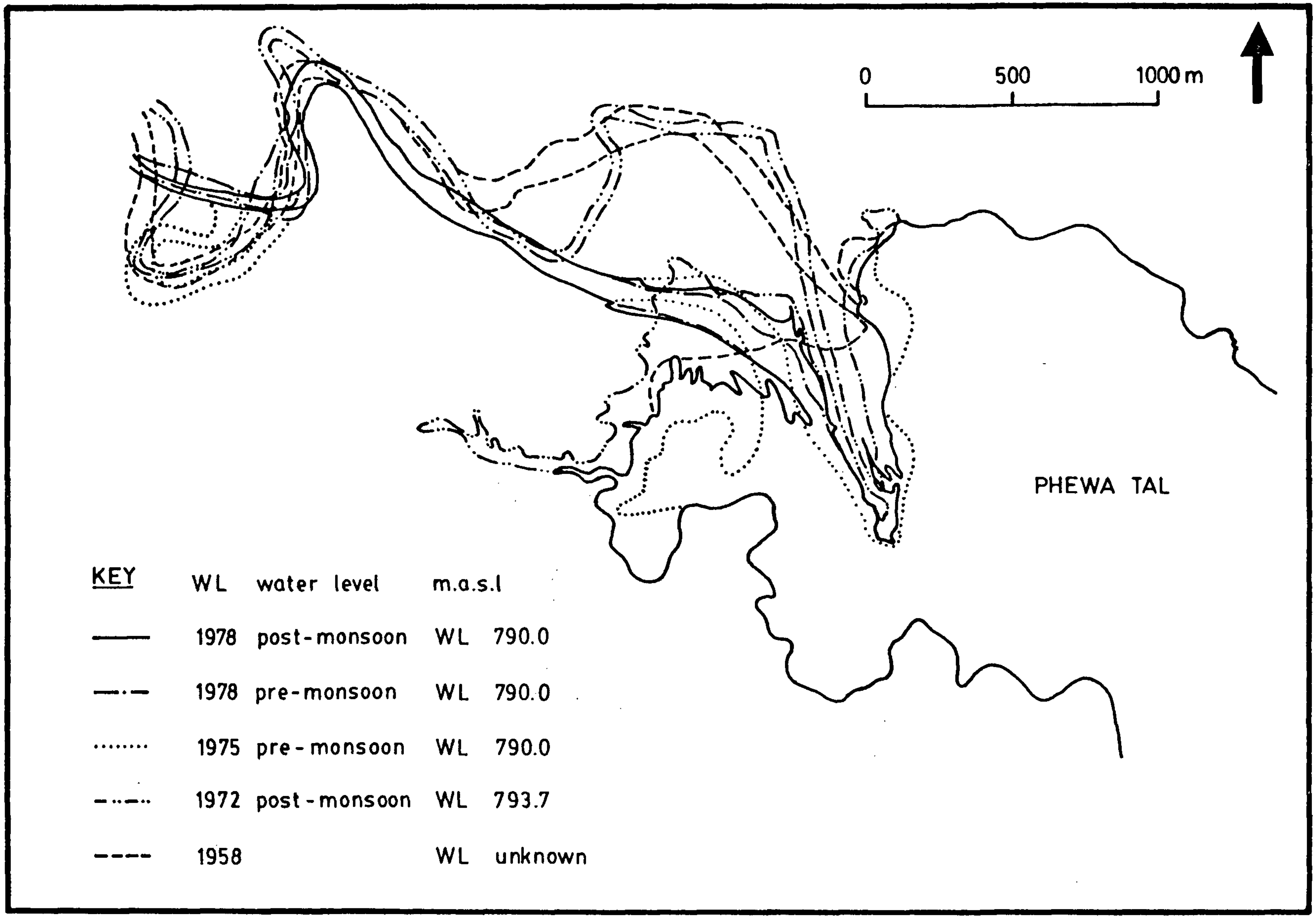

Figure 32. Growth of delta in Phewa Tal, 1958 to 1978.

confident in the result, an indication of the sediment delivery ratio in the catchment could be gained by reconciling the estimate of sediment yield in the river with the estimates of erosion computed from the survey of hillslope processes.

4.3 RESULTS AND DISCUSSION

4.3.1 CHANNEL GEOMETRY

Long profiles of the Harpon Khola and its two tributaries, the Andheri Khola and Sidane Khola, are shown in Figure 33, together with the profile of one of the steep, ephemeral channels on the south side of the Kaski ridge. The profiles were developed from the 1:25,000 topographic base map (I.W.M. 1979), and emphasize the steepness of the upper parts of the catchments. Here, headward erosion is destroying the old surfaces, and a number of nickpoints can be seen on the profiles. In these reaches (Stations 1–6, Figure 31), the valley profile is strongly V-shaped, with forested slopes of approximately 45^0 rising for 100–200 m to a marked break which forms the lower limit of cultivation. The channels have characteristics typical of mountain streams, with limited width (6–24 m, Table 9), intermittent bedrock beds, rough longitudinal profiles with angles of $2-14^0$ and numerous waterfalls (Figure 34). Between stations 7 and 8 a marked change is apparent. This is the junction between the high and low relief areas of the watershed, and for some 500 m the Andheri Khola becomes transitional, with downcutting, lateral corrasion, and minor alluvial terraces all present.

From this point until Stations 11–12, both the Andheri Khola and the Sidane Khola are braided. The river beds are wide, choked with coarse material, and laced by anastomosing channels (Figure 35). Minor lateral corrasion may occur where the thalweg abuts valley side slopes. Gradients are low, $\leq 1.5^0$. However, beyond Station 11 another change occurs. The river reverts to a single channel, which meanders across a

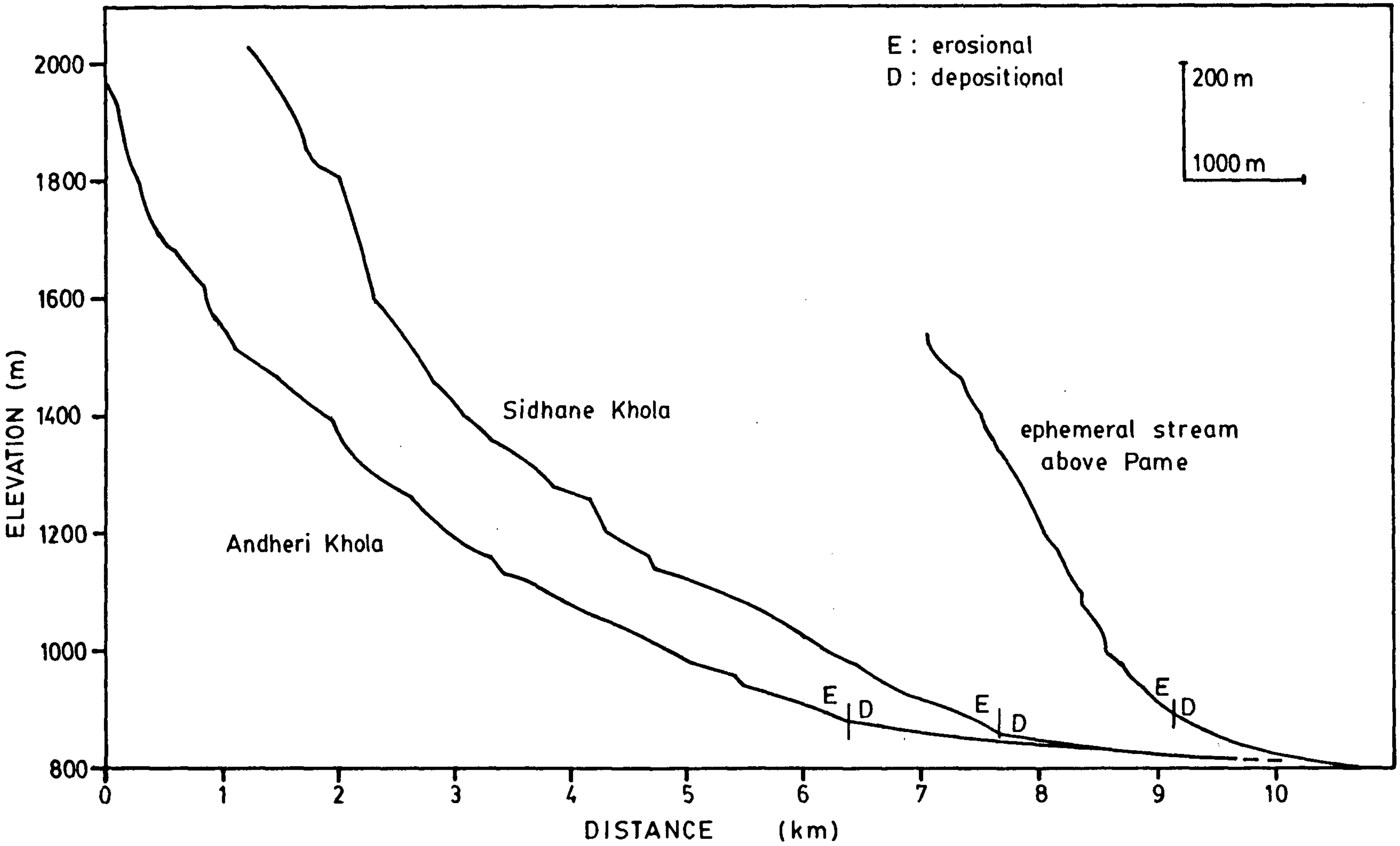

Figure 33. Phewa Valley: long profiles of the Andheri Khola, Sidane Khola, and an ephemeral stream on the south side of the Kaski ridge near Pame.

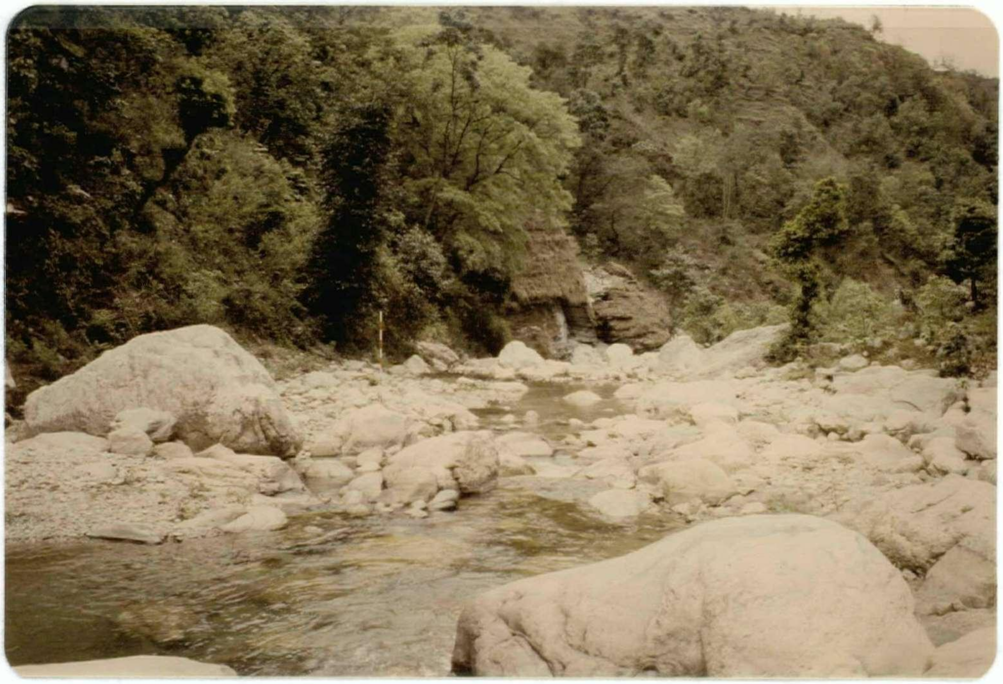

Figure 34. Station 5, Andheri Khola, looking downstream.
Note:
(1) The variability of particles sizes in the channel bed.
(2) The fresh rockfall from the base of the vegetated cliff in the background directly into the stream.

Figure 35. View upstream towards Station 9, from the confluence of the Andheri Khola and the Sidane Khola. The braided channel has been partially controlled by a gabion diversion built to protect *khet.*

cultivated floodplain to the lake (Figure 6).

Channel size. Size increase downstream was irregular (Table 9), although linear regressions of capacity (C) on distance downstream from source (D) and area drained (A), were significant at the 95% and 99% levels. The use of capacity as a measure of size allows comparison with the results of other workers. For example, a power regression of C on A and D for the 15 stations gave:

$$C\ (m^2) = 4.621\ A^{0.720}\ (km^2) \quad (r=0.854)$$

$$C\ (m^2) = 3.232\ D^{1.308}\ (km) \quad (r=0.833)$$

The exponents in these regressions are very similar to those found by Caine and Mool in the Kathmandu area, respectively 0.784 and 1.363, and are within the range of values found in mid-latitude areas (Caine and Mool 1981). However, Caine and Mool found their coefficients to be 0.667 for C on area, and 1.482 for C on distance, respectively, which they considered high. They suggested that this might indicate a relatively high yield of runoff from their catchments. Continuing the same argument, the even higher Phewa coefficients may reflect the steepness of the catchment and the intensity of monsoon rainfall events.

Channel shape. Channel shape was highly variable, with abrupt changes graphically illustrated in Figure 36, a plot of shape (defined as width, W, divided by hydraulic radius, R) against distance downstream. This variation is a reflection of the three distinct forms assumed by the stream: the rapidly eroding upper reach involving both headward erosion and lateral corrasion, the central braided reach, with flow disappearing in the dry season, and the meandering reach above the lake with flow confined to an active but well-defined channel. This downstream change in channel morphology and valley shape is largely a result of the presence of the lake, which

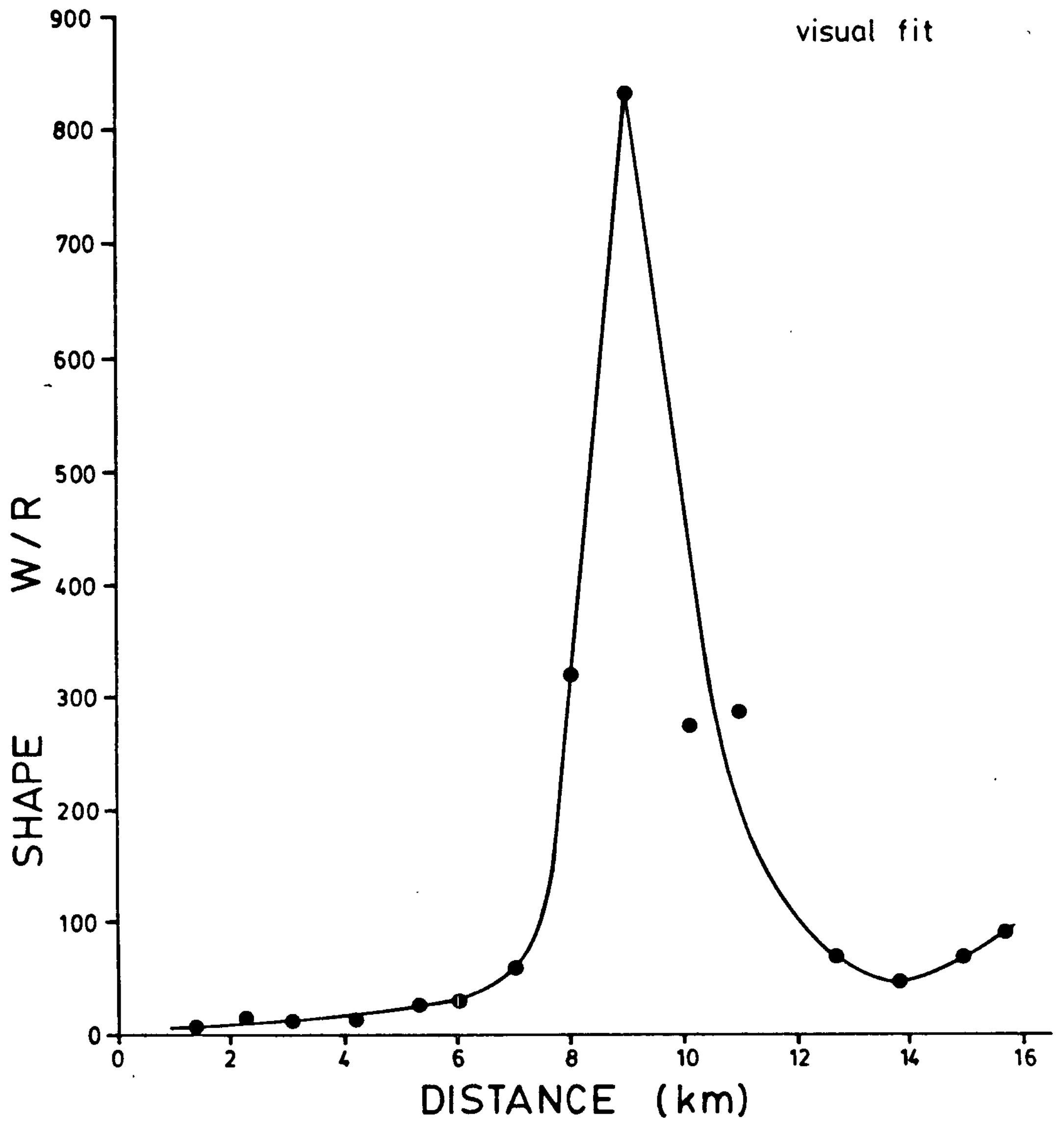

Figure 36. Graph of channel shape against distance. Data from Table 9.

has caused aggradation. It is also due in part to the movement of coarse sediments through the system. Variations in hydraulic geometry appear to be a complex response to both the water and sediment moving through the channel and the character of the material in the bed and banks (Gregory and Walling 1973). Typically, braided channels occur where stream gradients drop, hydrographs are flashy, and bedload is high (Gregory and Walling 1973). All these conditions apply in the Phewa valley.

Channel roughness. Roughness decreased rapidly with distance downstream, which is consistent with a diminution in particle size. A plot of Manning's n on distance (Figure 37) could be interpreted as sigmoid curve, reflecting the rapid changes in the channel between stations 5 and 8. Linear regression of n on distance downstream gave:

$$n = 0.069 - 0.0024 \text{ D (km)} \qquad (r=0.958)$$

significant at the 95% level.

Stream discharge. The mean velocities (V_m) shown in Table 9 were calculated using Manning's equation, an empirical equation which relates velocity to water surface slope (S), roughness (n), and hydraulic radius (R):

$$V_m = \frac{1}{n} R^{2/3} S^{0.5}$$

Discharge (Q) was calculated from mean velocity and capacity, and increased downstream according to linear functions with the form:

$$Q \text{ (m}^3\text{/s)} = 63.8 + 4.04 \text{ A (km}^2\text{)} \qquad (r=0.770)$$

$$Q \text{ (m}^3\text{/s)} = - 3.32 + 25.9 \text{ D (km)} \qquad (r=0.711)$$

both significant at the 99% level.

Before discussing discharge estimates, it is advisable to glance at the error values in Table 9. For the morphometric data these error figures are subjective assessments of the accuracy of the field measurements, and serve to emphasize the crudeness of the

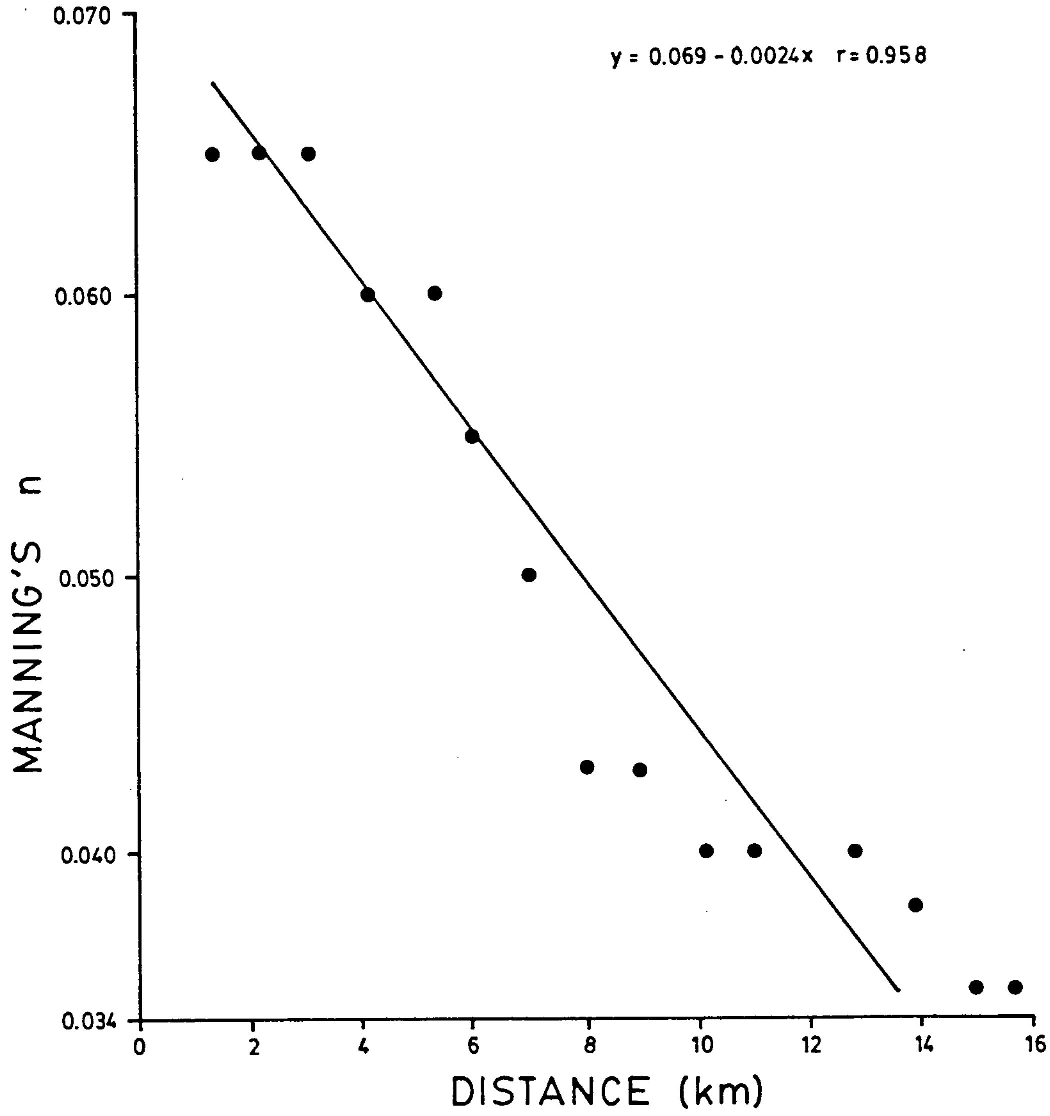

Figure 37. Regression of Manning's *n* on distance. Data from Table 9.

derived values. Nevertheless, the discharge at station 16 indicated by the regressions, 400 m^3/s, compares well with an estimate for the 100 year flood event at the Pardi Dam at the outlet of the lake of 630 m^3/yr, a figure derived by extrapolation from the Andhi Khola at Dumrichaur (Nippon Koei 1976b). The flood estimate is equivalent to a runoff 4.9 $m^3s^{-1}km^{-2}$ (msk) from the whole catchment, compared to 4.8 msk from the regression of Q on A above. The *slope* of the regression line indicates a unit discharge of approximately 4 msk in addition to the intercept value. Assuming 100% runoff (a fully saturated mantle), this is equivalent to a rainfall intensity of some 350 mm/day, a possible event in the area (see Figure 11). Caine and Mool (1981) also report estimated peak flows of up to 4.0 msk in both the streams which they investigated near Kathmandu.

The absence of flow records prevented any attempt to assess runoff coefficients, or the influence of land use on stream flow.

4.3.2 SEDIMENT TRANSPORT

Table 9 summarizes the dominant particle size class by weight[61] found at the various stations. In general, particle size diminished with distance downstream, although not in a regular fashion. Below station 12 (Figure 31) only sand and silt fractions were present.

A plot of dominant size class and secondary peaks (Figure 38) revealed two distinct phenomena: firstly, an abrupt reduction in particle size between stations 7 and 8 where the stream debouches onto the valley floor; secondly, the presence of very large material at some, but not all, stations[62]. The reduction in particle size

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[61] Equivalent sieve size class. See Appendix 3.

[62] The very high dominant size at station 6, 1200 mm+, is a genuine product of the sampling procedure, but should obviously be classed with the occasional boulders comprising the "secondary peak" column. Finer material may have been present at the site but protected by an armour layer, and so not sampled, or the location could have been a depositional site for large debris from a point source on the hillslopes above.

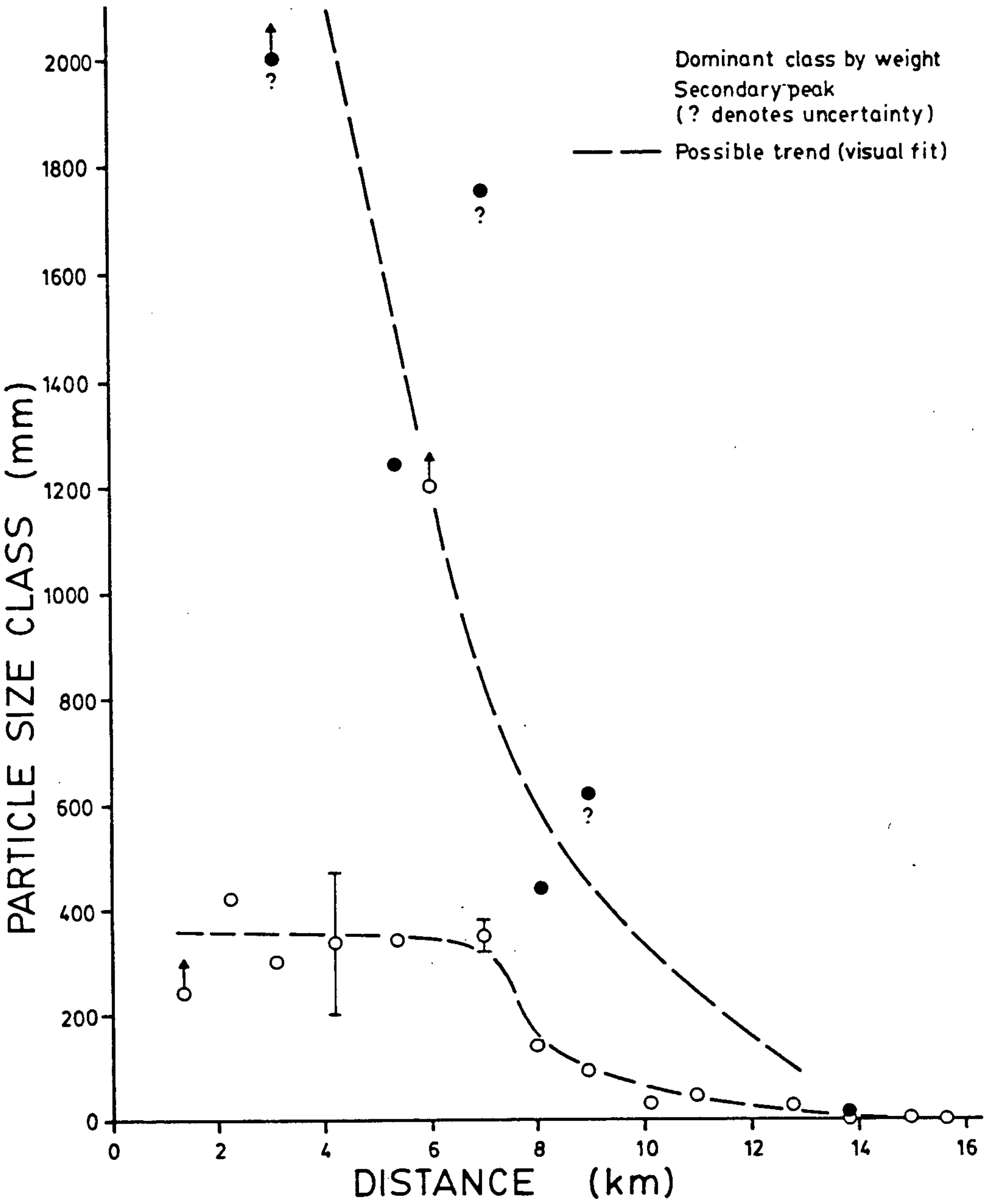

Figure 38. Graph of dominant particle size class against distance. Data from Table 9.

downstream can be accounted for by both attrition and sorting, and so is a result of both lithology and process. The boulders (some are visible in Figure 33) were invariably quartzite, rather than the phyllitic schist predominating in the bedload, and so more resistant to abrasion and comminution. Many were far too large to be moved by normal fluvial events, which suggests that they may be relicts, deposited in the valley bottom by hillslope processes and subsequently exposed as fluvial erosion removed the matrix surrounding them. No records of local stratigraphy were made and so it is not possible to determine whether this matrix was alluvial or the result of a debris torrent or similar event.

The sudden reduction in particle size between stations 7 and 8 can be explained in two ways. The reduction in gradient and increase in channel width at this point cause a marked diminution of the river's transport capacity, and so materials are deposited here. In addition, it is the point at which a large debris fan is spreading across the valley, built up from sediments transported by gullies from the long slopes above.

Scour depths were observed to be 1 m or less along the braided section of the river, between stations 8 and 11, increasing to approximately 2 m downstream around stations 12 to 15. Upstream, along the V-shaped gorge above station 6, scour depths again appeared to be approximately 1 m, but the extremely rough channel precluded accurate measurement.

To estimate flow velocities and depths required to move the very large particles in the stream bed a multiple-technique approach similar to that of Bradley and Mears (1980) could be used. Bradley and Mears were interested in determining what magnitude of flow was required to move large boulders in a creek in Colorado. By using six empirical and two theoretical techniques to convert particle size to competent velocity, and three other equations to estimate flow depths, they were able to give a confident statement that, in their stream, boulders with a mean intermediate dimension of 1.88 m would probably be moved by flows with a velocity of 4.7–7.6 m/s and a depth of 3.4–4.9 m (Bradley and Mears, 1980). The associated discharge was of the order of 625 m^3/s. Their confidence was based on the relative consistency of the values predicted by the different techniques.

4.3.3 SEDIMENT YIELD

Figure 39, an enlargement and simplification of Figure 32, clearly shows the rapid growth of the delta of the Harpon Khola in Phewa Tal between 1958 and 1978. Local opinion associates much of this growth with two erosional features, the mass movement catchment near Pame, and a deep and active gully in the same sub-watershed climbing up the Kaski ridge near Toripani (Figure 16), now stabilised by gabion check-dams.

In order to calculate sediment yield from a delta, it was necessary to know the composition and density of the materials deposited. Visual inspection and hand-texturing indicated a predominance of sand and silt size classes on the riverbed at station 15 on the Harpon Khola. Fleming (1978) described sediment "from the lake bottom" as being clay for at least 2 m depth, but the location of his sampling sites was not reported. It is probable that the delta can be classified as a ***bar-finger sand*** delta (V. Galay, pers. comm.), an elongated sand body of greater density than the pro-delta sediments, and with a bi-convex form in cross-section (Reineck and Singh 1973). The bi-convexity is caused by the gradual sinking of the sand under its own weight as the sediments below consolidate[63].

For further calculation, the density of the delta deposits could be assumed from these characteristics, but before doing so an additional problem intervened. This was

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[63] For a comprehensive introduction to lake sedimentology which emphasizes the implications for environmental management, see Håkanson and Jansson (1983).

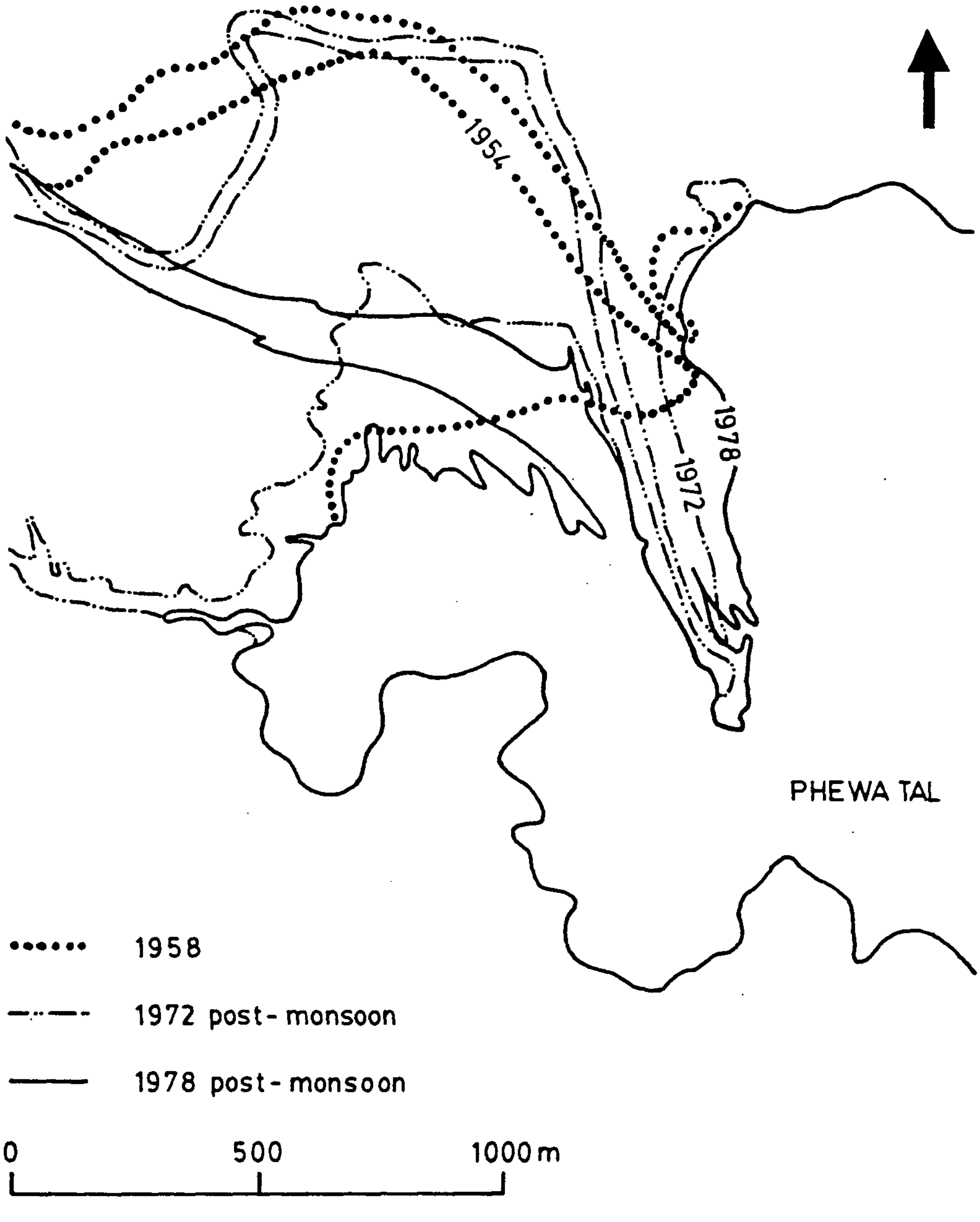

Figure 39. Growth of delta in Phewa Tal, enlarged.

that the water level in the various images was not constant (Figure 32), and the shallowness of the lake in the vicinity of the delta meant that any fluctuation in water levels resulted in large movements of the shoreline, and corresponding uncertainty concerning the size of the delta.

As mentioned in Chapter 3, the Phewa Tal has been the subject of two bathymetric surveys: in October 1976 by Ferro and Swar (1978), and in late 1979 by Kraayenhagen and Impat (Impat 1981). Both surveys were carried out by towing an echosounder behind a rowing boat or dugout across the lake at steady velocity, fixing positions on transects by compass bearings, and interpolating the echosounder read-out to draw isobaths at 2 m intervals. Ferro and Swar (1978) present a map of these underwater contours at a scale of 1:28,100, but information on Kraayenhagen and Impat's work is limited to a table showing areas between isobaths for both surveys (Impat 1981). Both surveys were carried out with a water level controlled by the broken dam at approximately 790.0 m (Nippon Koei 1976a). Ferro and Swar's map indicates a delta front of approximately 18 m depth, but the complications of unknown sediment composition and density, uncertain bathymetry, and fluctuating water levels combined to make any estimation of sediment yield by the method proposed hazardous, and it is not attempted here.

However, before leaving the subject, it is important to emphasize that neither rates of sedimentation in nor rates of sediment delivery to Phewa Tal are known. This emphasis is necessary to counteract the tendency in the region for first approximations to be quoted as facts. With regard to the lake, two of these approximations are circulating in Nepal. The first is Fleming's estimate of sediment delivery based on a mass balance analysis of phosphorus dynamics in Phewa Tal (in Fleming 1978, repub. as Fleming 1983)[64]. In March and May 1978 Fleming found the concentration of

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[64] In these papers Fleming also presents a simplified water balance for the watershed, but includes in it a value for evaporation from the lake of 51 x 10^6 m^3/yr. Since

phosphorus in the surface waters of the lake to be 0.16 mg/l[65]. By making major simplifying assumptions, including constant concentration throughout the lake, no overall gain or loss from year to year, an annual throughput equivalent to the rate of flushing (defined as total flow/lake volume), and an annual loss in sedimentation on the lake bed, he concluded that the input of phosphorus to the lake was 13,862 kg/yr. Since the soils on the "highly erodible" north side of the watershed were "two thirds clay", and the sediments on the lake bottom were also clay, Fleming then made the surprising assumption that the sediment delivery ratio of nutrients and soil to the lake was also about two thirds (Fleming 1978, p. 17; Fleming 1983, p.240).

The second approximation is Impat's estimate of the longevity of the lake based on the bathymetric surveys and on sediment sampling in the Harpon Khola[66]. The difference in estimated lake volume between the two surveys was 3%, which is appreciably less than the error inherent in the method[67]. Despite this, Impat extrapolated the difference to give an estimated useful life for the lake, and correlated this estimate with a sediment load delivered to the lake by the Harpon Khola of some 9.84 t $ha^{-1}yr^{-1}$ (Impat 1981). This last value is based on suspended sediment sampling in 1979 at Chankapur, the meander below Pame. Individual grab samples were taken daily between April and December from "a little bit below the surface", analysed for sediment concentration, and the results multiplied by an estimate of discharge (obtained from cross-sectional area and estimated velocity) to give daily

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[64](cont'd) the lake area is only some 6 km^2 this is an evaporation rate of some 8500 mm/yr!

[65] Usually indicative of eutrophication. Earlier limnological investigations in the Pokhara area are reported in Hickel (1973).

[66] Nippon Koei Co. also estimated lake life during their design studies for the new Pardi Dam. They based their figures on data from the Poonch River in Pakistan "because of similar geographical features in both river basins" (Nippon Koei 1976b). The Poonch River basin has an area of 2470 km^2 and is not directly comparable with the Phewa watershed, either in terms of area or physiography.

[67] See Rausch and Heinemann (1984) for a description of techniques for measuring reservoir sedimentation.

suspended sediment transport. The total sediment load for the year was then calculated, including estimates for the first three months of the year, and an assumed 20% contribution for bed load (Impat 1981). Readers are referred to the authors noted under Table 1 for an explanation of the errors inherent in such a technique.

4.3.4 SEDIMENT SYSTEMS

The sediment production and transport system in the valley reflects, on a more moderate scale, many of the features described by Brunsden *et al.* (1981) in eastern Nepal. The fluvial system is supplied with sediment from a number of different sources, including:

* mass movement activity on river banks and lower valley slopes;
* lateral corrasion by rivers and streams;
* vertical incision of headwater channels;
* erosion of fans on the valley floor;
* mass movement catchments;
* ephemeral streams and gullies;
* generalised surface erosion.

Except for activity in mass movement catchments, sediment movement is confined almost entirely to the monsoon season. Material is transferred during storms from the valley side slopes to streams and river channels. Much of this sediment arrives as pulses of debris when rivers are in flood, and is deposited as the flood stage falls, both on the valley bottom, and as fans at the base of the slopes. Both these sediment stores are continually reworked as channels meander over their surfaces. Comminution proceeds rapidly owing to the softness of the principal rock types, with both attrition and sorting contributing to reductions in dominant particle size with distance downstream.

Currently, the transport capacity of the fluvial system in the valley bottom has been exceeded. The river is energy-limited owing to the perched base level caused by the Pardi dam. Very large quantities of coarse material remain to be moved from the upper end of the valley floor to Phewa Tal. Data were insufficient to allow the estimation of sediment residence time in fans or gravel bars. However, the remote sensing images provide an excellent record of channel changes in the valley over time, and could be very useful in a study of bank recession and downstream migration of meander bends.

Chapter 5

SUMMARY AND CONCLUSIONS

5.1 THE PROBLEM

As elsewhere in the Himalaya, the Middle Mountains of Nepal are densely settled, and support an agroecosystem which is dependent on energy and nutrient subsidies from the forest for its continuation. The land surface has been extensively modified in order to allow arable agriculture, and increasing population and unfavourable institutional arrangements have resulted in degradation of the forest resource.

Recurrent, and supposedly worsening, landslides, floods, and associated sediment deposition downstream have resulted in concern being expressed that some critical environmental threshold has been reached, and further deterioration becomes inevitable. The principal cause of this environmental deterioration is widely perceived to be deforestation.

Owing to remoteness and lack of infrastructure, little work has been done to define rates of natural processes in the Himalaya, or how these processes are currently affecting the landscape. Original studies on hillslope and fluvial processes are few in number, sometimes of limited availability, and often of doubtful accuracy.

5.2 EROSION IN THE PHEWA VALLEY

The Phewa Valley lies in the Middle Himalaya of Nepal at the foot of the Annapurna massif. It has an east-west structural trend, and is formed in moderately hard to weak metamorphosed rocks, with phyllite predominating. The area of the watershed is approximately 122 km^2, and elevations range from 800 m to 2500 m. Mean annual precipitation is dependent on elevation, and averages 4202 mm.

Between 500 and 1100 years ago alluvial deposits accumulated rapidly, or perhaps catastrophically, in the Pokhara Basin, and blocked the entrance to the valley, forming a lake, Phewa Tal. Sediments from incising streams in the headwaters above the lake have accumulated in the base of the valley, creating a flat valley floor. Debris carried by ephemeral streams on the steep valley sides has been deposited at the foot of the side slopes, forming alluvial fans.

Mass movement processes identified in the area included rockfalls, rockslides, shallow translational failures, flows, and creep. In areas associated with incompetent rock or structural discontinuities, complex failures with steep debris tracks developed. Mass movement activity was seasonal, with dry season movement confined to flows in groundwater discharge zones. No data relating individual failure events to precipitation are available.

90% of all the material displaced by mass wasting in the watershed originated in large failures, which had a mean estimated age of 24 years. Shallow debris slides, the most common form of failure, had a mean volume of approximately 400 m^3, and a mean estimated age of 5.5 years. An estimate of surface lowering in the Phewa Valley due to landsliding is 2.5 mm/yr, based on the morphometric attributes and estimated ages of the sample surveyed, and on air photo interpretation.

Surface erosion in the watershed, estimated from very limited data from small runoff plots, is approximately 5–6 mm/yr on overgrazed areas, 1–2 mm/yr on protected pasture, and <1 mm/yr under forest. Soil loss from cultivated areas has not been measured. The total amount of soil lost by surface erosion remains unknown. Active gullies existed on the Kaski ridge, but no reliable figures on sediment production from them are available. Losses due to solution and shallow creep are not known.

If not delivered directly to the valley floor, materials displaced by mass movement activity are transferred downslope in high angle channels which are transitional between streams and gullies. The ratio of material displaced to material delivered to the valley floor is not known, but is probably high, owing to the steepness of the relief and the intensity of evenst.

Once in the valley bottom, sediments undergo fluvial sorting. The tributaries of the main river, the Harpon Khola, have braided channels for some 4 km after they debouch on to the valley floor, and sediment transport here is energy-limited. Hydrographs are flashy. Flow estimates suggest a unit runoff at bankfull stage of some 4 $m^3s^{-1}km^{-2}$, which, with 100% runoff, is equivalent to a 24 hr precipitation value of about 350 mm. Intensity-duration-frequency curves developed from 7-10 years of data at Pokhara Airport indicate that values in the region of 300 mm/day are not unreasonable. Reliable records of rainfall approaching this figure exist.

The delta of the Harpon Khola in Phewa Tàl has grown rapidly over the last 30 years, possibly associated with specific erosional sites on the slopes on the north side of the valley. The records of its growth provided by remote sensing could be used to determine sediment yield, given information on delta volume and density not currently available.

Several authors have attempted to quantify rates of erosion and sedimentation in the Phewa Valley, but often the original data have been extrapolated unwisely. The author of the present study would like to emphasize that his own figures for failure age, volume, and frequency (and hence the estimate of surface lowering by landsliding), should never be used without the prefix "based on a small sample". They are probably as valid, or invalid, as the estimates made by Caine and Mool (1982), and Starkel (1972a, 1972b).

5.3 THE EROSION SYSTEM IN THE MIDDLE HIMALAYA

The few studies of Himalayan geomorphology that have been carried out to date suggest a dynamic environment in which orogenesis, relief and climate combine to give rates of denudation in large catchments of up to 5 mm/yr. Locally this rate may be exceeded. The principal mechanism by which this high rate of denudation is achieved appears to be an integrated slope development and sediment transfer system which is dominated by mass wasting on slopes, and which is synchronized with high discharges in river channels. The frequency of formative events is unknown, but values ranging from 10–25 years have been proposed. At less frequent intervals, perhaps on a scale of centuries, catastrophic changes occur, with major slope failures precipitating both channel scour and terrace accumulation, as in the Pokhara Basin.

The erosional system is characterised by extreme seasonality, with virtually all work being carried out during the monsoon months of July, August, and September. Within this period, slope failure and fluvial sediment transfer occur episodically, triggered by intense and prolonged rainfalls which commonly exceed 150 mm/day. The coincidence of seismic shaking with one of these rain events, or simply with high groundwater conditions, causes widespread failure release, but the magnitude of shock needed is not known.

Hillslopes in the Middle Himalaya display a wide range of mass movements, including translational and rotational failures, flows, creep, and transitional forms. Volume and velocity of movement are equally diverse. The type of material involved varies according to lithology and relief. Shallow failures generally remove mantle material, which consists of either untransported regolith, or colluvium from earlier erosion/deposition cycles. Large failures often involve rock weakened by deep weathering.

The most common failures are shallow translational slides with extended runout paths. Typically, these occur in mid-slope positions, and heal within 5–10 years. Larger failures are associated with undercutting, unfavourable geology, and structural discontinuities. Particularly dynamic failure complexes develop where these factors combine, and may become self-reinforcing through the interaction of mass movement and mass transport processes, area exposed, and precipitation. Such mass movement catchments are closely associated with, and sometimes transitional to, high-angle fluvial features. Runoff generated in the larger slides often results in the rapid integration of failure scars into the drainage net.

Sediment transferred to the valley bottom by mass movement or mass transport is either deposited in fans where gradients lessen, or enters stream channels. Down-channel movement is then proportional to clast size and river stage. Turnover times for the various sediment stores are not known.

Intense precipitation and steep slopes combine to cause high runoff, and this is reflected in the rapid rise and fall in stage noted on the few rivers in Nepal for which discharge measurements are available. The entry into the channel of displaced materials from point sources during storm events results in pulses of sediment moving downstream. Suspended sediment concentrations of $\leq$25,000 ppm have been recorded in the Narayani. These materials are deposited in the Terai, forming vast alluvial fans.

The principal controls on this system are geological and climatic, and disturbance of the land surface is unlikely to have any great effect on long-term rates of landscape change. However, in the short term, deforestation and construction activities have both been implicated in increasing rates of sediment production. Deforestation enlarges the area of marginal agricultural land, which is then subject to surface erosion, gullying, and possibly shallow landsliding. Construction activities cause deeper failures. Insufficient data are available to quantify man's influence on the magnitude and frequency of erosional events, but on the basis of the evidence available, it seems reasonable to suggest that man may have caused a slight increase in rates of mass wasting, but has had a marked effect on surface erosion and gullying. Although the latter have a more insidious effect on the productivity of the village agroecosystem, the former are nore immediately hazardous, and provide much of the sediment input to the fluvial system.

5.4 CONCLUSIONS AND RECOMMENDATIONS

Rates of erosion and sedimentation in the Himalaya are extremely high. To live in harmony with such a dynamic geomorphological environment, man must learn to accommodate these natural processes, and to discriminate between those which are amenable to modification and those which are not. The following points should be made:

(1) In Nepal, the causes of mass movement, *sensu stricto*, are primarily geological, and so cannot be influenced by man. Intervention is extremely expensive, and can only be justified where high-value infrastructure is threatened. Even then, it is not always successful.

(2) Engineering structures must allow for this environment; they cannot hope to subdue it. Briefly, particular consideration should be given to:

* Siting: linear features (roads, canals) require careful alignment to avoid the most unstable areas.

* Lower specifications: environmental impact can be reduced by, e.g., reducing road widths, so that a smaller area of ground is affected.

* Adjusting the design and management of hydraulic installations to cope with high sediment loads. For example, sediment intake to pumps and irrigation canals can be reduced by adjusting pumping schedules and incorporating sediment bypass features in the intake structures.

* Adapting specifications to ensure the survival of structures when major hazards cannot be avoided, albeit at the cost of slightly lower performance. For example, low level road crossings survive floods better than bridges,

and can be constructed at much lower cost.

* Planning for high levels of siltation behind dams. In most situations, catchment conservation programmes will have negligible impact on fluvial sediment load (although benefitting individual farmers).

(3) Mass movements and associated erosional features are the principal contributors of material to valley bottom sediment transport systems. They are probaby responsible for the very high peak sediment loads recorded in Himalayan rivers.

(4) Infrequent catastrophic events, up to several orders of magnitude larger than the majority of failures, have had and will continue to have a major effect on the landscape in Nepal. These usually involve slope failure and subsequent landslide-dams and dam-bursts.

(5) Deforestation is unlikely to affect the scale and timing of large slope failures, but may increase the incidence of shallow debris slides. In volumetric terms, these small slides do not appear to be major contributors of sediment to river systems.

(6) Throughout the Middle Mountains, deforestation and the abandonment of marginal arable land are associated with an increase in the area of barren land and unproductive communal grazing areas. These sites are rapidly degrading, and, locally, are responsible for high rates of sediment production through surface erosion and gullying.

(7) Soil loss from terraces, *khet* or well managed *bari*, is probably low, although not as low as the loss from forested areas.

(8) The nutrients carried by eroded soil are useful, if not essential, in maintaining fertility in fields at lower elevations.

(9) Notwithstanding the role of erosion in nutrient transfer, the degradation of surface soils is a serious problem in the Middle Mountains. This is due to not only the loss of soil off-site, but also deterioration in some of the physical and chemical soil properties which affect fertility. The most important of these are structure,

permeability, and organic matter content. The consequences are a lower production potential, and a higher susceptibility to erosion.

(10) If the productivity of marginal areas drops sufficiently, due to soil deterioration and loss, they are abandoned. In the absence of management, free-ranging livestock increase site degradation by trampling and the suppression of vegetation. Owing to the generation of excessive runoff these areas then become the sites of gully initiation.

(11) Once started, gullying is difficult to control, and can rapidly destroy terraces and other productive land by lateral and headward expansion. The large volume of coarse sediments produced by gullies cutting into mantle materials forms a hazard to bottom lands. Gully prevention is simpler than cure.

(12) The emphasis in conservation programmes should be to reduce surface erosion and gullying by improving management on these low-productivity areas.

(13) Forests, which supply the nutrients to maintain crop yields, have retreated due to excessive harvesting of forest products and damage to young growth. Localized excessive harvest occurs where, for socio-economic or political reasons, normal methods of distributing demand over a larger area have broken down. Concentric rings of forest degradation then spread out from consumption centres, i.e. villages. Such a pattern is widespread in the Middle Hills of Nepal. Forest productivity can be improved by reinstating methods for spreading demand over the larger area. Where this improvement is insufficient owing to an absolute limit on yields imposed by the degraded condition of the forest, improved silvicultural practices can assist geographical control of harvesting in increasing productivity.

(14) The majority of forest products go towards maintaining the livestock population. Supplying alternative sources of fodder, such as forage crops, will reduce the pressure on the forest. However, any attempt to diversify fodder sources must

confront the problems of the extra labour demand which it may create. Who will harvest the grass for the stall-fed cow, which previously collected its own feed? How will the new crops be protected from unrestrained animals? Any alteration of land management practices at the village level (the only valid level for improving the lot of the individual), requires both an objective appraisal of the land resources available to the village,[68] and a thorough appreciation of the social dynamics of the community.

(15) Although not insoluble, the scale of the problem of environmental deterioration in Nepal defies imposed solutions. The most effective kind of management involves day-to-day decisions, and should devolve directly to resource users, in this case the panchayats. The community forestry programme[69] is a useful step in this direction.

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It is interesting that, in addition to man affecting erosion processes, the hazardous environment has also affected man. In order to live in and off a landscape where dangerous high magnitude geomorphological events occur on a quasi-continuous basis, man has had to adapt his behaviour. By definition, such behavioural adaptations cannot involve complete hazard avoidance, but they do include both physical damage-limitation and control techniques (see Johnson *et al.* 1982), and cultural and religious defence mechanisms - the Hindu philosophy of *Majaburi* or "things we must bear" (Carson, in press). Physical damage-limitation involves practices such as land use deintensification, e.g. changing irrigated *khet* to rainfed *bari* to reduce water saturation when signs of slope movement appear, and the construction of levees along river banks. *Majaburi* developed as a philosophical response to the landslides, earthquakes,

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[68] See, e.g., Carson (1985) for a technique for "rapid rural appraisal", based on the use of large scale aerial photographs, and applicable to Nepal. See also Shah and Shreier (1985) and Whiteman (1985) for recent exercises in, respectively, land evaluation in Kailali District, and experimental agronomy in the Jumla area.
[69] See Gilmour and Applegate (1984); Pelinck *et al.* (1985).

floods, droughts, and other recurring but unpredictable disasters common on the subcontinent, and performs an essential function in providing moral support in the face of calamity. It is the appropriate attitude to adopt when faced by a large, deep-seated landslide. However, it is not appropriate to apply the same philosophy to surface erosion and gullying. Both constitute an immediate and severe threat to the rural resource base, and, as a product of man's misuse of the environment, are intrinsically controllable.

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APPENDIX 1. LANDSLIDE DATA FROM PRASAD (1975)

The following table is a facsimile of Table 1 in Prasad (1975), and shows events recorded in the Durbasha watershed near Chatra in east Nepal. The rainfall data are composite figures from a number of gauges at different points in the watershed. Size and type of failure were not reported, and earthquake size classes were not further defined.

TABLE—1.

SHOWING THE MEAN CRITERIA OF PRECIPITATION, INTENSITY, NO. OF RAINY DAYS, EARTHQUAKE AND LANDSLIPS. (1963-72)

Sl. No.	Month	Average rainfall intensity for 30 minute in mm/hr.	Average precipitation mm.	Average no. of rainy days.	Average no. of earthquake				Average Total.	Total No. of Landslides.	Averge No. of Landslides.
					Mild	Feeble	Slight	Moderate			
1.	January.	7.5	12.8	1	3	8	3	—	14	—	—
2.	February.	6.5	7.2	1	4	4	4	—	12	—	—
3.	March	12.2	23.7	2	4	6	3	—	13	—	—
4.	April.	30.4	61.2	4	3	5	2	—	10	—	—
5.	May.	45.9	123.2	6	6	6	1	—	13	—	—
6.	June.	65.4	362.8	13	12	4	1	—	17	—	—
7.	July.	68.0	715.3	20	10	3	1	1	15	23	2.3
8.	August	58.0	429.7	17	8	5	1	—	14	26	2.6
9.	September.	62.1	317.0	14	6	2	1	—	9	1	0.1
10.	October.	43.9	134.6	5	4	5	1	—	10	—	—
11.	November.	6.2	11.9	1	2	4	3	1	10	—	—
12.	December.	1.6	1.7	—	3	4	2	—	9	—	—
	Total.	—	2201.1	84	65	56	23	2	146	50	5.0

APPENDIX 2. EROSION PLOT DATA, 1979, PHEWA VALLEY

The following tables show:

A) Monthly precipitation, runoff, and soil loss values for 1979 for four 10 m^2 erosion plots at Banpale, near Naudanda, Phewa Valley, Nepal, as reported by Impat (1981). Site conditions are summarised in Table 2 (p. 22).

B) Precipitation, runoff, and soil loss values for 1979 for a single 10 m^2 plot in dense forest at Tamagi, Phewa Valley, Nepal, as reported by Impat (1981). Site conditions are summarised in Table 2 (p. 22).

A

		PROTECTED PASTURE MIXED WITH FOREST				OVERGRAZED LAND			
MONTH	RAINFALL	PLOT 1		PLOT 3		PLOT 2		PLOT 4	
	(mm)	Runoff (litre)	Soil loss (t/ha)	Runoff (litre)	Soil loss (t/ha)	Runoff (litre)	Soil loss (t/ha)	Runoff (litre)	Soil loss (t/ha)
Jan	7.0								
Feb	N D								
March	N D								
April	83.5								
May	154.9								
June	564.7	370	0.1985	335	0.3420	730	3.8310	530	2.2140
July	1070.0	715	0.1904	385	0.1770	3350	2.7340	1820	1.4020
Aug	1285.5	2565	0.2734	765	0.2553	8445	3.2370	4885	1.7480
Sept	644.5	1465	0.1770	700	0.2294	3610	1.8043	1945	1.9819
Oct	285.0	595	0.1662	130	0.0194	2030	0.3567	995	0.3929
Nov	30.0								
Dec	0.0								
TOTAL	4125.0	5710	1.0055	2315	1.0231	18065	11.9630	10175	7.7388

N D: No data

B

DATE (duration)	RAINFALL (mm)	RUNOFF (litre)	SOIL LOSS (t/ha)
1-2 July	5.2	4	0.0087
3-9 July	73.8	12	0.0259
10-16 July	231.3	27	0.0216
17-23 July	274.5	46	0.0772
24 Jul-6 Aug	682.9	78	0.1185
7-20 Aug	385.4	36	0.0590
21-27 Aug	525.8	65	0.0429
28-30 Aug	48.3	7	0.0268
31 Aug-3 Sept	77.2	13	0.0221
4-9 Sept	253.5	43	0.0146
10 Sept-7 Oct	223.7	33	0.0151
TOTAL	3843.1	364	0.4324

Appendix 3. Sediment Load: Dominant Particle Size

Many geomorphic and hydraulic problems involve particles sizes coarser than sand, and the samples required for the determination of particle size distribution are too large and heavy to be brought into the laboratory for weighing. Some quantitative expression of sediment size is needed to describe the material. The size of sediment particles is usually expressed as a distribution graph, showing the percentage by weight in the sample represented by each size class, determined by sieving through a nest of sieves (Dunne and Leopold 1978). A procedure described in detail in Leopold (1970) allows the rapid, quantitative field assessment of the dominant particle size of material on a surface. This is the size class that represents the largest percentage of the total sample by weight, and it approximates the result that would have been obtained by sieving. It involves the measurment of 100 particles picked up at random from the surface under investigation. Briefly, the procedure is as follows:

(1) A relatively homogeneous area is chosen as the sample site.

(2) The researcher walks over the site, and with eyes averted, reaches over the toe of his boot and touches whatever particle is there with an extended finger. The rock is picked up and its intermediate or b axis measured. The measurement is recorded in mm as the lower limit of the size class into which it falls. Size classes vary by the square root of 2, so that the series progresses 2, 2.8, 4, 5.6, 8, 11 mm, etc. Material <2 mm in diameter cannot be counted by this method, but its presence is recorded by an entry in the <2 mm class.

(3) When about 100 rocks have been measured, counting stops. The data are tabulated as a frequency against the lower limit of their size class.

(4) Multiplication of the numbers in a size class by an average weight (determined experimentally in the laboratory; see Leopold 1970) gives a total weight for that size class.

(5) Because large rocks present greater surface areas than small ones, they have a higher probability of being chosen, and therefore a correction is made by dividing the total weight for each class by the square of the mean diameter of the size class. These values are then transformed into percentages.

(6) A final transformation to make these percentages independent of the particular sieve size used is achieved by dividing by the log of the diameter interval of the size categories.

(7) These values are plotted on log–log paper against the geometric mean size of the interval, giving a curve of the percentage by weight/log sq. root of two against particle size in mm. The dominant particle size is determined as the asymptote of the plotted curve.

The method is simpler to carry out once learned, but readers should consult the original reference (Leopold 1970) for a full description and a discussion of the assumptions involved.

APPENDIX 4. PARTICLE DIMENSIONS

During the survey of fluvial characteristics, the a, b, and c dimensions of 20 of the largest particles deposited by recent flows, and 10 particles judged not to have moved, were measured at each station, for possible use in empirical methods of flow velocity estimation (see Caine and Mool (1981) for application of the technique in Nepal). These values are given below.

STATION	PARTICLE DIMENSIONS					
	PARTICLES MOVED (mm)			PARTICLES NOT MOVED (mm)		
	a	b	c	a	b	c
1	42	31	17	70	48	29
2	54	36	21	67	54	31
3	46	33	17	73	48	31
4	34	22	14	46	30	19
5	53	36	18	78	56	38
6	38	30	17	43	35	23
7	43	33	16	54	39	24
8	47	33	20	61	43	32
9	39	30	18	54	36	25
10		all moved			all moved	
11		"			"	
12		"			"	
13		"			"	
14		"			"	
15		"			"	