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THE EFFECTS OF FORESTATION ON SOIL HYDRAULIC PROPERTIES IN THE MIDDLE HILLS OF NEPAL: A PRELIMINARY ASSESSMENT[1]

D. A. GILMOUR[2], M. BONELL[3], AND D. S. CASSELLS[4]

ABSTRACT There is much international interest in the ecological condition of the heavily populated mountain region of the Nepal Himalaya. Claims are frequently made that deforestation in this heavily populated region has negative effects on downstream flooding and sedimentation. The implication is that deforestation results in compaction of the soil with a consequent decrease in infiltration capacity and an increase in surface runoff (and hence flooding potential).

This study examines soil hydraulic properties of a typical area in the Middle Hills where a forestation programme has been in operation for about 12 years. Measurements of infiltration and permeability were made at a range of depths up to one metre in areas representative of the various forest land-use categories.

The results indicate that in a site which has been deforested for probably a century, and very heavily grazed, the surface 10 cm was noticeably compacted. However, under the prevailing rainfall regime only 17 percent of the monsoon season rain-days included rainfall events for which the 5-minute intensity exceeded the surface infiltration rate. Five- and 12-year-old plantation forests established on such sites exhibited higher surface infiltration rates than the grazed area and this probably reflects an amelioration in the surface soil condition following plantation establishment and protection from grazing.

The general conclusion is that infiltration of most of the monsoon season rainfall would not be impeded by the soils measured in this study and very little overland flow could be expected except in the heaviest of the monsoon season rain events. The findings are relevant for the humid sections of the Himalaya and do not necessarily apply to areas characterized by semi-arid conditions. The data refute the contention that deforestation necessarily results in an increase in large-scale flooding, and conversely that forestation would decrease the frequency or magnitude of such flooding.

RÉSUMÉ *Évaluation préliminaire de l'effet du boisement sur les propriétés hydrauliques du sol dans les montagnes centrales du Népal.* Il existe à présent un gros intérêt international au sujet de la situation écologique des régions montagnardes très peuplées de l'Himalaya népalais. Il est souvent mentionné que le déboisement de ces régions contribue aux inondations et à la sédimentation en amont. L'implication est que le déboisement entraîne un compactage du sol qui réduit sa capacité d'infiltration et augmente l'écoulement de surface, donc les risques d'inondations.

Cette étude examine les propriétés hydrauliques du sol dans une région typique des montagnes centrales, où un programme de boisement a été mis en oeuvre il y a une douzaine d'années. Des mesures de l'infiltration et de la perméabilité ont été faites à différentes profondeurs jusqu'à un mètre, dans plusieurs zones représentant les différentes catégories d'utilisation des forêts.

Les résultats indiquent que pour un site ayant été déboisé pendant probablement un siècle et très fortement brouté, la surface du sol était compactée sur une profondeur de 10 cm. Néanmoins, si l'on considère le régime des pluies prévalent dans la région, au plus 17 pour cent des jours de mousson comprennent des périodes pour lesquelles l'intensité de la pluie pendant 5 minutes dépasse la vitesse d'infiltration à la surface du sol. Les forêts plantées il y a 5 et 12 ans sur de tels sites ont des vitesses d'infiltration plus élevées que la zone broutée, reflétant probablement une amélioration de la surface du sol dûe à la plantation d'arbres et la protection contre le pacage.

La conclusion générale est que l'infiltration des eaux de pluie pendant la mousson ne devrait pas être affectée par les sols mesurés dans le cadre de cette étude, et que l'écoulement de surface devrait être minime si l'on ignore les courtes périodes de pluies diluviennes. Ces résultats s'appliquent aux secteurs humides de l'Himalaya, mais pas nécessairement aux zones caractérisées par des conditions semi-arides. Ils contredisent l'opinion populaire que le déboisement contribue à une augmentation des inondations catastrophiques, et inversement que le boisement réduirait la fréquence et l'importance de telles inondations.

ZUSAMMENFASSUNG *Die Folgen der Aufforstung auf hydraulische Bodeneigenschaften in den Middle Hills, Nepal: Eine vorläufige Bewertung.* Es besteht großes, internationales Interesse an dem ökologischen Zustand des dicht besiedelten nepalesischen Himalaya Berggebietes. Oft wird behauptet, daß die Entwaldung dieser dicht besiedelten Region nachteilige Folgen auf Überschwemmung und Sedimentation flußabwärts hat. Entwaldung führt zu Bodenverdichtungen mit folgender verringerter Einsickerungsfähigkeit und erhöhter Abschwemmung (was die Überschwemmungsgefahr erhöht).

Diese Arbeit untersucht die hydraulische Bodenbeschaffenheit eines typischen Gebietes in den Middle Hills, Nepal, in dem während der vergangenen 12 Jahre ein Aufforstungsprogramm betrieben wurde. Messungen von Einsickerungs- und Durchlässigkeitsraten

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[2]Team Leader, Nepal-Australia Forestry Project, Australian National University, Canberra, A.C.T. 2601, Australia.
[3]Geography Department, James Cook University of North Queensland, Townsville, Queensland 4811, Australia.
[4]Department of Ecosystem Management, University of New England, Armidale, N.S.W. 2351, Australia.

wurden in Gebieten, die in verschiedene Waldnutzungskategorien eingeteilt waren, bis zu einer Tiefe von 1 m durchgeführt. Die Ergebnisse zeigen, daß in einem Gebiet, das über die vergangenen 100 Jahre entwaldet und überweidet war, die oberen 10 cm meßbar verdichtet sind. Unter dem vorherrschenden Regenzyklus enthielten nur 17% aller Regentage in der Monsunzeit solche Regenfälle, bei denen die 5 Minuten Intensität die Oberflächeninfiltrationsrate überschritt. Fünf und zwölf Jahre alte Schonungen, die im Testgebiet gepflanzt waren, zeigten höhere Einsickerungsraten als das Weideland, was möglicherweise auf eine verbesserte Durchlässigkeit der Bodenoberfläche zurückzuführen ist, nachdem die Aufforstung vorgenommen war.

Die Schlußfolgerung ist, daß Einsickerung des stärksten Monsunregenfalls bei den in dieser Arbeit untersuchten Böden nicht erschwert wäre und, abgesehen von starken Regenfällen in der Hauptmonsunzeit, wären nur geringe Überschwemmungen zu erwarten. Diese Feststellungen sind für die feuchten Gegenden des Himalaya relevant und können nicht unbedingt auf semi-aride Gebiete übertragen werden. Die Daten widerlegen die Behauptung, daß Entwaldung zwangsläufig zu häufigeren, größeren Überschwemmungen führt und umgekehrt wird widerlegt, daß Aufforstung die Häufigkeit und das Ausmaß solcher Überschwemmungen mindert.

INTRODUCTION

The Himalayan mountain chain is an area of recent orogenesis and mountain building processes are still very active. Consequently the hill and mountain regions of Nepal contain some of the most rugged landscape in the world. In spite of the physical difficulties, substantial areas are farmed at subsistence levels using an elaborate system of terraces. Because of the recent orogenesis and the steep nature of the topography, natural erosional processes are very active (Carson, 1985), although no doubt efforts to use the land for farming have added to this very high rate of natural erosion.

The largely rural population of Nepal's Middle Hills has a high demand for forest products—chiefly fodder for animal feed and fuelwood for cooking. In much of the densely populated regions the usage of forest products exceeds the ability of the forests to provide the products on a sustainable basis. This has given rise to a situation where the density and quality of forests is steadily declining (Nield, 1985). There is a long history of deforestation in the Middle Hills region of Nepal and Mahat (1985; Mahat *et al.*, 1986a, 1986b, 1987a, 1987b) concluded that the majority of the deforestation evident today occurred more than a century ago, largely due to the land-use and taxation policies of the time.

There has been a tendency during recent years to cast much of the blame for flooding and sedimentation problems experienced in areas downstream from the Nepal mountain regions, on poor land-use practices (and particularly deforestation) in these mountains (e.g., Eckholm, 1976; Pereira, 1981; Pandey *et al.*, 1983; Nautiyal and Babor, 1985). The rationale generally proposed to support these claims is outlined by Nautiyal and Babor:

> With the depletion of the forests in the Himalayas, many previously perennial hill streams are now dry for much of the year. Increased flooding during the rainy season and extended periods of drought are afflicting the northern plains. . . . The once dense forest cover of the Himalayas helped maintain a shallow layer of topsoil by increasing its water retention capacity and reducing surface runoff and soil erosion. (1985: 27)

This unilinear problem of cause and effect is also seen to have a unilinear solution—reforestation. Nautiyal and Babor state:

> observers have noted that there are no self regulatory forces, as in natural ecosystems, that will prevent the destruction of forest and grazing lands in the Himalayas. . . . The situation has cataclysmic implications, for the inhabitants both of the Himalayas and of the plains below. . . . However, there may still be a reasonable chance of restoring the ecological balance of the Himalayas by increasing forest cover and changing the lifestyle of the people if there is sufficient political will to do so. (1985: 28)

In addition, much of the popular literature (including the popular press) takes the same stance as outlined above by Nautiyal and Babor, and it is probably fair to say that they represent the most widely held view in the Indian subcontinent, if not elsewhere. However, almost all of the scientific evidence accumulated during the past several decades by hydrologists and watershed researchers (summarized by Bosch and Hewlett, 1982) fails to link deforestation with reduced dry season flows or with increases in large-scale downstream flooding.

One difficulty in supporting or refuting the various hypotheses regarding the link between deforestation and changes in the water regime is the dearth of sound scientific experiments in the Himalayan region. It is generally accepted that one of the key elements in the argument is the ability of the soil to accept rain-water and the way this is changed by deforestation and forestation. The object of the study reported in this paper is to measure the infiltration and permeability rates of soils at a range of sites in a typical Middle Hills region and to determine the effects of forestation on these parameters and the likely impact on the water regime.

STUDY AREA

The area selected for study is in a region which has been subject to substantial deforestation dating back several centuries and where a forestation programme has been in operation for about 12 years. This forestation programme is supported by the Nepal–Australia Forestry Project, a bilateral aid project of the Government of Australia and His Majesty's Government of Nepal, and managed by the Australian National University, Canberra, Australia. Figure 1 shows the location of the study area, which is close to the District Headquarters of Chautara, about 40 km

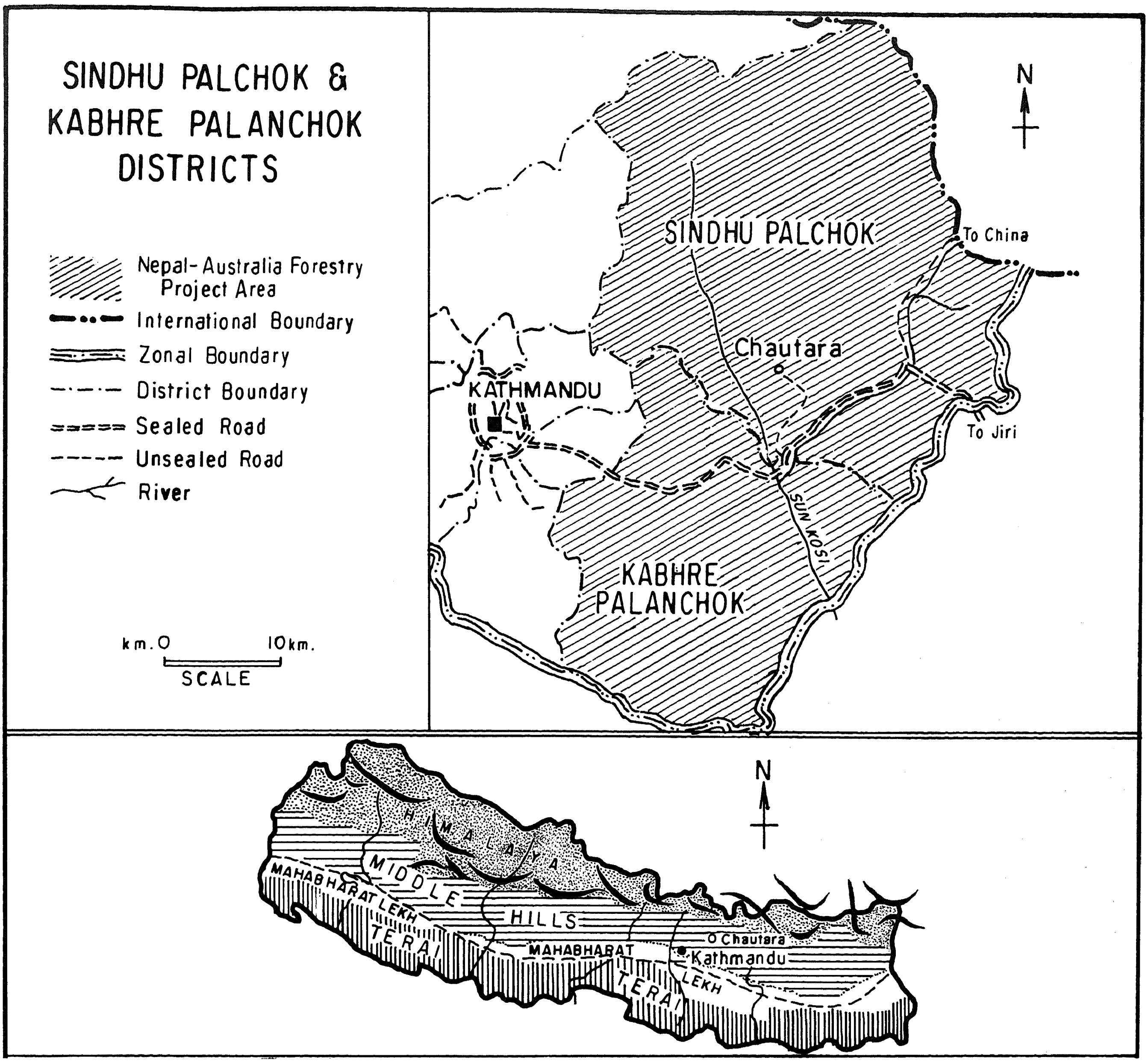

FIGURE 1. Map of Nepal showing location of the town of Chautara, near which the study was carried out.

northeast of Kathmandu. The area is at an altitude of 1,660 m and experiences a typical monsoon climate with about 85 percent of the median annual precipitation of 2,008 mm occurring during the summer months from June to September inclusive.

The study sites (details of which are given in Table 1) represent various stages in the process of forestation ranging from a very heavily grazed and trampled grass area, typical of much of the degraded grassland that is available for forestation (Figure 2), to a relatively undisturbed religious forest, which is as close as could be obtained to a natural forest site (Figure 3).

METHODS

The field testing programme consisted of determining values of field saturated hydraulic conductivity, K, for various layers in the soil profile at each of the sites. The combination of persistent rainfall, most of which is concentrated in a few months of the year, and near-saturated profiles makes field saturated hydraulic conductivity a meaningful parameter in evaluating the runoff process. The layers chosen for taking measurements were standardized

Table 1
Characteristics of the study sites

Site	Aspect	Slope (°)	Description
1	ENE	16	Probably deforested more than 100 years ago. Patches of surface soil exposed and surface erosion widespread. Grass cropped to soil level. Heavily grazed and trampled grassland.
2	ENE	17	Planted with *Pinus patula* five years ago. Adjacent to Site 1 and identical in condition prior to planting. Soil surface now covered with a thin layer of pine needles and short grass cover. Villagers cut grass by hand but grazing animals are excluded.
3	ESE	19	Planted with *Pinus roxburghii* 12 years ago. Similar to Site 1 prior to planting. Soil surface now covered with a layer of pine needles and patches of grass with a number of broadleaved trees developing as a minor understorey. Villagers cut grass by hand but grazing animals are excluded.
4	NE	24	Planted with *P. roxburghii* 12 years ago. Adjacent to Site 1 but the vegetation prior to planting consisted of low shrubs and herbs about 40 cm high plus a few scattered remnants of the original forest. Surface now covered with a dense layer of broadleaved shrubs and trees as an understorey beneath the pines. Leafy material cut by villagers for animal bedding and fodder. Grazing animals are excluded.
5	NE	24	Religious forest—probably a near-natural stand consisting largely of a mixture of *Schima wallichii* and *Rhododendron arboreum* with a few other minor species. Soil surface is covered with shrubs and moss but little grass. Some leafy material cut for animal bedding and fodder. Grazing animals are generally excluded.

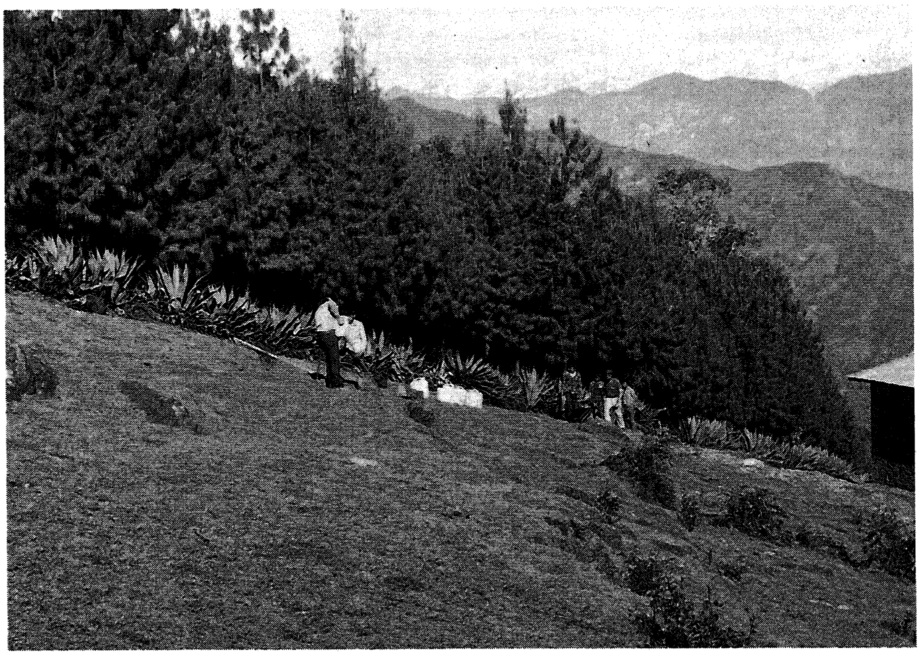

Figure 2. Heavily grazed and trampled grassland (Site 1) with 5-year-old *Pinus patula* plantation (Site 2) in background.

for all sites as 0–0.1 m; 0.1–0.2 m; 0.2–0.5 m, and 0.5–1.0 m depth from the soil surface. It was considered that measurements at these soil depths would provide sufficient information to characterize the nature of water movement through the soil profile. For the surface horizons of 0–0.1 m and 0.1–0.2 m an infiltrometer ring (0.3 m dia., 0.1 m deep) and a constant head permeameter (Talsma, 1969; Dunin, 1976) were used for the measurements (Figure 4). For the deeper soil layers of 0.2–0.5 m and 0.5–1.0 m a simplified well permeameter (Talsma and Hallam, 1980) was used (Figure 5). This technique enables the attainment of steady state for three-dimensional flow within eight minutes in wet soils. The field procedure involved a pre-wetting phase of 20 minutes in newly augered holes before the constant head permeameter was placed over the cavity and measurements taken.

At each of the five sites 25 measurements were taken for each of the soil profile layers. Whilst such measurements in aggregate do not represent either a large area (rings) or volume (auger holes), the sample sizes selected are large in comparison with most forest hydrology studies. The work of Talsma and Hallam (1980) is one of the few exceptions. Details of the techniques used and of the calculation of hydraulic conductivity have been given elsewhere (Bonell

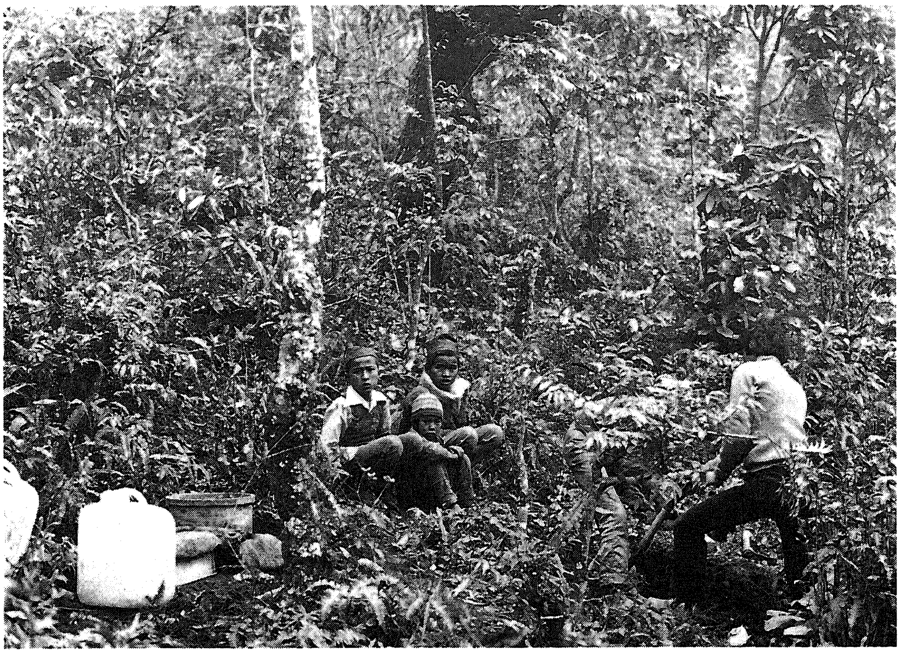

FIGURE 3. Protected natural (religious) forest (Site 5) of *Rhododendron arboreum* and *Schima wallichii* with well-developed shrubby understorey. Soil surface reasonably well covered with leaf litter.

FIGURE 4. Surface infiltration being measured in Site 4 (12-year-old plantation of *Pinus roxburghii*) using infiltrometer ring and constant head permeameter. Note well-developed shrubby understorey.

FIGURE 5. Subsurface permeability being measured at Site 2 (5-year-old *Pinus patula* plantation) using simplified well permeameters.

et al., 1983). Previous work has indicated that the K data frequency distributions are closely approximated by the log-normal function. Consequently, the use of $\log_e$ means for inter-layer comparisons of K is a more appropriate measure than the use of arithmetic means (Talsma, 1965; Nielsen *et al.*, 1973). The antilog of the standard deviation of the log transformed K data (antilog S_1) is also included as an index of variability (Baker, 1978). A value of 2 was suggested by Rogowski (1972) as the upper limit of uniformity of K in soil series.

RESULTS AND DISCUSSION

The hydraulic conductivity data for the various depths at each site are presented in Table 2 and shown graphically in Figure 6.

For all sites the K values measured at the deepest layer of 0.5–1.0 m showed relatively little difference, with the log-mean values varying from only 29 to 60 mm hr^{-1}. However, the variability between sites increased closer to the surface with maximum differences occurring at the surface layer 0–0.1 m. At this layer the range between sites was from 39 to 524 mm hr^{-1}. The site with the lowest surface K value (Site 1) represented the area which was totally deforested and had been subjected to heavy grazing and trampling for many decades. The adjacent area (Site 2) which was reforested five years ago appears to have shown a slight improvement in soil surface conditions with a K value of 51 mm hr^{-1}. Similarly, the 12-year-old plantation (Site 3) has shown even further improvement with a value of 183 mm hr^{-1}.

As near as can be determined from perusal of old photographs and from discussions with local villagers, the surface conditions and previous land use at sites 1, 2, and 3 were similar prior to reforestation. At this stage it is impossible to determine the K values of the sites prior to reforestation, but it seems reasonable to assume that present measured differences are due to the changes in soil surface conditions brought about by the change in land use. Of particular importance would be the reduction in compaction by the exclusion of grazing animals, and an improvement in soil aeration through greater activity of soil microflora and fauna associated with higher levels of soil organic matter.

The surface soil conditions at Site 4 reflect the conditions prevailing in an original forest as, prior to reforestation, a short (0.5-m high) but dense shrubby cover was present and grazing was not heavy due to an absence of palatable species. Hence the measured K values are very high at 525 mm hr^{-1}. The surface K values measured in the religious forest (Site 5) are also high, but somewhat lower than those measured at Site 4.

The trend of increasing K for the surface 0–0.1 m layer with age of plantation is shown in Figure 7. The values measured at Sites 4 and 5 probably represent values close

TABLE 2

Log-mean values of field saturated hydraulic conductivity K (mm hr^{-1}), the limits of ± 1 log standard deviation, range of K, and the variability of index antilog S_1 for the four soil layers at each site

Site	Depth interval (m)	Hydraulic conductivity (mm hr^{-1}) Log mean	± s.d.	Range	Antilog S_1
1	0–0.1	39.30	19.95– 77.42	16.72– 305.32	1.97
2		51.19	29.25– 89.58	23.95– 108.81	1.75
3		183.33	48.50– 692.99	43.15–39911.67	3.78
4		524.62	188.04–1463.69	59.01– 3563.54	2.79
5		370.38	178.93– 766.69	99.45– 1710.50	2.07
1	0.1–02	87.17	50.98– 149.06	35.49– 272.82	1.71
2		88.05	51.79– 149.68	27.37– 312.14	1.70
3		117.68	68.02– 203.59	45.41– 516.91	1.73
4		195.52	105.69– 361.71	40.58– 475.14	1.85
5		309.96	180.21– 533.13	81.84– 610.89	1.72
1	0.2–05	62.91	30.25– 130.85	7.66– 192.02	2.08
2		119.41	91.15– 156.43	71.81– 243.06	1.31
3		37.88	27.45– 52.27	16.20– 61.17	1.38
4		100.78	59.99– 169.31	25.28– 230.91	1.68
5		95.55	61.65– 148.10	54.69– 382.82	1.55
1	0.5–1.0	49.36	30.10– 80.95	17.44– 118.64	1.64
2		60.35	36.36– 100.18	12.53– 138.40	1.66
3		29.59	10.17– 86.11	12.79– 896.83	2.91
4		44.29	28.57– 68.65	17.48– 103.80	1.55
5		25.68	18.34– 35.95	14.67– 56.47	1.40

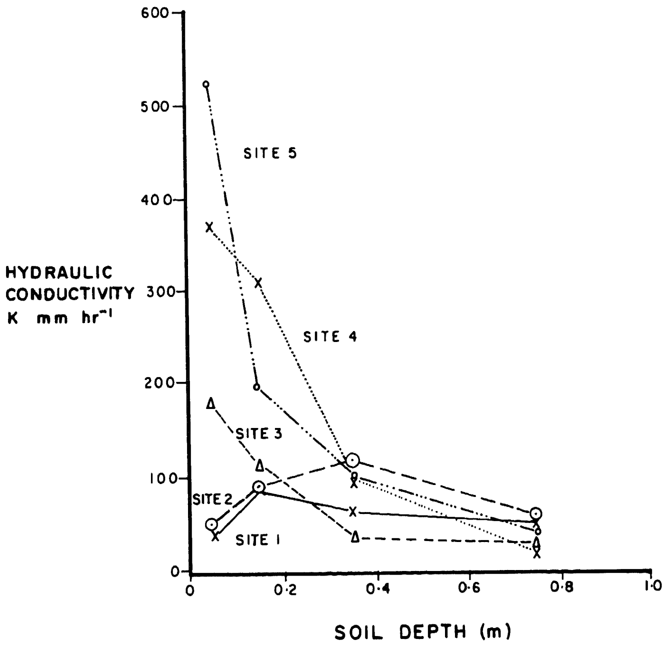

FIGURE 6. Field saturated hydraulic conductivity values (K) for each of the sample sites at various depths. (K values plotted against the mid-point of the sampled soil layer.)

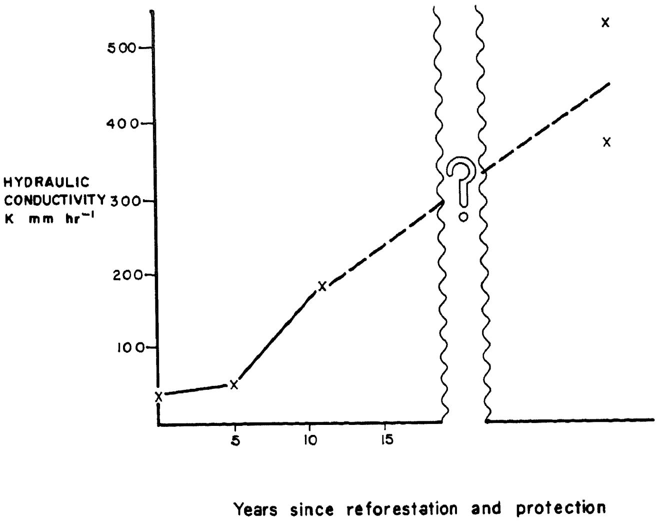

FIGURE 7. Likely trend of changes in field saturated hydraulic conductivity (K) of surface (0–0.1 m) soil following reforestation and protection of heavily grazed and trampled grassland.

to those for natural or near-natural forest sites which experience only limited disturbance. It is not clear the period of time required to return a heavily grazed and trampled site to near natural conditions but it would undoubtedly be many decades. The K values for the layers between the surface and 0.5–1.0 m layers were generally intermediate between these two.

While it is tempting to use the K values alone to interpret the effect of changes on the disposition of rain-water in the soil profile, it is important to consider the characteristics of the rainfall events themselves. For example, although the K value of the surface 0–0.1 m layer of soil at Site 1 is only 39 mm hr^{-1}, if the rainfall intensity rate never exceeds this value, then all of the incident rain would infiltrate into the surface and no surface runoff would occur. The fact that the surface K value of Site 4 is 13 times higher has little practical significance in considering the fate of rain-water after it strikes the soil surface. Thus it is necessary to consider both the K values and the rainfall characteristics before drawing conclusions regarding any likely changes to the water regime.

As indicated in the introductory section, the median rainfall at the study site is 2,008 mm with a strong summer maximum. In terms of the generation of overland flow, it is the high intensity falls which are important to isolate, as falls which are below the threshold value imposed by the hydraulic conductivity of the soil will infiltrate, and not form any part of initial overland flow.

Detailed rainfall intensity data were not available for the Chautara area, so the data for Kathmandu (40 km to the southwest) were used. It is considered by the authors that these data give a close approximation to the rainfall intensity patterns which occur at Chautara. It is the short periods of high intensity rainfall which generate overland flow and cause surface erosion to occur. Consequently it is desirable to isolate these short period events from the rainfall record.

It was possible to determine rainfall intensity data for 5-minute intervals from a nine-year period of record (1971–1979). The 5-minute rainfall intensities are expressed as equivalent hourly intensity (mm hr^{-1}). This allows a direct

TABLE 3
Annual frequency (number of days) of 5-minute rainfall intensity of different values during main monsoon period (June–September). Record for Kathmandu for period 1971–1979

Rainfall intensity class (mm hr^{-1})	No. of days
0– 9.99	26.2
10– 19.99	9.8
20– 29.99	6.7
30– 39.99	4.9
40– 49.99	2.3
50– 59.99	0.8
60– 69.99	1.6
70– 79.99	0.7
80– 89.99	0.3
90– 99.99	0.6
100–109.99	0.1
110–119.99	0.0
120–129.99	0.4

TABLE 4

Annual number (and percentage) of rain-days during main monsoon season where 5-minute rainfall intensity exceeds the log-mean field saturated hydraulic conductivity for the impeding layers at each site

Depth interval (m)	Number of rain-days				
	Site 1	Site 2	Site 3	Site 4	Site 5
0 -0.1	6.7 (17%)	3.7 (9%)	tr	tr	tr
0.1–0.2	tr	tr	0.4 (1%)	tr	tr
0.2–0.5	tr	tr	6.7 (17%)	0.6 (1%)	0.6 (1%)
0.5–1.0	tr	tr	11.7 (29%)	4.4 (11%)	11.7 (29%)

Note: 1. tr—soil layer transmissive to water moving through from above. 2. percentage figures in parentheses.

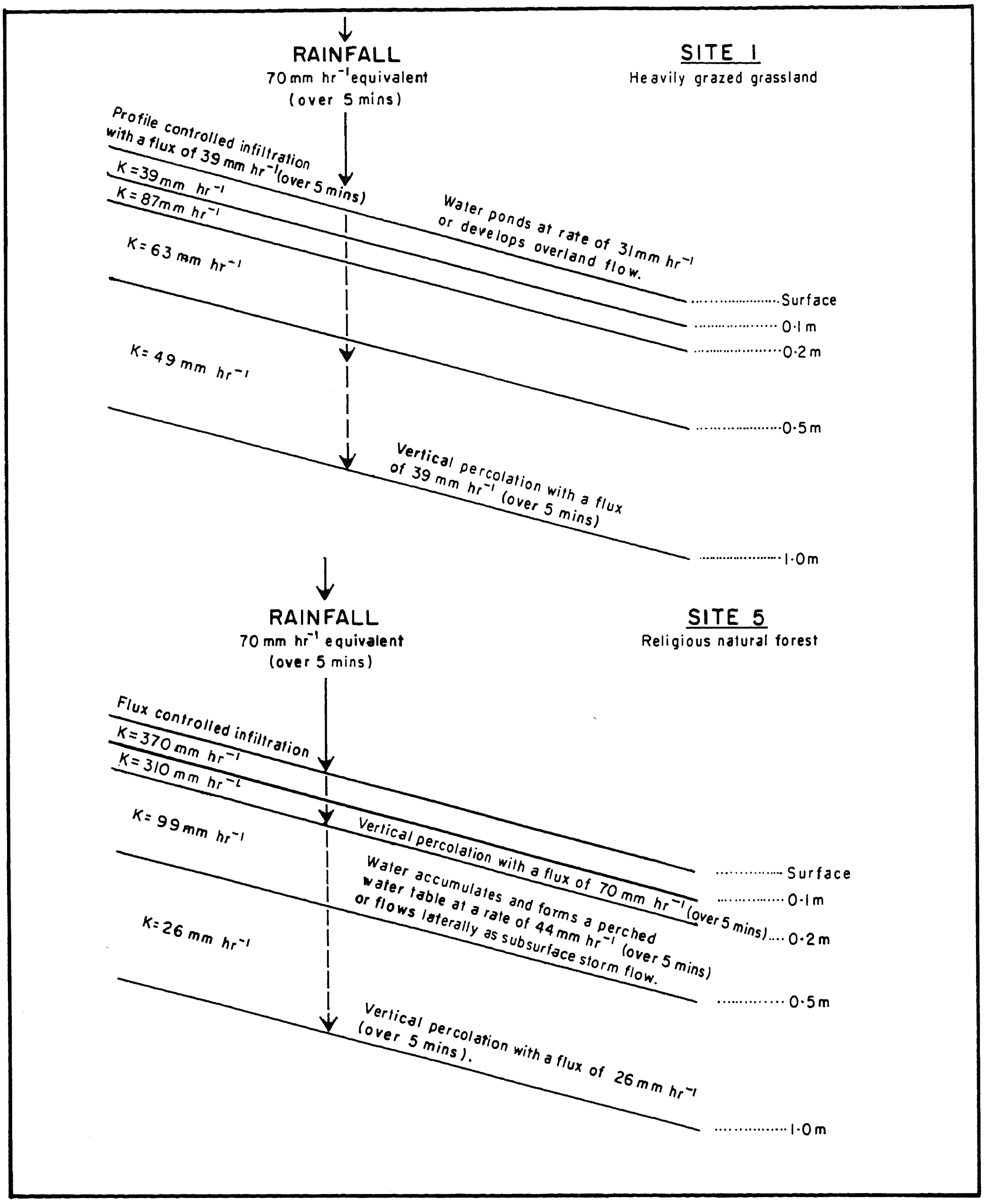

FIGURE 8. Disposition of water through the various soil layers at Sites 1 and 5 from a storm with a 5-minute intensity of 70 mm hr^{-1}.

comparison with the measured soil K values which are also expressed in mm hr^{-1}.

The highest 5-minute intensity recorded was at the rate of 120 mm hr^{-1} and this rate was recorded on four occasions during the nine years of record. This rate is only modest by tropical Australian standards (Gilmour and Bonell, 1979; Bonell and Gilmour, 1980). The frequency of occurrence of different values of 5-minute rainfall intensity for the main monsoon period (June–September) during the period of record is shown in Table 3.

The maximum 24-hour rainfall totals recorded during a 10-year period from 1972 to 1982 (excluding 1973 where the record is lost) varied from 59 mm to 117 mm. It is clear that while the area experiences a monsoon rainfall climate, the intensity of the rainfall is not particularly high.

In each soil profile there is normally one layer with a lower K value than the others. This layer (the impeding layer) will act as a throttle to water passing through the profile. If water is delivered to this layer at a rate that exceeds its K value then water will pond and/or move laterally. If this occurs at the soil surface then surface runoff will occur. It is now possible to determine the number of rain days with a 5-minute intensity rainfall which exceeds the K value of the impeding soil layer at each of the sites. These data are shown in Table 4.

If the worst possible situation (i.e., Site 1, the heavily grazed grassland) is considered, the data in Table 4 indicate that on average, 6.7 rain-days (17 percent of all rain-days) during a monsoon season contain a 5-minute intensity period which exceeds the K value of the surface soil. During these occasions surface runoff would be expected to occur, with the amount depending on the actual intensity and quantity of rain. However, on the remaining 83 percent of rain-days the 5-minute rainfall intensity is less than the threshold value of 39 mm hr^{-1}, so virtually complete infiltration would occur.

At the other end of the spectrum at Sites 4 and 5 the soil layers down to 0.2 m are transmissive to virtually all of the 5-minute rainfall intensities during the main monsoon season. The soil layers of 0.2–0.5 m would be expected to pond water for a very short period each year while the deeper 0.5–1.0 m layer would experience a significant number of rain-days (4.4 and 11.7, respectively) where ponding of water would occur. On these occasions a temporary perched water table would probably develop until the excess water had infiltrated laterally or vertically. Sites 2 and 3 exhibit characteristics which are intermediate between Site 1 and Sites 4 and 5.

It is instructive to consider the disposition of water at Sites 1 and 5 from a hypothetical storm of 70 mm hr^{-1} (during a 5-minute period). Such a storm would occur, on average, on 2.1 days in a monsoon season (see Table 3). Figure 8 shows the situation graphically. At Site 1 rainfall permeates the soil profile to at least one metre at a rate of 39 mm hr^{-1} but infiltration excess or Horton-type overland flow (as defined by Kirby, 1978, p. 368) is generated at the rate of 31 mm hr^{-1} (over a 5-minute period). At Site 5 there is no impedance to vertical water flow until the 0.5–1.0 m layer is reached. Water flows through this layer at a rate of 26 mm hr^{-1} and water would pond above it as a perched water-table or flow laterally as subsurface stormflow (as defined by Kirby, 1978, p. 373) at a rate of 44 mm hr^{-1} over a 5-minute period. Should subsequent rain cause the parched water-table to emerge at the surface, then saturation overland flow (as defined by Kirby, 1978, p. 371) is possible from direct rainfall onto this saturated area.

Discussion so far has concentrated on the various mechanisms by which stormflow can develop over a small area of each land type. We have no information concerning the spatial variability of K over a drainage basin and so detailed comment on how this soil hydraulic property influences the variable source area concept of runoff generation (Hewlett, 1961; Kirby, 1978) cannot be made. These preliminary results, however, give some indication whether there are any significant changes in the disposition of rainwater which could influence the generation of flood events.

SIGNIFICANCE OF FINDINGS

Generation of Flood Events

The previous discussion has indicated that short-term (5-minute) rainfall events are likely to cause more surface runoff on areas such as Site 1 than on well-protected forested areas such as Sites 4 and 5. However, it is normally much longer duration events which cause downstream flooding. Caine and Mool (1982) provided information on rainfall intensity–duration for Kathmandu and this can be used to gain an insight into the likely effects of changes in land use (and consequent soil K values) on downstream flooding. From Caine and Mool's data it can be determined that a one-hour-duration storm of 40 mm hr^{-1} would have a recurrence interval of only one in 25 years. Thus, it is the sort of event that is likely to cause a degree of local flooding. At the most degraded site measured (Site 1) such a severe storm would generate only 1 mm hr^{-1} of surface runoff. Clearly the impact of deforestation in this case would have little effect on the generation of major flooding (that is, on the Ganges Plain, far downstream). Conversely, the improvement to surface soil conditions caused by forestation would result in the absorption of an additional 1 mm hr^{-1} of rainfall – not the sort of result likely to have any noticeable effect on downstream flooding. These findings support the results of the majority of researchers (see reviews by Boughton, 1970; Hewlett, 1982; Hamilton, 1983; Gilmour, 1986) that deforestation and reforestation would not, by themselves, influence major flooding. Major floods are primarily influenced by precipitation factors in association with the geomorphology of the catchment. Distinction must be made, however, between "humid area concepts" and "semi-arid area concepts". The present study falls within the former and the findings introduced in this paper may have limited or no relevance to semi-arid areas because processes are quite different. This is an important qualification because many areas in the Himalayan chain experience semi-arid conditions.

The other factor to be considered in this discussion is the extent of poor quality catchment cover and the degree to which this can be improved. Data collected by Nield (1985) indicated that grassland accounted for seven percent of the land area in the Middle Hills region. Even if all of this area was reforested (in itself a mammoth task) it would be likely to have only a very minor effect because of the broken and scattered nature of the grassland.

EFFECT ON SOIL EROSION

As previously discussed, the development of a well-vegetated and protected soil surface is likely to decrease the incidence of overland flow from short-duration, high-intensity rainfall events, which occur several times each monsoon season. While this is likely to have little impact on downstream flooding it is almost certain to have an important local effect on reducing surface soil erosion (but not mass soil movement). This reduction in soil erosion, with the obvious consequences for maintenance and improvement of site productivity is probably one of the major site benefits to accrue from improved protection associated with forestation. Nevertheless, emphasis must be placed on the great difference between local flooding relationships and the much larger question of major downstream effects on the Ganges Plain that many writers have assumed are caused by deforestation in the mountains.

CONCLUSIONS

- Forestation of heavily grazed grasslands can lead to significant increases in surface soil infiltration capacity as measured by near-saturated hydraulic conductivity.
- It is likely to take several decades after initial forestation and protection before the changes in soil conditions approach those of a near-natural forest.
- The increases in surface infiltration rate which can accompany forestation are likely to have no significant effect on the incidence of downstream flooding.
- The increases in surface infiltration rate which can accompany forestation could have a major impact in reducing surface sheet and gully erosion because of the reduction in surface runoff from high-intensity short-term rainfall events.

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REFERENCES

Baker, F. G., 1978: Variability of hydraulic conductivity within and between nine Wisconsin soil series. *Water Resources Research,* 14: 103–108.

Bonell, M. and Gilmour, D. A., 1980: Variations in short-term rainfall intensity in relation to synoptic climatological aspects of the humid tropical north-east Queensland coast. *Singapore Journal of Tropical Geography,* 1: 16–30.

Bonell, M., Gilmour, D. A., and Cassells, D. S., 1983: A preliminary survey of the hydraulic properties of rainforest soils in tropical north-east Queensland and their implications in the runoff process. *In* de Ploey, J. (ed.), Rainfall Simulation, Runoff and Erosion. *Catena* Special supplement no. 4: 57–78.

Bosch, J. M. and Hewlett, J. D., 1982: A review of catchment experiments to determine the effect of vegetation changes on water yield and evaporation. *Journal of Hydrology,* 55: 3–23.

Boughton, W. C., 1970: Effects of land management on quantity and quality of available water. Univ. of New South Wales, Water Res. Lab. Rep., No. 120. 330 pp.

Caine, N. and Mool, P. K., 1982: Landslides in the Kolpu Khola drainage, Middle Mountains, Nepal. *Mountain Research and Development,* 2(2): 157–173.

Carson, B., 1985: *Erosion and Sedimentation Processes in the Nepalese Himalaya.* ICIMOD Occasional Paper No. 1. Kathmandu, Nepal. 39 pp.

Dunin, F. X., 1976: Infiltration: Its simulation for field conditions. *In* Rhodda, J. C. (ed.), *Facets of Hydrology.* Wiley Interscience, London, pp. 199–227.

Eckholm, E. D., 1976: *Losing Ground.* Worldwatch Institute, W. W. Norton, New York. 223 pp.

Gilmour, D. A., 1986: Reforestation or afforestation of openland — a Nepal perspective. *In* Pearce, A. J. and Hamilton, L. S. (eds.), *Land Use, Watersheds and Planning in the Asia-Pacific Region.* Regional office for Asia and the Pacific Region, FAO, Bangkok, 1986. RAPA Report, 157–169.

Gilmour, D. A. and Bonell, M., 1979: Six-minute rainfall intensity data for an exceptionally heavy tropical rainstorm. *Weather,* 34: 148–158.

Hamilton, L. S., 1983: *Tropical Forested Watersheds: Hydrologic and Soils Response to Major Uses or Conversions.* Westview Press, Boulder, Colorado. 168 pp.

Hewlett, J. D., 1961: Watershed management. *U.S. Dept. of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, Report for 1961,* pp. 61–66.

———, 1982: Forests and floods in the light of recent investigations. In *Proc. Hydrological Symposium, June 14-15, 1982*. Fredericton. Nat. Res. Council, Ottawa, pp. 543-560.

Kirby, M. J., 1978: *Hillslope Hydrology*. Wiley-Interscience, Chichester. 389 pp.

Mahat, T. B. S., 1985: Human impact on forests in the Middle Hills of Nepal. Ph.D. Thesis, Australian National University, Canberra, Australia. Two vols. 490 pp.

Mahat, T. B. S., Griffin, D. M., and Shepherd, K. R., 1986a: Human impact on some forests of the Middle Hills of Nepal. 1. Forestry in the context of the traditional resources of the state. *Mountain Research and Development*, 6(3): 223-232.

———, 1986b: Human impact on some forests of the Middle Hills of Nepal. Part 2. Some major human impacts before 1950 on the forests of Sindhu Palchok and Kabhre Palanchok. *Mountain Research and Development*, 6(4): 325-334.

———, 1987a: Human impacts on some forests of the Middle Hills of Nepal. Part 3. Forests in the subsistence economy of Sindhu Palchok and Kabhre Palanchok. *Mountain Research and Development*, 7(1): 53-70.

———, 1987b: Human impacts on some forests of the Middle Hills of Nepal. Part 4. A detailed study in southeast Sindhu Palchok and Kabhre Palanchok. *Mountain Research and Development*, 7(2): 111-134.

Nautiyal, J. C. and Babor, P. S., 1985: Forestry in the Himalayas—How to avert an environmental disaster. *Interdisciplinary Science Reviews*, 10: 27-41.

Nield, R. S., 1985: Fuelwood and fodder—problems and policy. Working paper for Water and Energy Commission Secretariat, Kathmandu, Nepal. 44 pp.

Nielson, D. R., Biggar, J. W., and Erh, K. T., 1973: Spatial variability of field-measured soil-water properties. *Hilgardia*, 42: 215-260.

Pandey, A. N., Pathak, P. C., and Singh, J. S., 1983: Water, sediment and nutrient movement in forested and non-forested catchments in Kumaun Himalaya. *Forest Ecology and Management*, 7: 19-29.

Pereira, C., 1981: *Feasibility for High Altitude Agricultural Research*. FAO, Rome.

Rogowski, A. S., 1972: Watershed physics: Soil variability criteria. *Water Resources Research*, 8: 1015-1023.

Talsma, T., 1965: Sample size estimates in permeability studies. *Proceedings of American Society of Civil Engineers*, 91: 76-77.

———, 1969: *In situ* measurements of sorptivity. *Australian Journal of Soil Research*, 7: 269-276.

Talsma, T. and Hallam, P. M., 1980: Hydraulic conductivity measurements of forest catchments. *Australian Journal of Soil Research*, 18: 139-148.