Mauritius Research Council

Water Quality Modelling Along Rivers in Mauritius

Final Report

April 1998

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RUN - 9503.

WATER QUALITY MODELLING ALONG RIVERS IN MAURITIUS

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MAURITIUS RESEARCH COUNCIL UNIVERSITY OF MAURITIUS

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V. PROAG

FINAL REPORT

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SEDIMENTATION LOAD IN RIVERS

In Mauritius, during heavy rains, there is quite a lot of sediment load which is transported by the rivers. There have been many estimates of the actual load being carried away. In some cases, these sediments have formed deltas at the estuaries, such as at Grand River North West or river St. Louis.

A basic understanding of the process of sediment transport is essential to the scientist, engineers, and technologist who may be engaged in geology, hydrology, irrigation and other aspects of civil, marine or environmental engineering.

This study was proposed so that an estimate might be made on the values that actually occur in Mauritius, as well as understanding the parameters that are involved in the process.

Sediment load in rivers is caused by river flow arising from rainfall. This is why the study starts with an investigation of rainfall patterns to channel towards erosion and river flow.

Instead of measuring the sizes of sediments carried by the rivers, it was considered more convenient to carry out experimental work in the laboratory, where many factors could be controlled. This can then be compared with actual sediment data collected on various rivers.

Data has been collected by the Central Water Authority during floods following heavy rainfalls or just after cyclones.

It has been found more sensible to relate sediment load to river flow. River flow suffers a time lag from the rainfall causing it. In this sense, when there is a heavy rainfall, it causes some soil erosion which is carried to the river. Initially even before the flow has reached its time of concentration, the river may be carrying a substantial sediment load. Later on, when the flow reaches its peak value, the sediment load being carried has subsided. This is, of course, one scenario among many.

It is possible to describe the relationship between flow and sediment load through a series of minimum and maximum lines.

The minimum line shows the minimum sediment load that may be expected in the river as a function of the flow.

The maximum line shows a higher bound value for the sediment load.

It must be emphasised that these sediment loads occur mainly after heavy rains or cyclones. Once the occurrence of heavy rain is over, after some time (a few hours

ACKNOWLEDGEMENTS

This study was started at the request of Assoc. Prof. A.C. Chan Chim Yuk who encouraged me on this road when I joined the University of Mauritius.

Funding for this project was obtained from the Mauritius Research Council who have been helpful when required.

CHAPTER 1

INTRODUCTION

In Mauritius, during heavy rains, there is quite a lot of sediment load which is transported by the rivers. There have been many estimates of the actual load being carried away. In some cases, these sediments have formed deltas at the estuaries, such as at Grand River North West or river St. Louis.

A basic understanding of the process of sediment transport is essential to the scientist, engineers, and technologist who may be engaged in geology, hydrology, irrigation and other aspects of civil, marine or environmental engineering.

Most natural water ways and many canals are subjected to bed movement caused by the action of water transporting the sediment materials, thus forming a bed in the downstream direction.

This study was proposed so that an estimate might be made on the values that actually occur in Mauritius, as well as understanding the parameters that are involved in the process.

The plan adopted for the report is given below. It may be noticed that stress is laid more on sediment load rather than chemical pollutants. This aspect of the project as initially formulated was not approved by the MRC.

1. INTRODUCTION
2. RAINFALL PATTERNS IN MAURITIUS
3. SOIL EROSION DUE TO RAINFALL
4. RIVERS IN MAURITIUS
5. RIVER DYNAMICS
6. EXPERIMENTAL WORK IN CHANNEL
7. SEDIMENT DATA FROM RIVERS
8. DISCUSSION

Sediment load in rivers is caused by river flow arising from rainfall. This is why the study starts with an investigation of rainfall patterns to channel towards erosion and river flow.

Instead of measuring the sizes of sediments carried by the rivers, it was considered more convenient to carry out experimental work in the laboratory, where many factors could be controlled. This can then be compared with actual sediment data collected on various rivers.

CHAPTER 2

RAINFALL PATTERNS IN MAURITIUS

2.1 RAINFALL IN MAURITIUS

There are 306 raingauges in Mauritius, out of which 256 are considered in good working order. About 200 stations have been in operation before 1960 and among these 23 were installed before 1900. On the assumption that 256 raingauges are in use in Mauritius for a total area of 1862 km2, it is seen that this results in a very high raingauge network density, as compared with other countries.

2.2 RAINFALL PATTERNS

2.2.1 Yearly Rainfall Distribution

Rainfall distribution over the year indicates that in general February and March are the wettest months. The rainy season ranges from December to April, while the dry season extends from September to November.

The comparatively higher summer rainfall arises from the passage of low pressure troughs, sometimes weak depressions and occasional tropical cyclones. When cyclones pass in the vicinity of Mauritius, high intensity rainstorms are common and rainfall of the order of 812 mm (34 in) in 24 hours have been recorded. Localised falls of high intensity also occur during thunderstorms associated with unstable air mass movements. In those summers during which the island lies outside the paths of these depressions there is usually a rainfall deficiency and drought conditions prevail in the subhumid zone.

The rainfall station at Dubreuil (***Fig 2.1***) illustrates a typical example of the rainfall distribution described above. Similar patterns are observed at Réunion island, though less rain falls there in August. However, this type of graphical presentation does not reveal the annual variations which may be rather significant as may be noted from Trianon station (***Fig. 2.2***). Here the January to March rainfall is quite high compared with the precipitation during the rest of the year. However, in spite of the heavy rainfall from January to March 1980, monthly rainfall never exceeded more than one third of the mean annual rainfall.

It has been observed for Mauritius that over the period 1950-1989, 1983 has been the driest year for the Northern part of the island, whilst 1961 has been the driest for the South of the island.

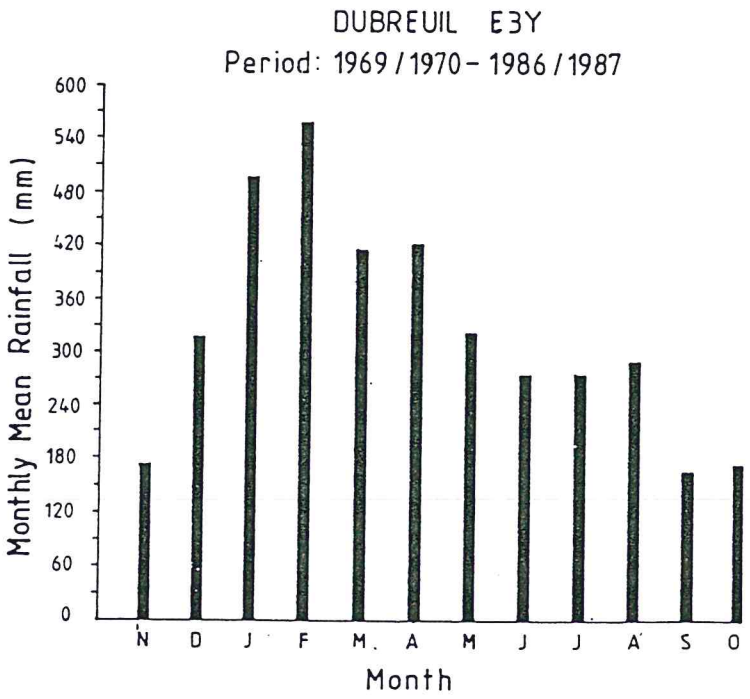
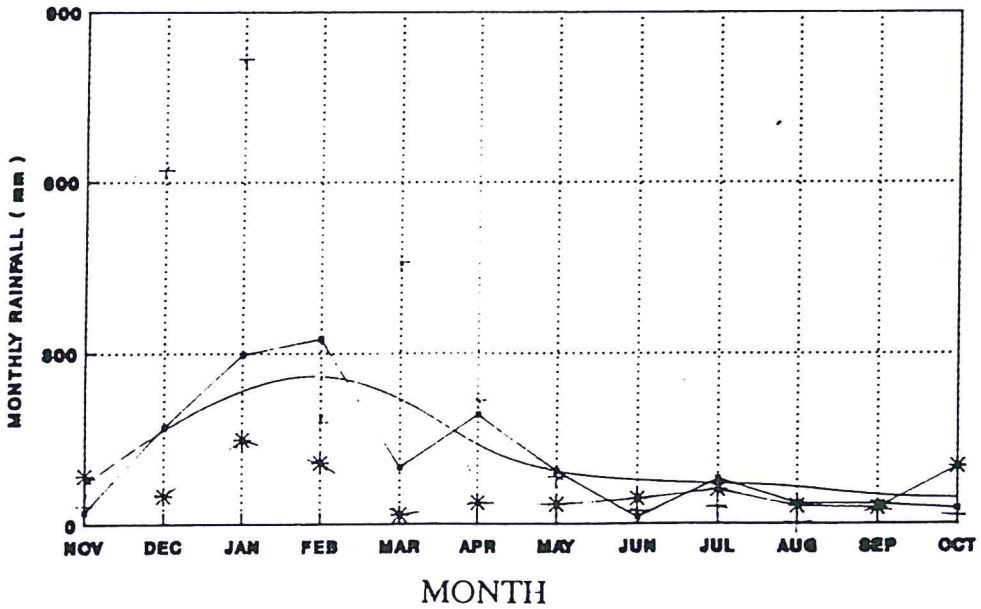


Fig. 2.1. Rainfall at Dubreuil



- = - 76 - 77 + 79 - 80 * 82 - 83 MEAN (51 – 87)

Fig. 2.2. Rainfall at Trianon

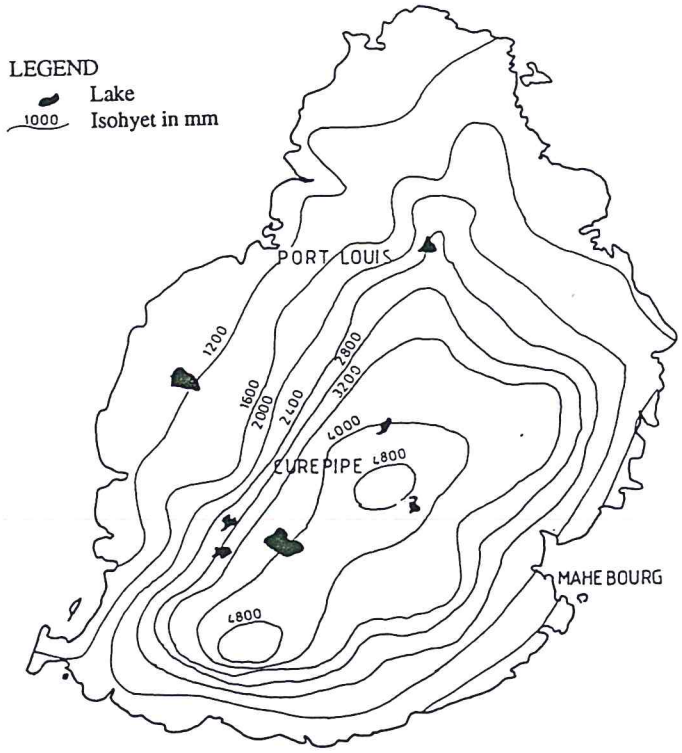


Fig. 2.3. Mean Annual Rainfall 1931-1960

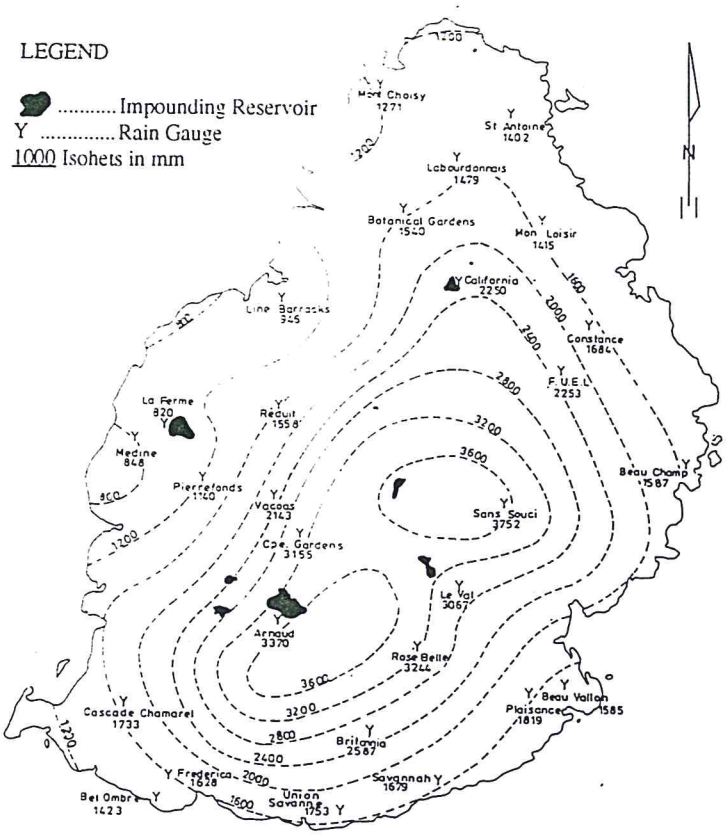


Fig. 2.4. Mean Annual Rainfall 1951-1980

2.2.2 Average Rainfall

Isohyet maps have been established for the periods 1931-1960 and 1951-1980 (***Figs. 2.3*** and ***2.4***). The question has often been raised if rainfall is generally decreasing as certain isohyet values (e.g. 5000 mm) do not appear in ***Fig. 2.4***. It is likely that this follows rather a long term trend. The influence of the prevailing South East Trade Winds and that of the relief may be noted. The average annual precipitation in Mauritius varies from 1300 mm on the east coast to 4000 mm on the Central Plateau, and 900 mm on the west coast (Médine) - ***Fig. 2.5***.

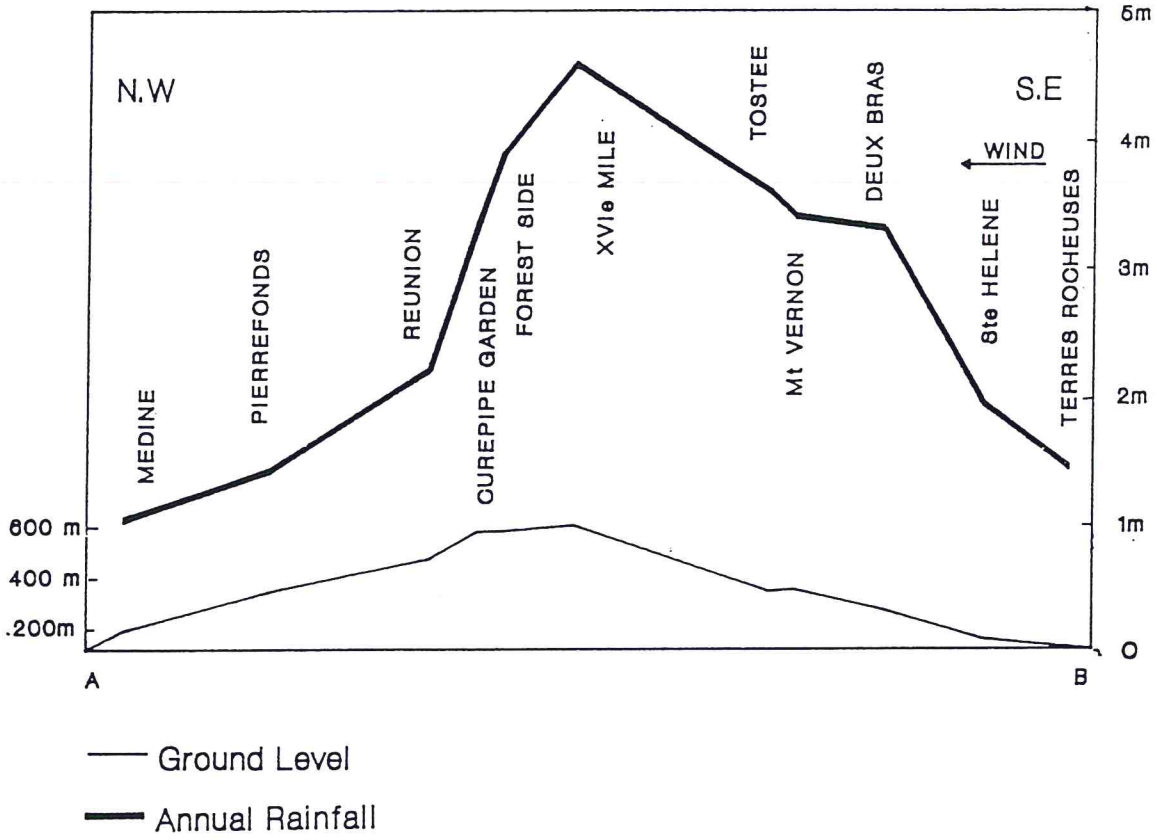


Fig. 2.5. Variation of Rainfall with Altitude

It may also be noted that while the highest figure in Mauritius is of the order of 4.5 - 5 m, the corresponding value in Réunion is 9 m.

The main reservoirs of Mauritius are located in the upper catchment of Grand River South East and the catchments of the Southern rivers (Riv. du Poste, Riv. des Anguilles, Riv. La Chaux, and Riv. des Créoles, ...) which receive much rainfall.

2.2.3 Long term rainfall variations

While parts of a precipitation record may suggest an increasing or decreasing trend, there is usually a tendency to return to the mean; abnormally wet periods tend to be balanced by dry periods. The regularity of rainfall fluctuations has been

repeatedly investigated over the world and more than 100 apparent cycles, ranging in period from 1 to 744 years, have been propounded.

Fig. 2.6 shows the total annual rainfall at selected stations during the period 1860 - 1990. It is not intended to determine any cycle. However, the graphs show that the dry and wet periods oscillate around the mean, with two observations. Firstly, while the wet periods last one to three years, the dry spells (rainfall below mean) may last much longer, even up to 10 years. Secondly, the wet and dry spells for all the stations do not occur at the same time. Thus on the one hand, due attention must be given to the long dry spells and on the other hand, it is probably fortunate that all the regions of the island do not endure dry or wet spells at the same time.

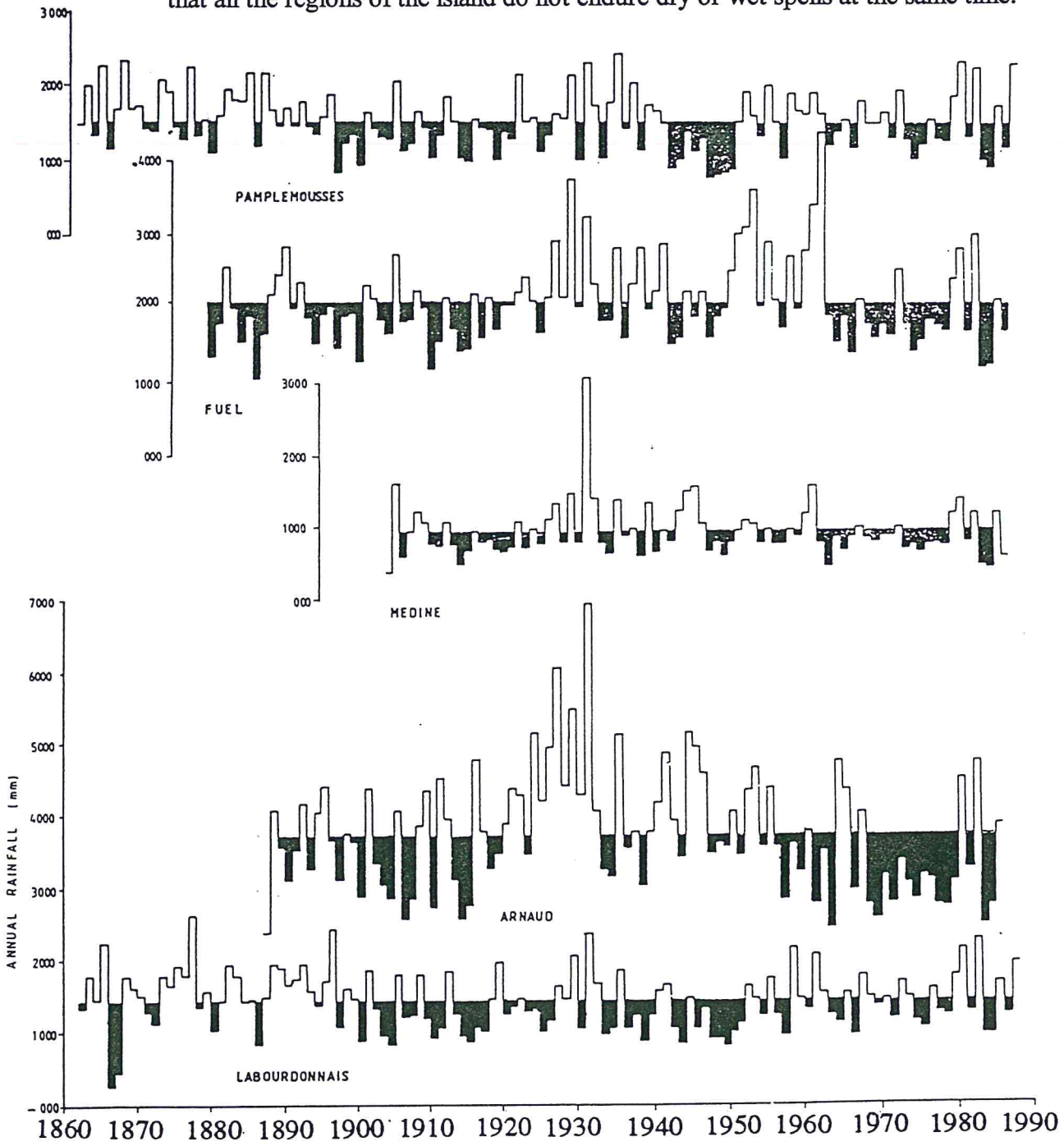


Fig. 2.6. Total Annual Rainfall (1860-1990)

It is noteworthy that extreme events, e.g. cyclones that may bring 200-1000 mm of rain in a few days, do not only influence the statistics but have a major bearing on the load carried by rivers.

2.3 RAINFALL EXTREMES

2.3.1 General

Annual precipitation values in Mauritius seem to follow the Poisson or log-normal distributions, (***Fig. 2.7***). For example, using annual totals over 107 years for F.U.E.L station we get the following information - mode 2000 mm, mean 2110 mm, minimum 1040 mm, maximum 4400 mm and standard deviation 580 mm. The values of 0.5 and 4.5, corresponding respectively to the ratios of minimum and maximum annual rainfall to mean annual rainfall, are obtained at quite a large number of stations.

2.3.2 Floods

A flood is an unusual high stage of a river due to rainfall runoff, too great to be confined in the normal water surface elevations of the river.

Flash floods are most frequently associated with violent, convectional storms which tend to be of short duration.

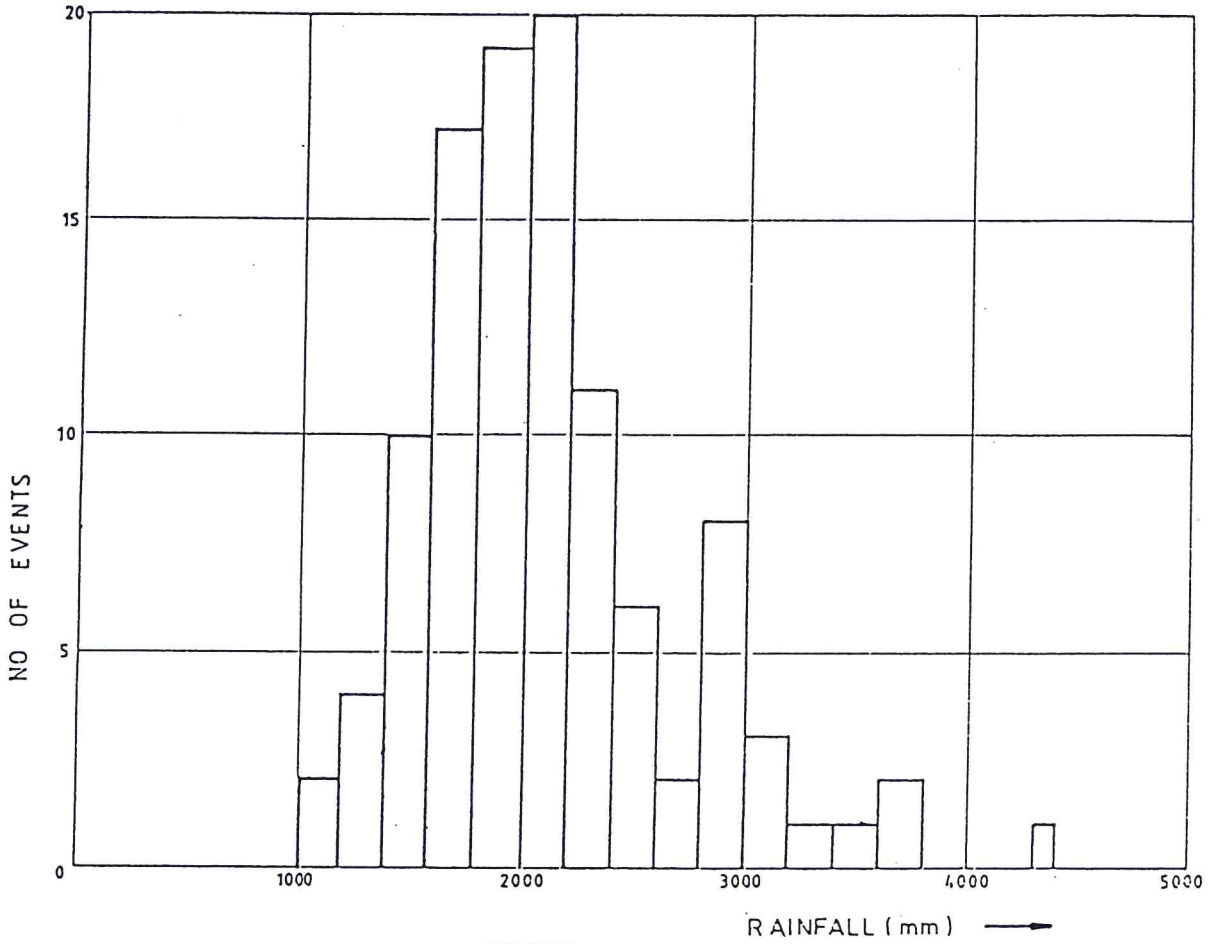
Single event floods have a single main peak discharge but have a substantially longer duration than flash floods. It usually results from rains of several hours' or days' duration moving over a drainage basin.

Multiple event floods result when successive flood peaks follow closely on each other in response to a more complex weather situation. Although the individual flood peaks may not exceed or even closely approach previous maxima, the flooding is often severe because its duration extends over a period of several weeks or months. On rare occasions, record peak discharges may combine with the extended duration of flooding to make multiple event floods the most disastrous flood occurrence.

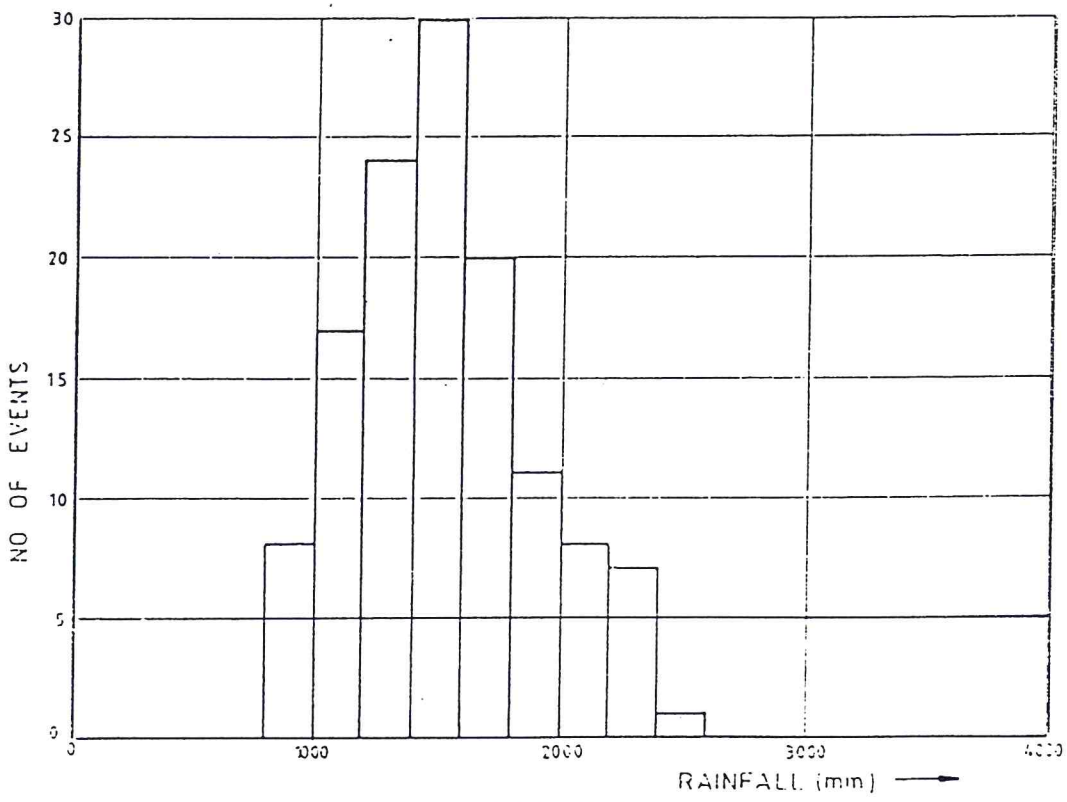
Seasonal floods are said to occur when multiple event flooding recurs annually on a massive scale, with the period of high water often extending over several months.

It has been mentioned above that flood is caused by rainfall runoff. It is thus useful to consider a frequential analysis of maximum rainfall on a daily or an annual basis. ***Figs. 2.8*** and ***2.9*** show the results for different areas of the island.

It may be noticed that the annual rainfall in the East exceeds 3000 mm with a return period of 25 years, while it is never less than 1000 mm. In contrast, in the West, the annual rainfall exceeds 1000 mm only once in 4 years.



FUEL



PAMPLEMOUSSES

Fig. 2.7. Rainfall Probability Distribution

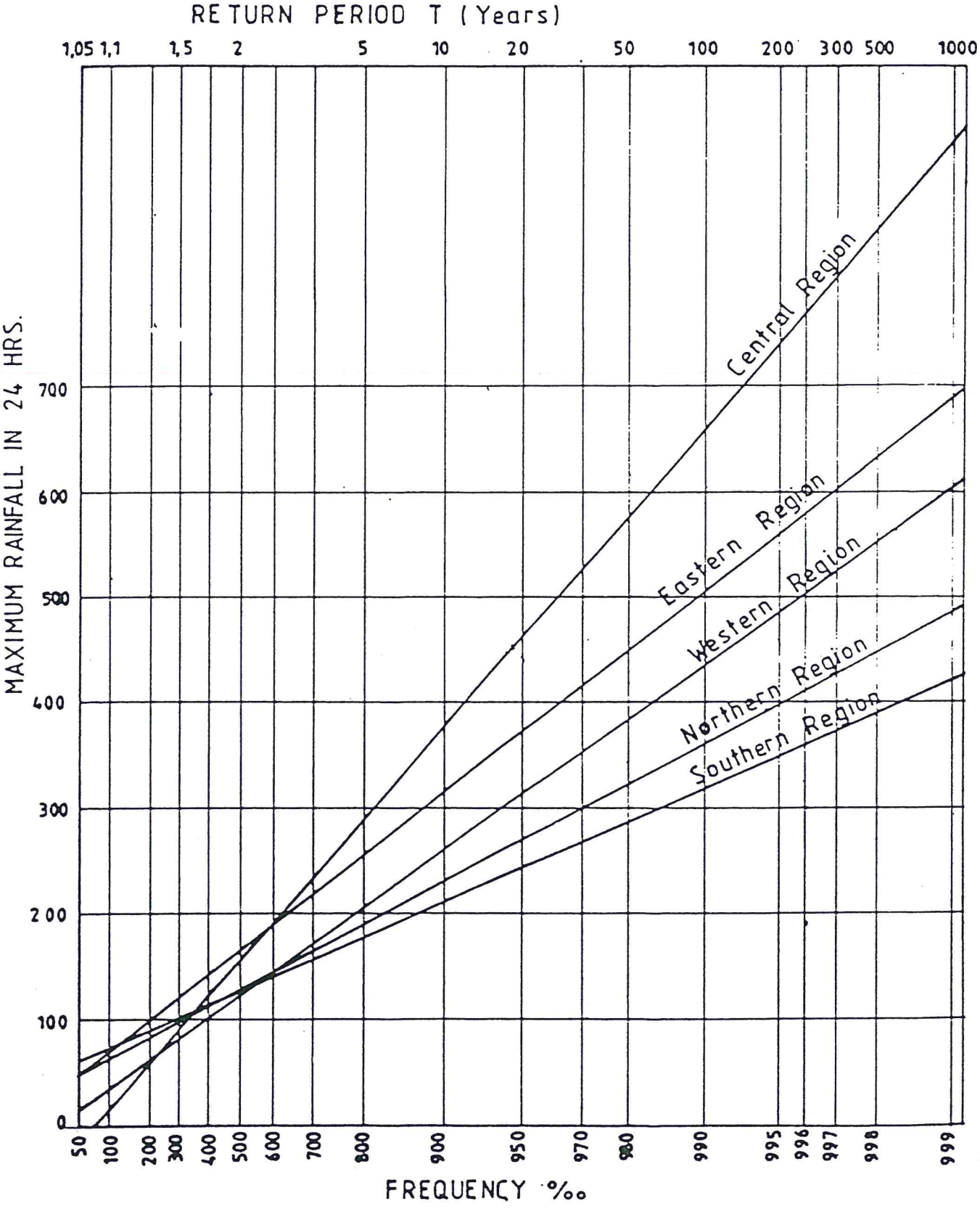


Fig. 2.8. Frequency Analysis for Maximum Daily Rainfall.

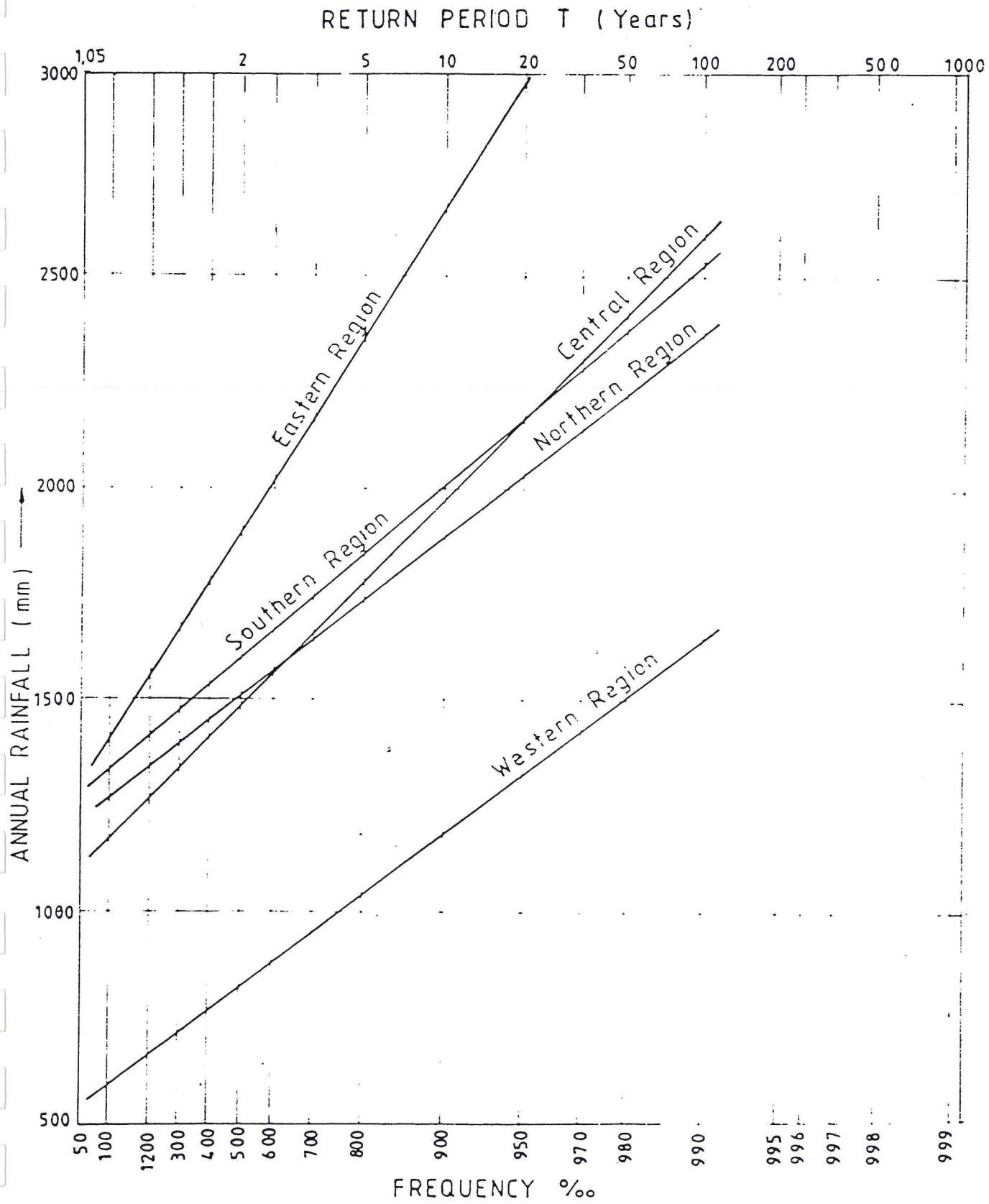


Fig. 2.9. Frequency Analysis for Maximum Annual Rainfall

The maximum daily rainfall is important as it may give rise to local flooding because drainage outlets are underdesigned, blocked, etc. ***Fig 2.8*** shows that while a maximum daily rain fall of 600 - 700 mm has an occurrence of more than a century, 200 mm in a day might occur with a return period of 3 years.

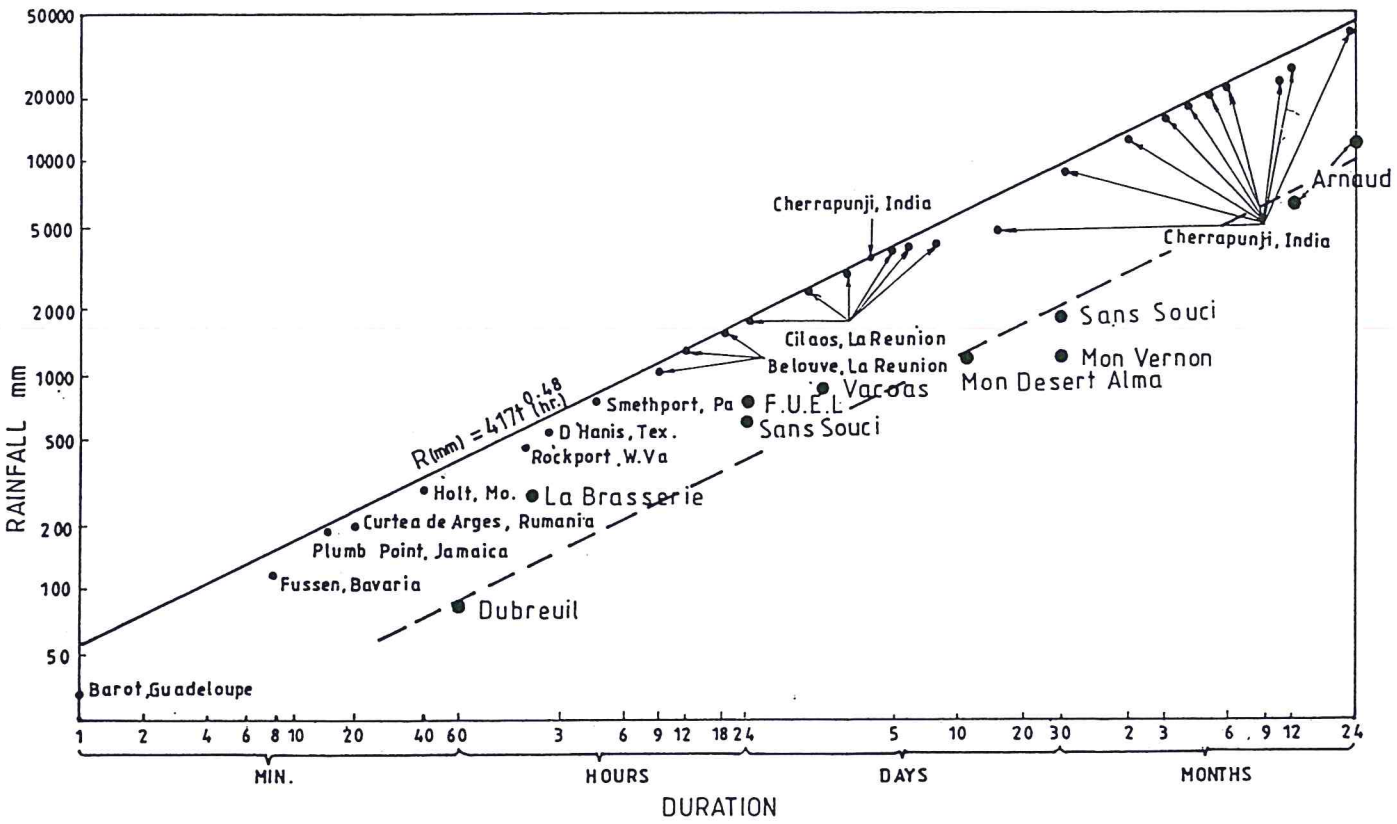


Fig. 2.10. Point Rainfall Extremes

Fig 2.10 shows how extreme precipitation values compare with other values observed elsewhere in the world.

2.3.3 Drought

Droughts are defined as periods when crops fail to mature for lack of rainfall or when precipitation is insufficient to support established human activities.

Drought conditions prevail when annual rainfall is deficient or poorly distributed in time; or when annual precipitation is concentrated in a few heavy rainfalls that drain away rapidly.

Droughts impose a critical demand
(1) upon works designed to furnish a continuous and ample amount of water,
(2) upon streams expected to carry away domestic and industrial effluents without nuisance.

Statistical studies of past droughts suggest a strong tendency for self-perpetuation. Some dry spells are broken ultimately only by a change in the seasons.

As ***Fig 2.6*** shows, Arnaud raingauge recorded an annual precipitation lower than the long term average for twelve years continuously from 1968 to 1979. A frequency analysis can be carried out similarly to determine the return periods of low rainfalls.

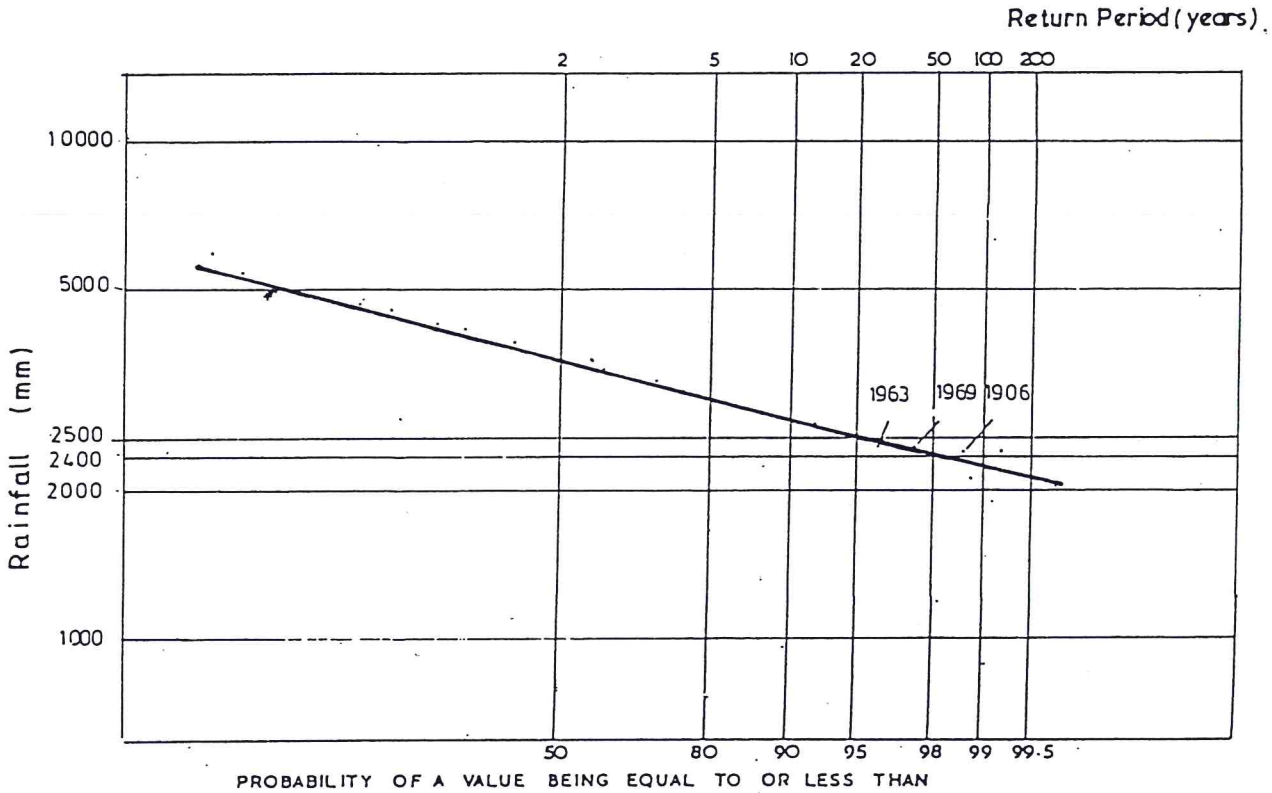


Fig. 2.11. Low Rainfall Analysis for Arnaud

Fig 2.11 shows the results of an analysis carried out for Arnaud with annual rainfall records between 1897 and 1972. It may be seen that a rainfall as low as 2400 mm may be expected once every 30 years. What could however appear as a pessimistic note would be the fact that there were low rainfalls of 2375 mm and 2436 mm in 1906 and 1963 (i.e. a period of 57 years), but followed by a low rainfall of 2397 mm after only 6 years (i.e. in 1969). This is a good example of how probability works. A 1 in 30 year probability has been translated by 3 events in 63 years but with spacings of 57 and 6 years, and NOT 30 and 30 years.

2.3.4 Rainfall Intensity

The study of flood conditions and the design of works for flood protection and drainage require information relating to rainfall intensity.

The curve relating maximum rainfall intensity and duration for any station can be shown to vary as a function of record length, for example, the probability of observing the maximum intensity of any given duration is greater in a 100-year record than in any one of the ten 10-year periods making up the total record. Thus, as most flood protection and water controlling structures are limited in capacity by economic considerations, it is usual to design for the most severe conditions to be expected with a certain average frequency of occurrence, i.e., with a specified mean recurrence interval or return period.

The return period selected varies with the importance of the structure, from some hundreds or thousands of years in the case of a major dam and spillway, where failure may cause loss of life and severe property damage, to say 50 years for the larger structures in an irrigation scheme and ten years for minor works where the cost of repairs is probably less than the extra cost of building and maintaining larger capacity protection works.

Figs. 2.12 and ***2.13*** show the rainfall intensity-duration-frequency relation for Pamplemousses and Vacoas.

Fig. 2.14 shows how the daily rainfall at Arnaud was analysed on a frequency basis to try to obtain a "normal" curve. For many problems, this type of distribution is easier to work with.

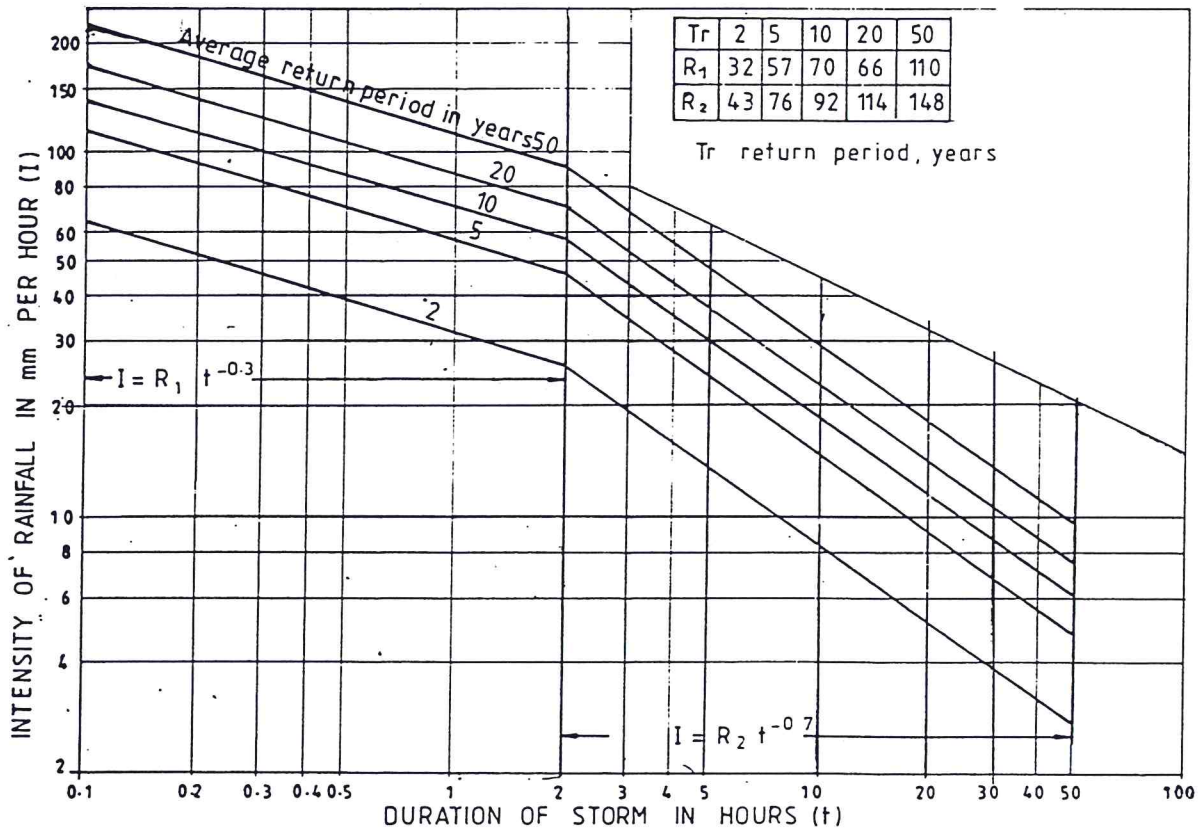


Fig. 2.12. Rainfall Intensity-Duration-Frequency at Pamplemousses

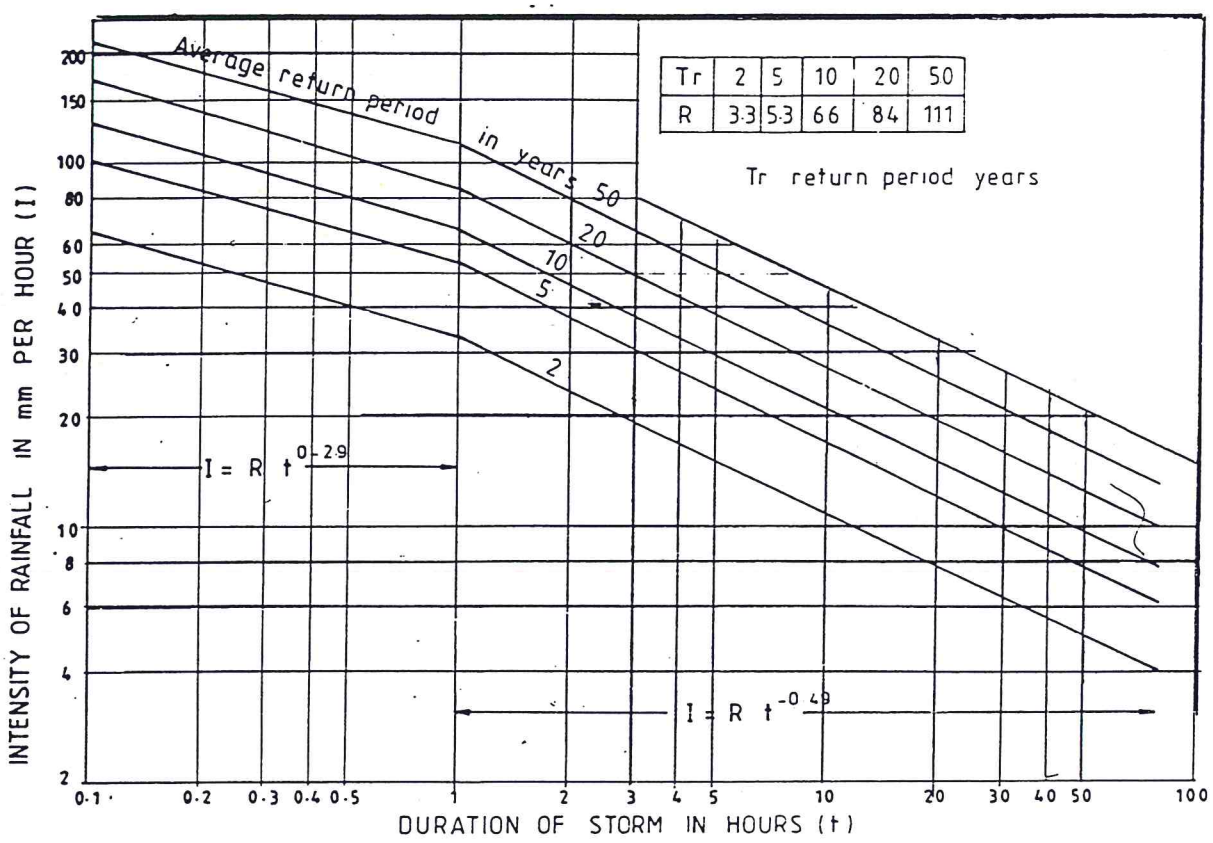


Fig. 2.13. Rainfall Intensity-Duration-Frequency at Vacoas

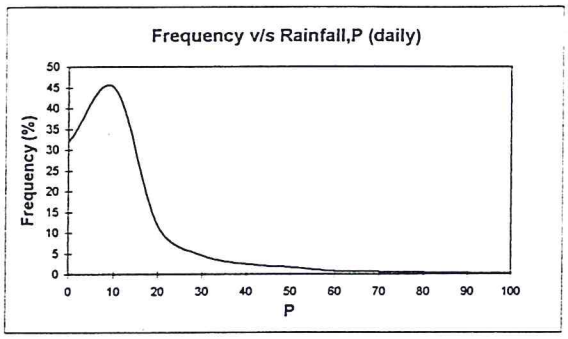


Fig 5.1.4(a)

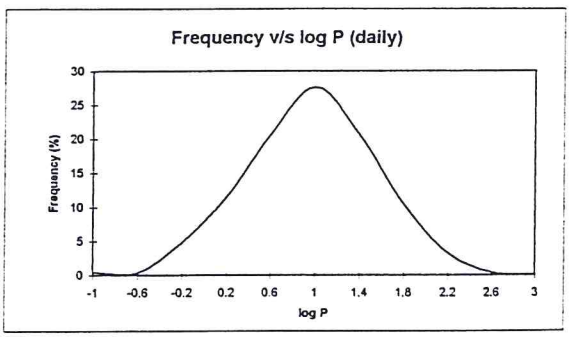


Fig. 2.14. Frequency Analysis at Arnaud

CHAPTER 3

SOIL EROSION DUE TO RAINFALL

3.1 LAND USE

3.1.1 Introduction

Does the availability of water resources influence the type of use land is put to or is it the converse? Water resources assessment and design must take into account the future catchment conditions resulting from past and present land use policies in order to predict the effect of such changes on flood and drought extremes and annual water yields.

In Mauritius, land ranges from barren mountain ranges to central plateau tropical forests. Land is used for growing food, timber, housing, parking facilities-, playing fields, manufacturing industries to name but a few of the many uses reflecting the complexities of modern life. The different uses may be summarised as below:

1. Land as ecosystem
2. Land as space
3. Land as landscape
4. Land as economic activity

Inversely, the water resources may be affected by

1. the presence of forests
2. the presence of grazing animals
3. the presence of croplands
4 urban development
5. the role of drainage or irrigation
6. recreation,

which are all factors influencing land use.

3.1.2 Land Use

Table 3.1 compares actual land use in Mauritius in 1965 and in 1986. The last column gives land suitability as studied in 1973.

The table clearly illustrates the dominant position of sugar cane in the agricultural economy of the island. Over half of the total land surface, and about 95% of the total cultivated area, is under sugar cane. It occupies almost all the land receiving an annual rainfall of between 1000 mm and 3800 mm except on steep mountain slopes, steep river valley sides and on rock lands (or worse of the lithosols).

Table 3.1: Land use in Mauritius, actual and suitability

	Area in hectares		
	Actual in		Suitability
	1965	1986	1973
Agriculture	106,228	90,065	106,000
Forests, scrubs, grass lands and grazing lands	64,465	65,330	39,300
Built up areas	11,857	25,500	13,200
Others (reservoirs, roads, rocks)	3,925	5,605	11,300
Under utilised			16,200
TOTAL ISLAND	**186,500**	**186,500**	**186,000**

Note: The small discrepancy in total area arises from measurement inaccuracies.

The scrub land, scrub-invaded forests, savanna and forest plantations which together amount to more than 30% of the land surface, cover the steeper parts of the mountain gorges and river valleys, much of the Central Uplands and the rougher parts of the Central Plateau. The potential for developing crop production on much of this land is negligible, the areas being best suited to forestry', livestock production and deer farming.

3.1.3 Forest Land

Early travellers who visited Mauritius in the seventeenth century described the island as having tropical forest and jungle from the mountain tops down to the sea. These accounts are mostly based on the rather meagre records made by the Dutch during their exploitation of the ebony forests of the lowlands. Only scattered fragments of these forests remain, so that their ecological features are rather difficult to define or pigeonhole onto any system of tropical woody vegetation. Suffice it to say that the ebony forests had a somewhat underfined stratification, a more or less open canopy allowing much direct sunlight to reach the forest floor and a scarcity of epiphytic ferns and orchids. There was a fair proportion of deciduous species which were able to make an important contribution to the leaf litter on the forest floor.

In the uplands, the increase in rainfall and diminution in daily hours of sunshine gave rise to a forest of a very different character. This formation may be regarded as a sub-tropical mountain rain-forest. Here the dominance of ebony *Diospyros tesselaria* is suppressed and replaced by other large tree species with a high proportion of *Sapotaceae*. Stratification is well marked, stocking very dense and light intensity in the interior of the forest is low. There is also a high and very constant humidity and in consequence ferns and epiphytes are abundant. Except in the special cases referred to below, the nature of the indigenous vegetation which developed on the island was governed essentially by climatic factors (in addition, of course, to the available plant species), whereas the different types of soils were of secondary importance. The opening up of the soil to cultivation and the loss of the humus increment provided by leaf fall, together with the gradual disappearance of

the original plant cover has led to profound and possibly irreversible changes in the microflora and fauna and perhaps other characteristics of the soil. These changes would seem to prelude subsequent re-population of indigenous species even supposing it were possible to attempt to establish them by artificial regeneration.

At the present day most of the indigenous vegetation is restricted to the lithosols of the mountain ranges and the gorges separating them. Very little original vegetation is to be found on the latosols or the deep latosolic soils stretching across the centre of the island.

There are a few special soil groups which call for mention here. The Low Humic Gleys of the uplands still support a peculiar flora containing a large percentage of indigenous marsh plants which have resisted with a fair measure of success the invasion by exotics. These soils are typical of the marsh lands near Pétrin and Midlands.

In the Pétrin area, on the Ground Water Laterite, is found the remnants of the cricoid heath vegetation, formerly of much wider extent. There is hardly any true soil here, the plants growing in the crevices of highly ferruginous slabs of cuirasse.

On Plaine des Roches, the progress of plant succession to a climax forest has been arrested by sheets of bed rock lava of geologically recent origin. This formation has, until the introduction of heavy agricultural equipment in recent years, held up the use of the area for agricultural purposes and as a result many of the indigenous plants have survived.

Along the coast may be found the Regosols with their typical littoral vegetation but in many places these have been much altered and stabilized by *Casuarina* plantations and the ground cover afforded by the common Herbe Bourrique *(Stenotaphrum dimidiatum).*

About 56,000 ha of land in Mauritius are classified as forest, reserves or scrub and grazing land (this excludes savannas, grasslands, meadows, etc.) Of these about 11,800 ha are plantations owned by the State. In addition there are some plantations on private land, although the precise area of these is difficult to establish. About 85% of all State owned land plantations are used for deer ranching and 15% of their area may be converted to fodder grass production. About 80% of State owned land plantations are of *Pinus elliotti* and other softwobds,. such as *Cryptomeria, Auracaria and Junipeus.* All these softwoods are mainly planted in the uplands. *Casuarina and Eucalyptus* occupy a further 14% and the remainder are miscellaneous hardwoods.

Large scale plantations of exotic species were started in the 1930s and by 1944 there were about 3,000 ha. These were d evastated by a cyclone in 1945'but replanting took place at the rate of 200-400 ha per year during the 1950s. In 1960 a violent cyclone destroyed 2,000 of an estimated 3,000 ha of plantations. Replanting began again, reaching a peak of 500-600 ha per year between 1973 and 1977, during the government relief work programme. Planting rates have declined

since 1978 and ranged between 100-200 ha per year from 1981 to 1985. ***Fig. 3.1*** shows the area covered by forests in Mauritius.

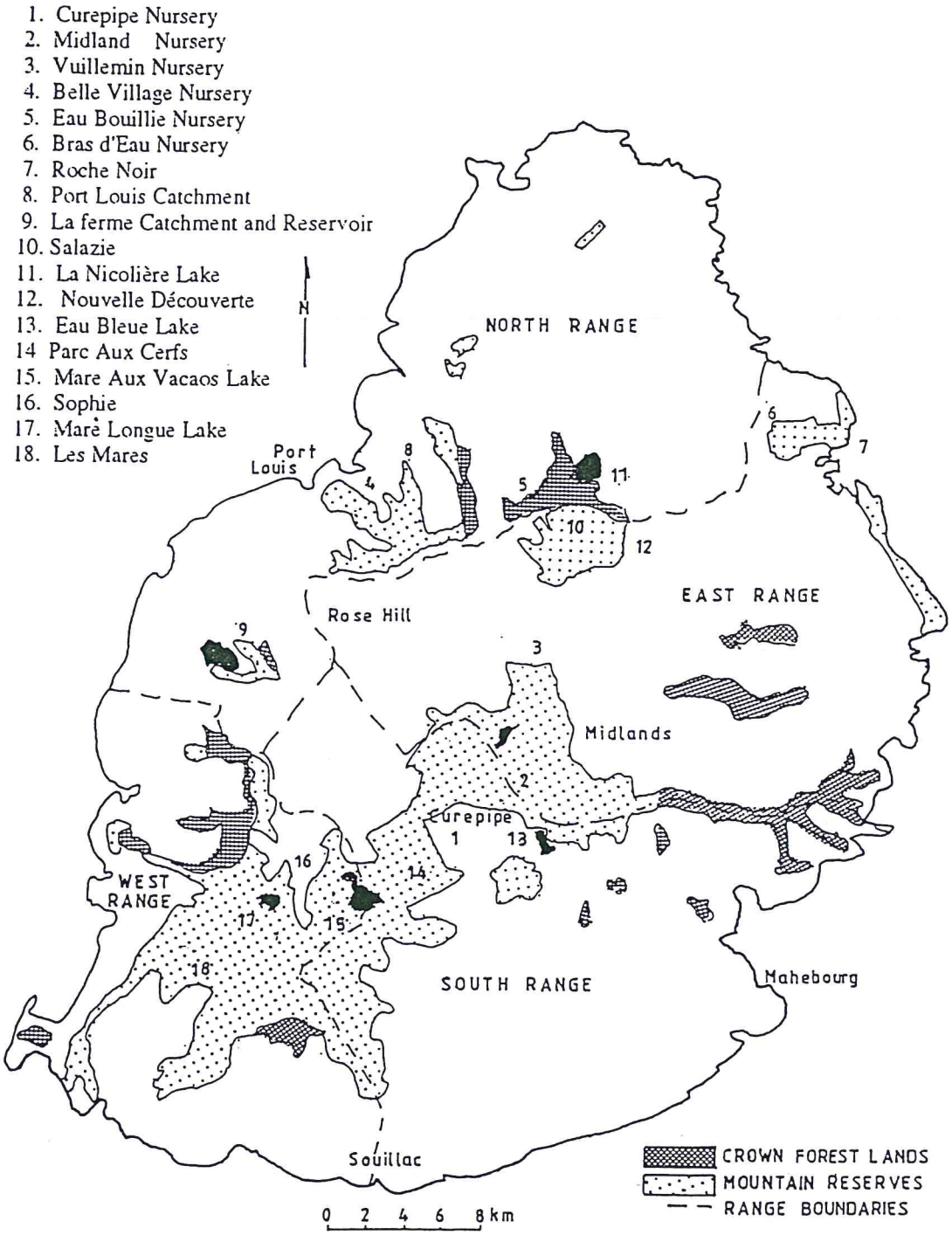


Fig. 3.1 Forest Area in Mauritius

3.2 THE EFFECTS OF FORESTS ON WATERSHEDS

When new land is urbanised, water engineers and meteorologists are rarely on hand to measure the effects which the changes in land use will have on water resources, i.e. on the volume and pattern of streamflow and on the depth and quality of the water in storage underground. Forests are felled or burned and natural prairie of Savanna grasslands are ploughed without consideration for catchment characteristics (e.g. forests in Brazil for paper production). Even where some streamflow and rainfall measurements are established the records are usually held by different public departments, none of which keep records of the uses to which land is put year by year.

3.2. 1 Forests And Mists

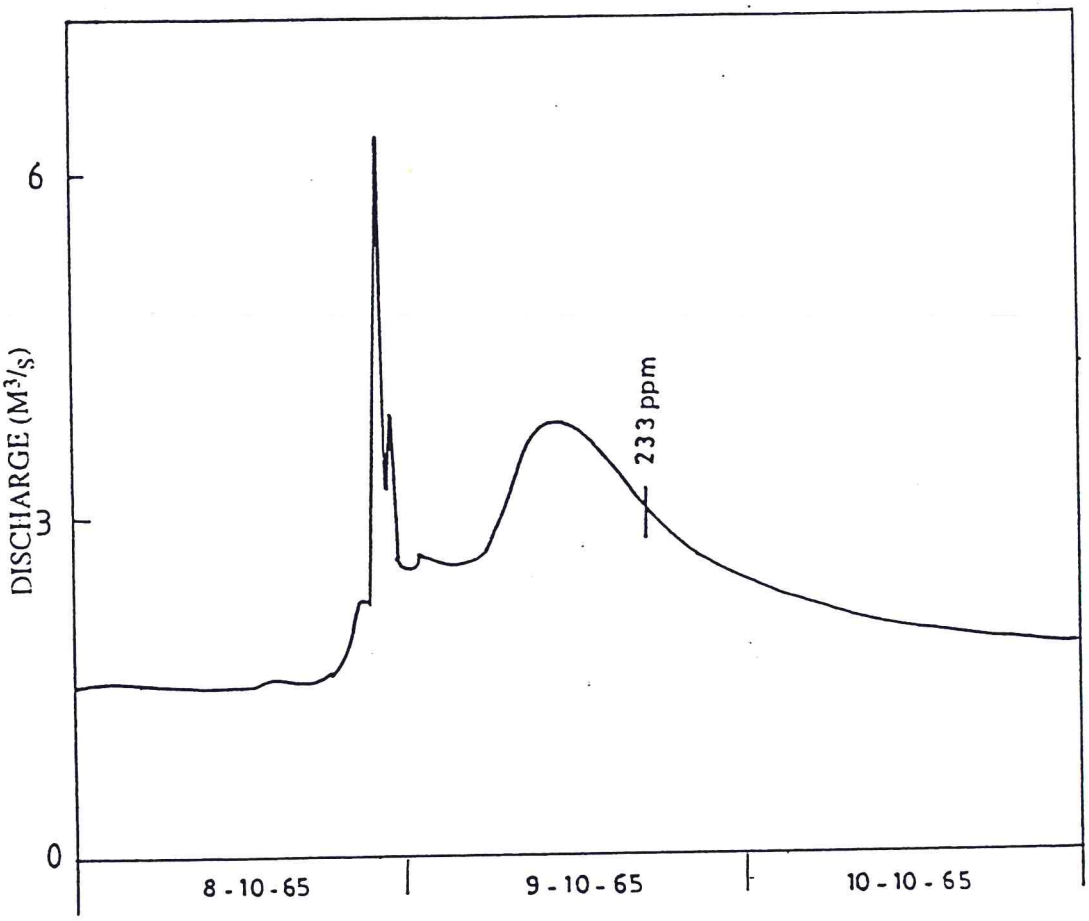
There are specific conditions in which forests can influence the occurrence of mists. The condensation of mist on to foliage can cause impressively heavy drip from trees. About 250 mm (10 inches) of drip were recorded during each of four rainless summers, from a pine tree on the Berkeley Hills overlooking San Francisco Bay (California). In Japan, belts of trees are planted along the coast to intercept the inland drift. of sea fogs. Similarly in Australia, under freezing conditions such interception is increased and is reported to increase catchment yield.

3.2.2 The Effects Of Fire

The protective function of forest cover is demonstrated most dramatically when the covering from large areas is suddenly removed by fire. A forest fire not only destroys the trees but may consume much of the litter which protects the soil. Where watershed areas are being managed deliberately for the harvesting of water supplies, a major problem is their protection from forest fires.

In the Australian Alps, a major uncontrollable forest fire occurred in rugged inaccessible mountain country. The catchment areas of the Wallace's Creek and Yarrangobilly River, of 41 and 224 km^2 respectively, were burned out. The Authority had gauged these catchments for the previous eight years, with detailed sampling of suspended soil loads. After the fire the flow pattern changed abruptly, with sharp flow peaks from the burnt areas (***Fig. 3.2***). Rainstorms, which from previous records would have been expected to give rise to flows of 60 to 80 cubic metres per second (cumecs), produced a peak of 370 cumecs. The suspended sediment content at a flow of 60 to 80 cumecs increased by 100 times in comparison with the soil content before the fire. A storm occurring some seven months after the fire gave highest sediment concentration yet recorded at Wallace's Creek. At a flow of 95 cumecs the concentration was 14.4% by weight, equivalent to 11,500 tons per day. This concentration is high by world standards. On the same day the Yarrango Billy River, with a flow of 47 cumecs, yielded an equivalent sediment load of45,000 tons per day. The combined effect of the increased flow rate and the increased sediment concentration was estimated by the Authority to have given a total sediment load in Wallace's Creek of 1,000 times greater than before the fire. Watershed experiments in Arizona foothills under chaparral scrub, which were denuded by a very destructive wildfire, gave a tenfold increase in water

yield (from 4% to 40% of 600 mm rainfall)., Erosion losses increased from one-thousandfold to three-thousandfold. The annual sand and gravel transport rose from 43 tons/km^2 in the previous three years to 50,000, 100,000 and 150,000 tons/km^2 respectively on three measured watersheds.



Spate Flow following Severe Fire in the Snowy Mountains

Fig. 3.2 Effect of Fire

In Mauritius fire is uncommon in the upland areas, but in the drier lowlands fires occur almost every year. These fires are frequently set deliberately by stock owners, to provide a flush of net growth. The Forestry Department has started to fence some of these areas and create firebreaks around the fenced area.

3.2.3 Streamflow Comparisons On Forested Watersheds

The main data available for hydrological study are the records of streamflow measured by water engineers in their assessment of local and regional resources.

For forest hydrology' the evidence is usually obtained from two types of watershed experiments

1. those of long-term comparison (regressions) between streamflows

2. those of intensive studies in which energy balance is applied to the annual water budget.

The first method assumes that, the variabilities of topography, geology, climate and vegetation interact in too complex a fashion for detailed analysis and that the only integrating measure is that of the flow of the stream itself. Weather variability from year to year imposes the necessity for long-term observations of streamflow both before and after change in land use. Most of the established evidence in.the subject has come from this method.

The first experimental study in which a planned 1and-use change was carried out in order to observe the effects on streamflow, began in the USA at Wagon Wheel Cap, Colorado, in 1910. There, streamflows from two similar watersheds of about 100 hectares each were compared for eight years. One valley was then clear-felled and records continued. From the calibration period the flow of one stream could be predicted from the other by simple regression calculations. After the clear-felling the annual yield of water was increased 17% above that predicted from the flows of the unchanged control valley. The differences were observed to diminish rapidly as sprouting aspen restored the vegetative cover.

At the Coweeta Hydrological Laboratory (USA), two small watersheds were compared for only three years of preliminary calibration; thirty-six monthly comparisons of water yield were made before one watersheds was clearfelled in 1940. The immediate result, in the first year after cutting, was an' increase in annual streamflow equivalent to 373 mm depth over the watershed area. The hardwood, forest was allowed to re-grow, and the streamflow decreased until, 23 years later, the flow was. only some 75 mm greater than that predicted from the full forest cover. The cut was then repeated in 1962: the increase in streamflow was almost identical with that produced in 1940. ***Fig. 3.3*** shows the annual *deviations from regression i.e.* differences of observed flows from the yields predicted by the relationship to the control watershed.

The curve, which fits the figures well, shows that the decline of yield increase is approximately proportional to the logarithm of the time in years since the felling of the forest.

Results from thirty-nine experiments, ranging from eastern. to western USA and including data from Japan, East Africa and South Africa show the immense scatter of the streamflow response in the first year after felling as illustrated in ***Fig.3.4a***. The one consistent factor is that a streamflow increase of 450 mm of water per annum over the cut area is a maximum under all of the wide range of environments tested.

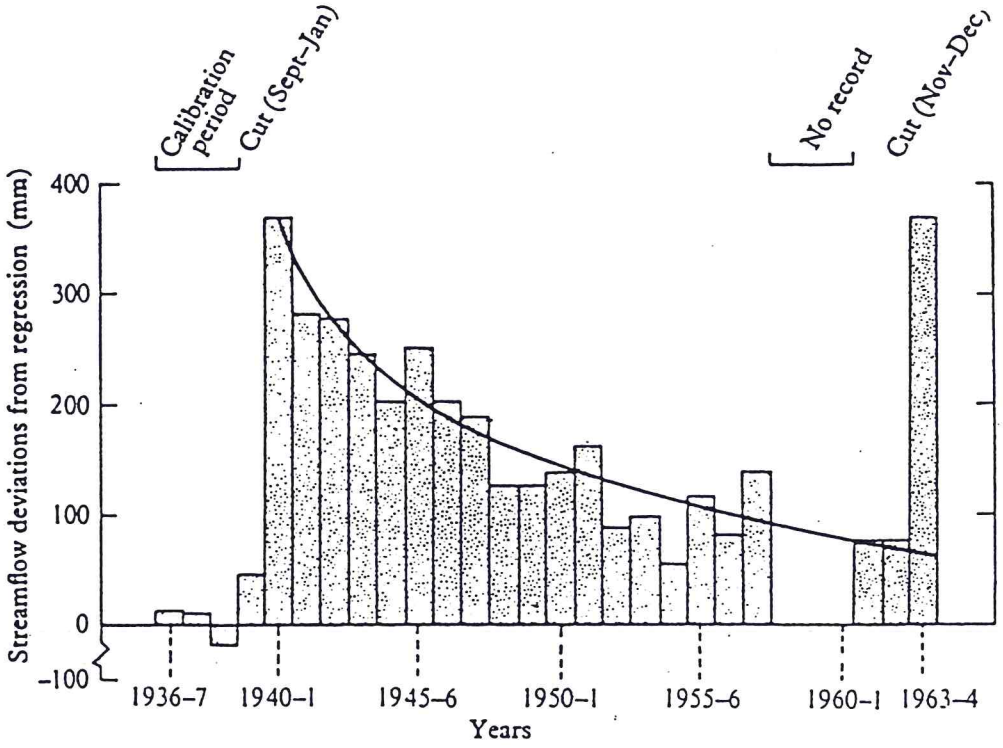


Fig. 3.3 Annual Deviation from Regression

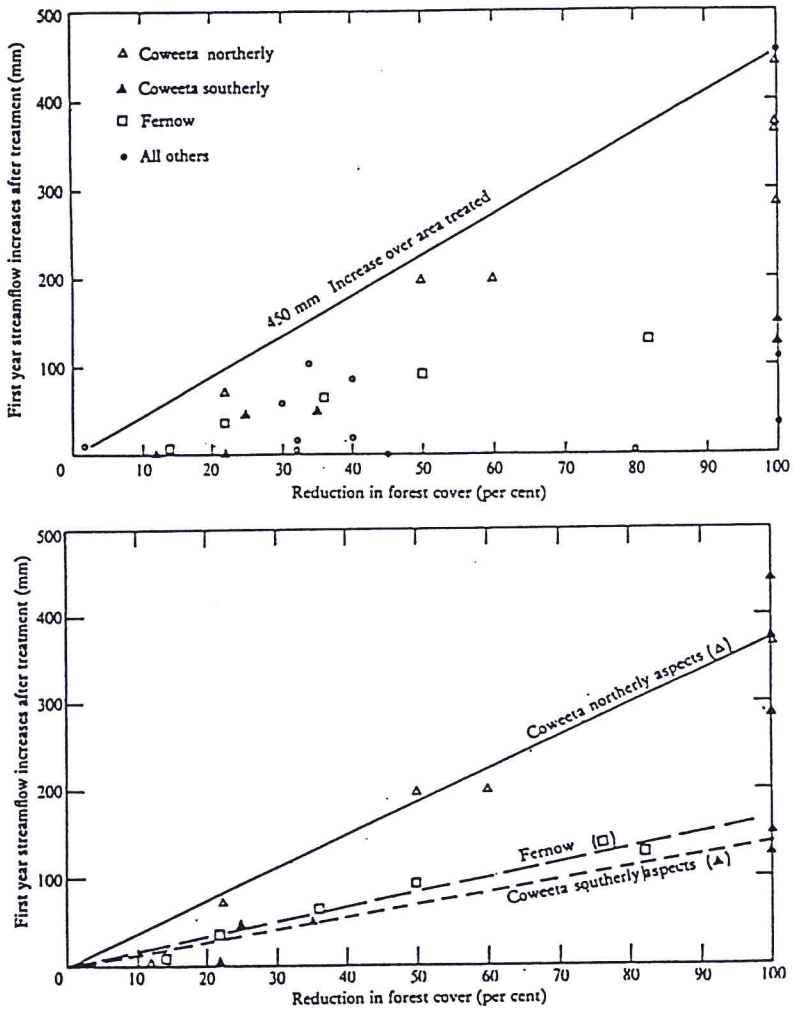


Fig. 3.4. Influence of Forest Cover on Streamflow

Most of the forest fellings produced less than half of this response. At Coweeta there were sufficient experiments under comparable conditions to observe that felling of forest northerly and north-easterly slopes produced about 350 mm of extra streamflow from the area cut, but that much smaller increases were obtained from clearing southerly slopes. In spite of this variability, world evidence is strong enough to conclude that in well-watered areas, streamflow response is proportional to the reduction in forest cover.

Prediction of the water yield from planned watershed management practices is certainly the most urgent of the estimates needed in water resource development, but these valley-comparison experiments can predict only in relative terms. We are thus very little closer to the understanding of watershed functions which is necessary for the extension of results from experimental valleys into other environments.

3.2.4 Experimental Study In Mauritius

The purpose of the experiment was to determine whether any changes in streamflow and soil erosion would occur if areas of native and exotic forest were replaced by tea plantation. The experiment consisted of three experimental catchments, shown in ***Figs. 3.5 and 3.6***.

Catchment area No. 1 (River Bateau) which has an area of 0.647 km^2 was to remain permanently under forest as the control experiment. However, after the 1960 cyclone Carol, the area was clear-felled and planted with young pines at different stages of growth. Through a misunderstanding, almost two-thirds of the basin was cleared by the Tea Authority in February 1971, but was later replanted with pine. A dense secondary growth covered the soil completely.

Catchment area No.2 (River Vacoas) which has an area of 0.725 km^2 was under natural scrub cover, interspersed with young eucalyptus trees, until January 1969, when clearing began and tea bushes were planted; clearing was completed by April 1971.

Catchment area No. 3 (River Gontran) which has an area of 0.596 km^2 was already under tea plantation of age from one to three years when the hydrological study began in 1967.

By comparing the streamflow characteristics for the three catchments, it was hoped to arrive at a quantitative estimate of the effect of re-afforestation. Daily streamflow records for the three catchments, daily rainfall records for eight raingauges in the area and daily evaporation records from one American class A evapotranspiration pan, were used.

As at 1976, the conclusions were as follows:

1. After April 1971, the response of the Vacoas basin to effective rainfall was significantly more rapid than for the period preceding April 1971. This change may

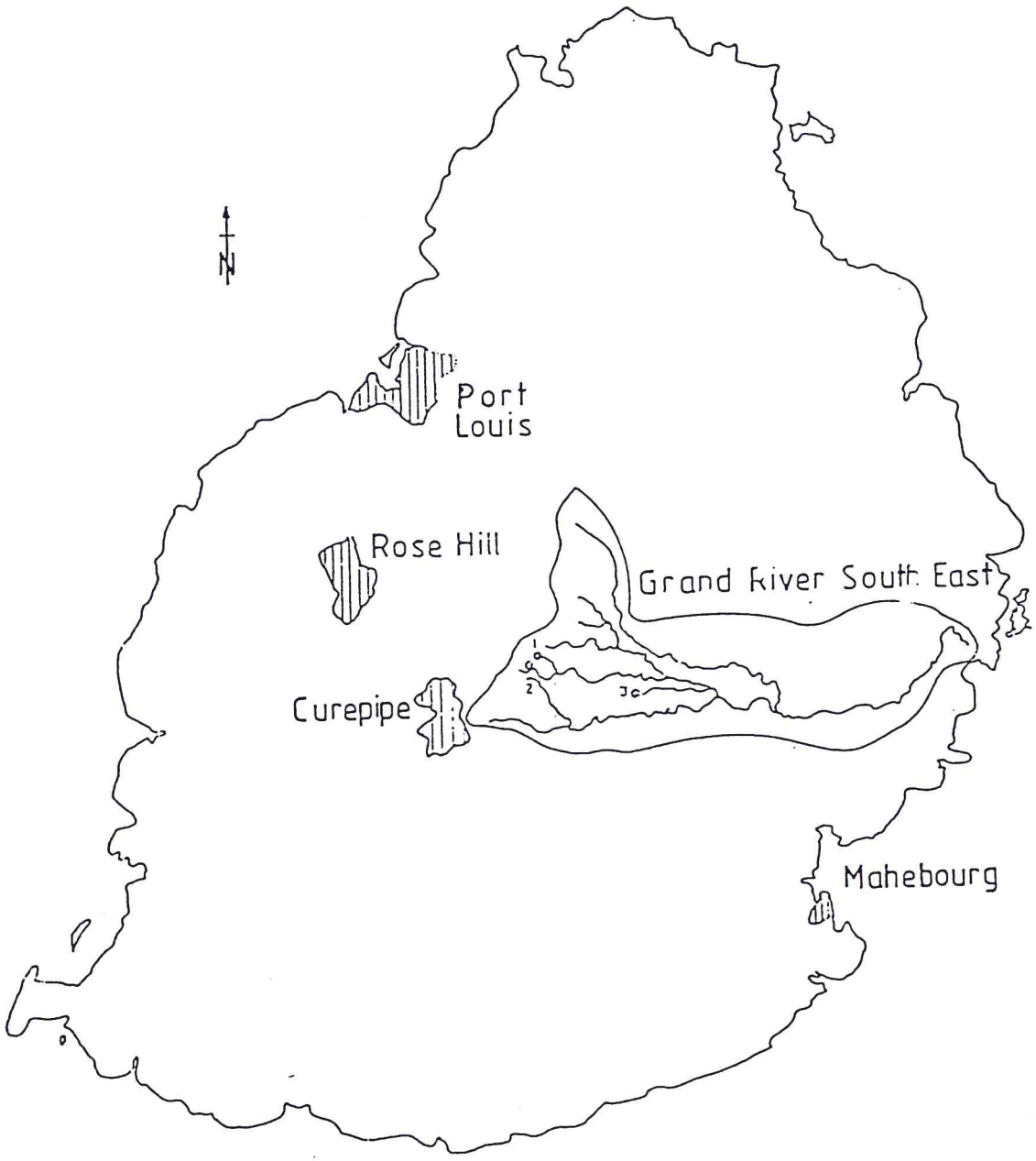


Fig. 3.5. Location of Experimental Catchments in Mauritius

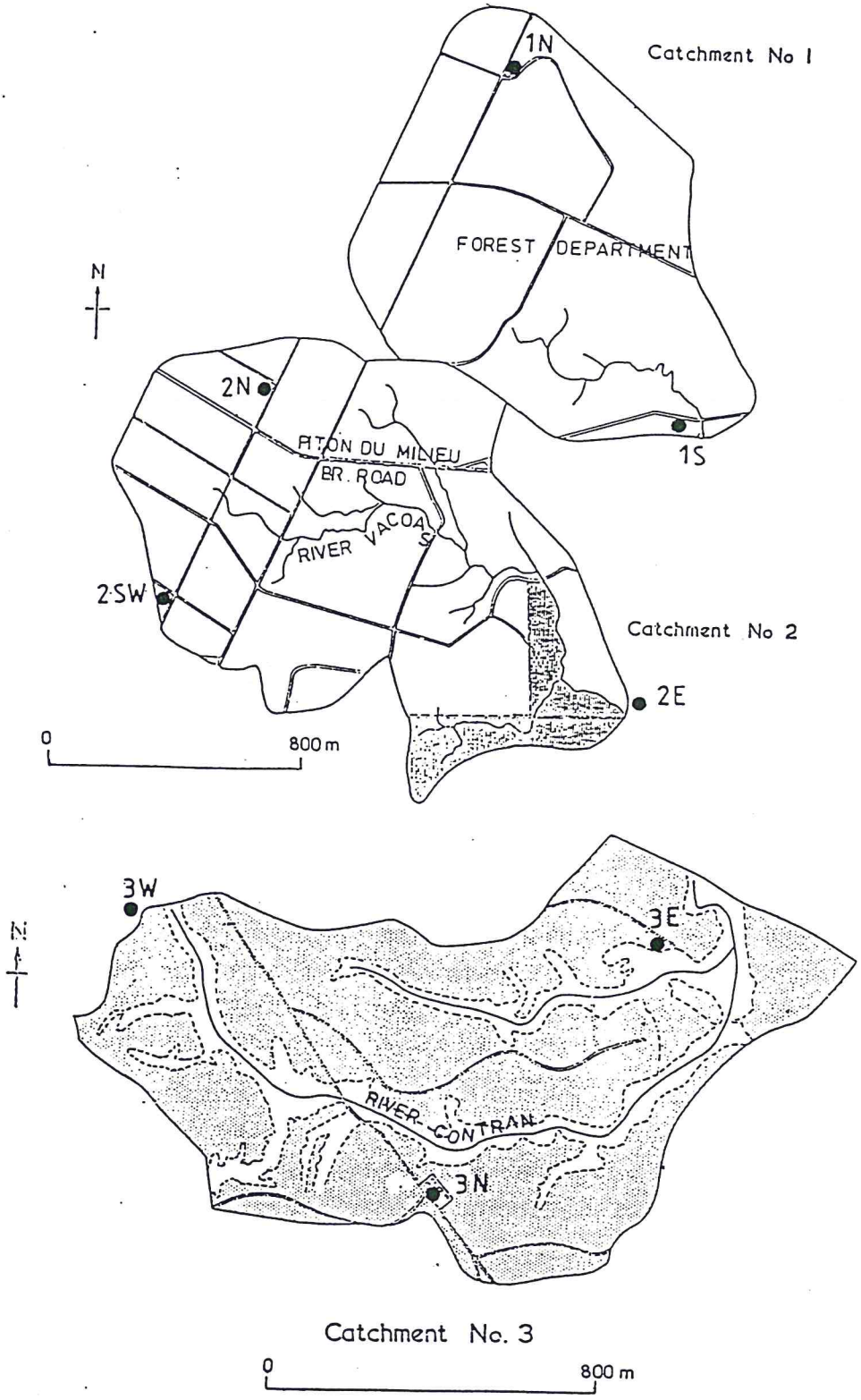


Fig. 3.6. Bateau, Vacoas and Gontran Experimental Catchments

be associated, in whole or in part, with the clearance of scrub, completed by that date, in preparation for tea planting.

2. Examination of the streamflows for each basin during the two periods 1968-71 and 1972-75 showed no evidence that differences between the period mean streamflows varied from basin to basin; the land use change therefore showed no evidence of having affected total annual streamflow, and its hydrological effect appeared to be that of changing the partitioning of total rainfall into rapid runoff and infiltration components.

3.2.6 Interception Of Rainfall

Most people have at some time sheltered under trees in light rainfall and are aware that few raindrops reach the ground; also that it is unwise to lean against the tree trunks, down which water may be flowing. Such observations obviously have led to a great deal of research on the interception - of rainfall by different types of vegetation and its re-evaporation from the surfaces of leaves and branches.

It has been established that interception depends primarily on the physical character of the rainfall.

Very light rainfalls of small drop size may be totally intercepted while heavy rainfalls of large drop size rapidly saturate the canopy, which thereafter transmits most of the water received. This is a physical process largely independent of the biological character of the foliage. It is well illustrated by Fig.3.7 in which rainfall interception over a range of storm sizes is compared for tropical bamboo forests, a cypress plantation near the equator in East Africa

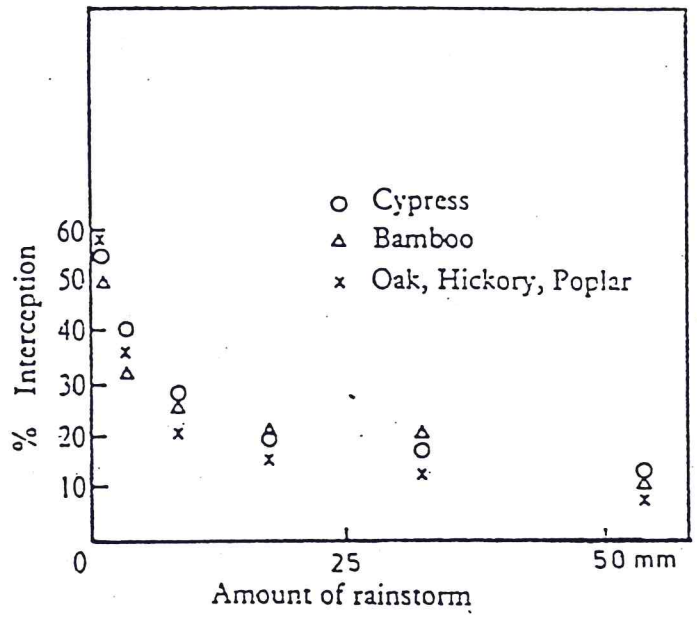


Fig. 3.7. Interception of Rainfall by Tropical and Temperate Forests

and a temperate zone hardwood forest in the Appalachian Mountains. The data are well fitted by hyperbolas. The same relationship to size of rainstorm has also been shown to apply to dense stands of Douglas fir in Oregon. Thus the hydrological importance of interception by a continuous forest canopy depends directly on the pattern of rainstorms and is similar for many species of trees.

There are obviously great differences in the total surface area of the foliage of different species of trees, shrubs and grasses, with the greatest contrast, on an annual basis, occurring between deciduous and evergreen species. However data shows that:

. Interception loss is mainly a function of size of storm.

· Most hardwood trees give similar interception effects during the growing season

· Interception loss is greater from needle-leaved trees than from broad-leaved trees

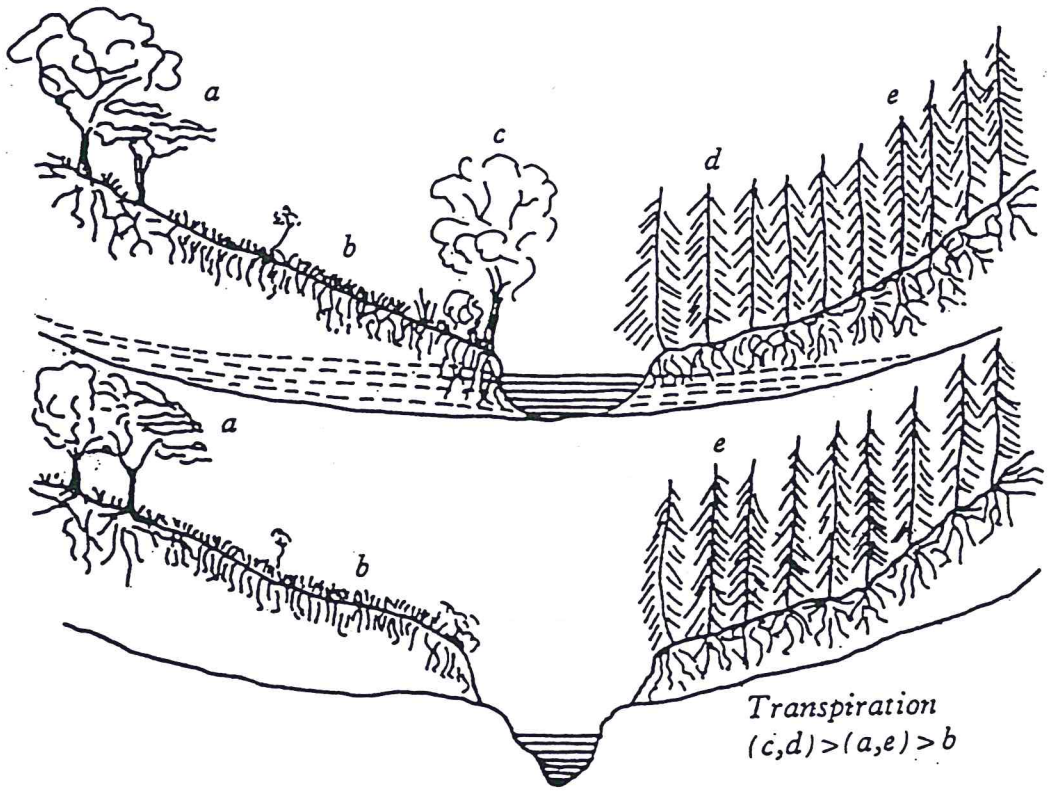
· Hydrologically, interception represents an additional but transient form of water storage in the vegetation of a watershed

· The main interest now centres on the relative contributions of transpiration and of direct evaporation to the overall water loss of the wetted foliage.

In dry climates the effect of streamflow is of importance to trees by concentrating light rainfall within their root zones. On a smaller scale the effect has been shown to be important for drought resistance in tall crop plants such as maize.

3.2.7 Effects Of Streambank Vegetation

The water which percolates beyond the range of roots of hillside vegetation is safe from evaporation losses until the drainage flow approaches the river bed. Rapid drainage into a deeply incised channel may provide an efficient path, but where the stream is flanked by water tables lying 'near to the surface, often in alluvial deposits in which vegetation roots freely, an ecological association of plants well adapted to wet soils accumulates to exploit the water supply. The water use of highly adapted streambank vegetation is of major economic importance in south-western USA, where the tamarisk *Tamarix pentandra,* known as the 'salt cedar', occupies thousands of hectares of the flood plains of major rivers. With roots either in the water table or freely supplied by the "capillary fringe" films of water above it, these shrubs have full potential transpiration opportunity. Direct measurement of their effects is difficult, but the difference between the day and night streamflow rates in dry weather gives a rough estimate. Clearing of large areas of salt cedar in Arizona, with studies by the US Geological Survey. of groundwater fluctuation, has indicated substantial savings of water.



This diagram illustrates that variation in rock structure can produce very different hydrological situations.

Fig. 4.8. The Case for Clearing Streambank Vegetation

It is argued that such water is made available without further costs to reservoirs, treatment plants and transmission systems already developed and is thus likely to be less expensive than the development of new sources. Wildlife,. fish habitat and scenery are all, however, at risk when streambanks are cleared, while soil protection is lost.

In South Africa forest plantations are not permitted within 20 m of streambanks,, leaving a band of natural, vegetation, but the dense phreatic vegetation, which usually develops on the streambanks, may account for vapour losses equal to those from plantations. It has been demonstrated for South African mountain streams that clearing of streambank vegetation increased flow. Advection from dry grassland adds to the water loss.

Farmers developing irrigation schemes in East and Central Africa have urged the adoption of the South African rule for restriction of afforestation near. td streambanks. That this cannot be applied usefully in the absence of a high water table is illustrated by Fig. 3.8, which summarizes the relationship between trees. and streams. Unless the trees and bushes are felled and regrowth is regularly cut or sprayed with herbicide, saving in water is small even on high water tables.

Maintenance of such strips as fire-breaks can sometimes be a solution, but in any case the extra water involves extra costs.

Riverside strips of vegetation are also protected by law in USSR, where margins 300 m wide are managed as protection forests. Some people argue that this width should be varied to include the whole of the river banks, the flood plains and any terraces flooded annually. This would involve a protection forest varying in width from 100 m to 1 km. They are concerned more with flood control than with water economy.

3.2.8 Mauritian River Reserves

In this section, the philosophy of approach to the erosion problem shows the apparent contradictions with the ideas presented in the previous section, which was more concerned with saving water. It would seen that some research is needed to find a compromise between the two issues.

River Reserves consist of the strip of privately owned land on. both sides of a water course. Water courses are classified in three categories depending on their flow namely:

(1) River
(2) Rivulet
(3) Feeder

The River Reserves in the case of a river, a rivulet and a feeder are 50 feet, 25 feet and 10 feet (15.24, 7.62, and 3.04 metres) respectively starting from the edge line as traced out by stones and boulders. These include escarpment of any river, rivulet or feeder.

The legal protection of the River Reserves dates back as far as 1769 when the first legislation, namely Article VI of *Règlement Economique* of 1769 came in force. Since then, other laws have been passed on River Reserves to reinforce protection and emphasise the need for keeping a permanent tree cover.

Ordinance No. 33 of 1965 proclaimed that. there was no need to maintain a permanent tree cover in all River Reserves below 152.4 m (500 feet) altitude. Immediately afterwards, people exploited most of the River Reserves and planted it with sugar cane or other cash crops. This was further detrimental to the already existing critical condition prevailing in the river reserves. This situation persisted until Forests and Mountain and River-Reserves Act 18 of 1971 came into force. This legislation re-installed legal control over all river reserves. Since then, all Reserves indistinctly are protected by law. Subsequently, the Forest and Reserves Act 41 of 1983 was proclaimed and further strengthened legal control over the reserves.

All the catchment areas are located in the humid and super humid regions of the uplands. During rainy seasons, all the rivers are flooded thus causing soil erosion from denuded river slopes. Very often, the velocity of the water flow is so great

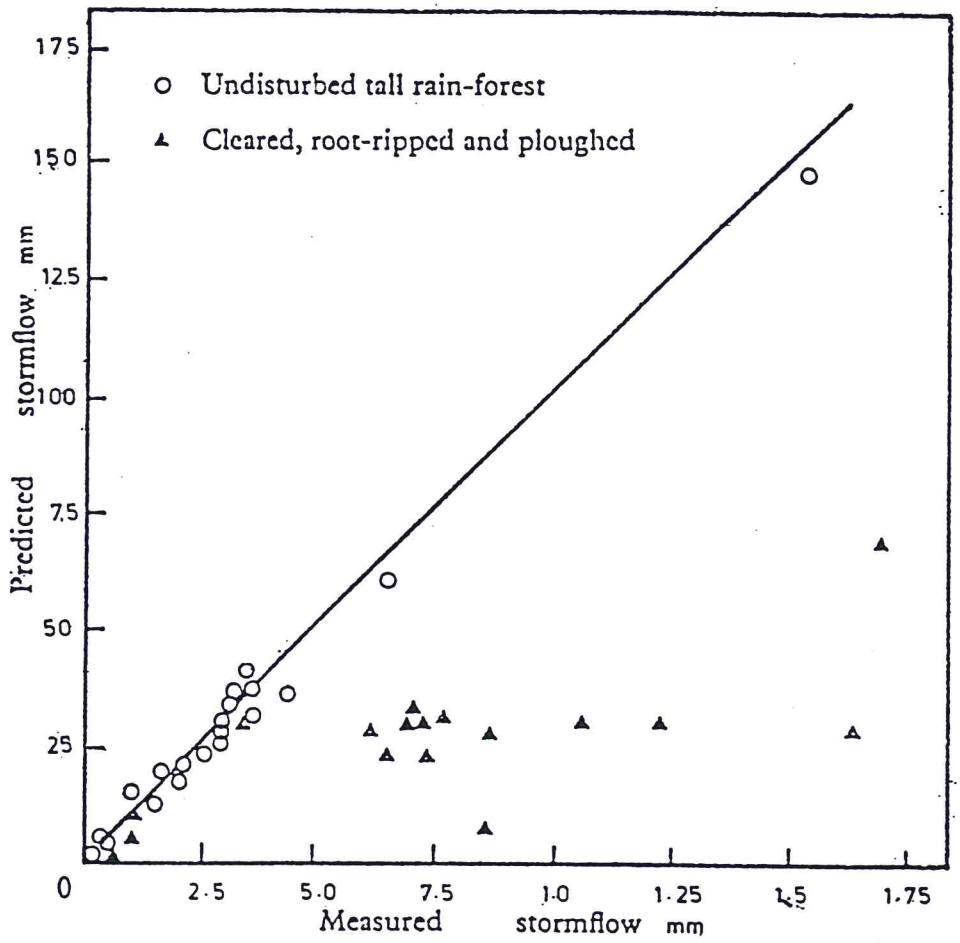


Fig. 3.10. Prediction of Stormflow from Rainfall Intensity

3.3 FACTORS CONTROLLING EROSION

The factors controlling the working of the soil erosion system are the erosivity of the eroding agent, the erodibility of the soil, the slope of the land and the nature of the plant cover. In order to understand when and how much erosion is likely to occur, these factors must be examined in detail and the relevant aspects of them identified more precisely. Much of our understanding stems from empirical studies in which a wide range of data on soil loss and presumed controlling variables is collected and the best relationships are sought using statistical techniques, particularly correlation and regression analyses.

3.3.1 Rainfall

Soil loss is closely related to rainfall partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff. This applies particularly to erosion by overland flow for which intensity is generally considered to be the most important rainfall characteristic. The effect of rainfall intensity is illustrated by the data for 183 rain events which caused erosion at Zanesville, Ohio, between 1934 and 1942 which show that average soil loss per rain event increases with the intensity of the storm (***Table 3.2***).

The role of intensity is not always so obvious, however, as indicated by studies of erosion in Bedfordshire, England. Taking data for the ten most erosive storms

between May 1973 and October 1975 (***Table 3.3***), it can be seen that whilst intense storms, such as the one on 6 July 1973 of 34.9 mm, in which 17.7 mm fell at intensifies greater than 10 mm/h, produce erosion so do storms of long duration and low intensity, like the one of 19 June 1973 when 39.6 mm of rain fell in over 23 h. A similar picture emerges from measurements of erosion made in 1975 in vineyards near Trier, West Germany.

Table 3.2: Relationship between rainfall intensity and soil loss

Maximum 5-min Intensity (mm/h)	**Number of Falls of rain**	**Average Erosion per Rainfall** ($kg\ m^{-2}$)
0-25.4	40	0.37
25.5-50.8	61	0.60
50.9-76.2	40	1.18
76.3-101.6	19	1.14
101.7-127.0	13	3.42
127.1-152.4	4	3.63
152.5-177.8	5	3.87
177.9-254.0	1	4.79

Table 3.3: Rainfall and soil loss in Bedfordshire

Date	**Rainfall** (mm)	**Intense rain** (≥10 mm/h) (mm)	**Rainfall Duration** (h)	**Soil Loss** ($g\ cm^{-1}$)
6.7.73	34.9	17.7	8.00	70.70
5.5.73	6.7	-	4.16	61.72
21.5.73	7.1	3.9	2.00	55.98
27.8.73	16.8	4.6	6.50	50.90
6.5.73	2.2	1.0	0.33	40.00
8.8.74	17.0	8.8	13.50	36.78
16.7.74	7.6	6.4	13.00	28.66
13.7.74	16.5	9.0	10.50	24.71
19.6.73	39.6	-	23.83	20.38
27.6.73	18.6	2.3	13.83	18.99

Note. Data for bare soil and 11° slope.

3.3.2 Effect Of Plant Cover

The importance of a plant cover in reducing erosion is demonstrated by experiments at the Henderson Research Station in Zimbabwe where, in the period 1953-56, mean annual soil loss from bare ground was 4.63 kg/m^2 compared with 0.04 kg/m^2 from ground with a dense cover of *Digitaria*. The major role of

vegetation is in interception of the raindrops so that their kinetic energy is dissipated by the plants rather than imparted to the soil. This role is emphasised by the mosquito gauze experiment of Hudson and Jackson (1959) in which soil loss was compared from two identical bare soil plots. Over one plot was suspended a fine wire gauze which had the effect of breaking the force of the raindrops, absorbing their impact and allowing the water to fall to the ground from a low height as a fine spray. The mean annual soil loss over a ten-year period was 126.6 kg/m^2 for the open plot and 0.9 kg/m^2 for the plot covered by gauze.

In addition to intercepting rainfall, a plant cover dissipates the energy of running water and wind, imparts roughness to the flow and thereby reduces its velocity. Since erosion rates vary with either the cube or the fifth power of velocity, the effect on soil loss should be considerable.

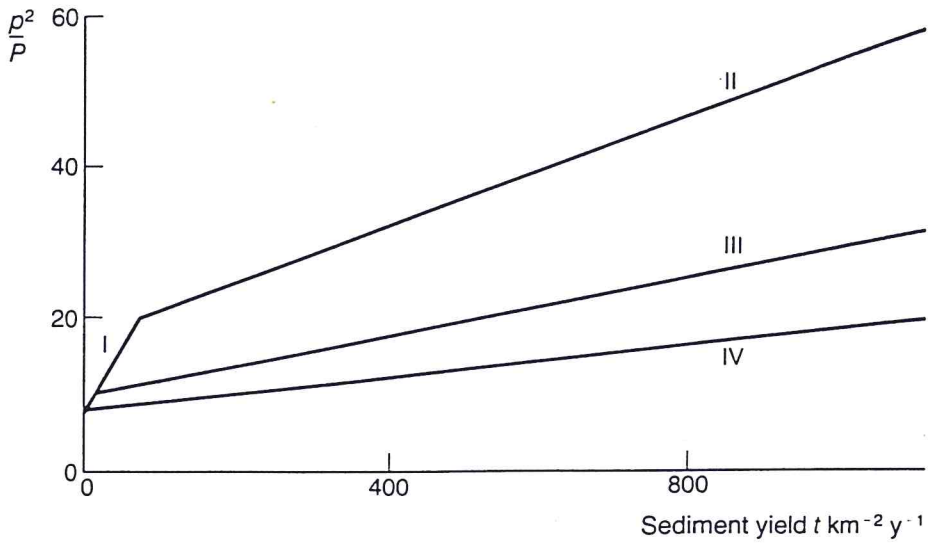
3.4 EMPIRICAL MODELS

The simplest model is a black-box type relating sediment loss to either rainfall or runoff. A typical relationship is:

$Qs = aQw^b$,

where Qs is sediment discharge and Qw is water discharge. Jovanovic and Vukcevic, using data for sixteen gauging stations in Yugoslavia, established that b = 2.25 whilst, according to Leopold, Wolman and Miller, b ranges in value from 2.0 to 3.0. The value of a is an index of erosion severity. Thus, in the Yugoslav example, a > 0.0007 denotes excessive soil loss and a < 0.0003 indicates a low erosion rate. Parsons, Apmann and Decker noted a fall in the value of b from 1.46 to 0.86 for the Buffalo River, New York, following channel stabilisation. Since the latter study is based on sediment concentration (ppm) rather than sediment discharge (kg/s), these values should be increased by 1.0 to compare with the Yugoslav work. It is not always possible to establish the values with confidence. The relationship between sediment and water discharge may vary with the volume of runoff and therefore change seasonally. During a single storm the value of b often differs on the rise of a flood wave from that on the recession. The main disadvantage of this type of model, however, is that it gives no indication of why erosion takes place.

Greater understanding of the causes of erosion is achieved by grey-box models. These frequently culminate in expressing the relationship between sediment loss and a large number of variables with a regression equation. One example is by Fournier relating mean annual sediment yield to rainfall, altitude and slope. Another by Walling which explains 96 per cent of the variation in suspended sediment yields (kg) of single storm runoff events for a small catchment near Exeter in terms of storm duration (DUR; h), peak runoff (Qw; L/s), peak surface runoff, defined as runoff less base flow (Qq; L/s), total surface runoff (QQ; mm), flow level preceding the hydrograph rise (Qap; L/s), and the day of the year (DY) evaluated as sine (radians) 2 π D/365, where D is the day of the year numbered from 1 January:



I Low relief (mean valley floor gradient < 1:100), $p^2/P \leq 20$

Sediment yield = $6.14 \frac{p^2}{P} - 49.78$

II Low relief (mean valley floor gradient < 1:100), $p^2/P > 20$

Sediment yield = $27.12 \frac{p^2}{P} - 475.40$

III High relief (mean valley floor gradient ≥ 1:100), $P > 600$ mm

Sediment yield = $52.49 \frac{p^2}{P} - 513.20$

IV High relief (mean valley floor gradient ≥ 1:100), $200 \leq P \leq 600$ mm

Sediment yield = $91.78 \frac{p^2}{P} - 737.62$

Method is inapplicable to areas where $P < 200$ mm

Fig. 3.11. Relationship between Climate and Suspended Sediment

Table 3.4: Values of Fournier Ratio (p^2/P) for Mauritius

	Maximum Monthly Rainfall p (mm)	Mean Annual Rainfall p (mm)	p2 p(mm)	Rainfall Period Used
Labourdonnais	237	1432	39	1862 -1980
Pamplemousses	248	1527	40	1862 -1980
Sans Souci	519	3659	73	1885 -1980
Fuel	338	2118	54	1878 -1980
Alma	465	3159	68	1871 -1980
Arnaud	477 (Jan)	3730	61	1887-1980
Vacoas	343 (Jan)	2188	54	1921-1980
Médine	183	927	40	1924-1980
Pierrefonds	228	1291	40	1921-1980
Beau Vallon	254	1631	40	1865 -1980
Ferney	368	2323	58	1878-1980
Britannia	388	2696	56	1886-1980
Bel Ombre	244	1564	38	1915-1990
Rodrigues	173	1228	24	1931-1980
Agalega	265	1735	40	1945-1980

Nb. The maximum rainfall month is usually March except where mentioned.

$$\log Qs = -1.1402 - 0.0524\,DUR - 0.7764 \log Qw + 1.373\,5 \log Qq + 0.9892 \log QQ - 0.4961 \log Qap + 0.2693\,DY.$$

Many of the variables included in this type of model are themselves intercorrelated and it is often difficult to identify the most important ones. Thus, although, as in this case, the equation may have a highly explanatory and, therefore, predictive value in a statistical sense, it has a low explanatory value conceptually. Walling suggests using a principal components analysis to reduce the number of variables by identifying the redundant ones. This technique was employed successfully by Douglas in a study of suspended sediment yields of rivers in northern Queensland. Ten possible controlling factors were reduced to four basic factors: wetness, drainage basin morphology, lithology and terrain roughness. He derived the following equation to explain 82 per cent of the variation in annual suspended sediment yield (SS; m^3/km^2).

$$\log SS = -8.73 + 3.81 \log QwA - 1.54 \log R/L + 4.82 \log DD,$$

where QwA is mean annual runoff (mm), R/L is the relief/length ratio of the drainage basin (ft/mi) and DD is drainage density (ft/mi).

A further problem of these empirical models is that the equations cannot be extrapolated beyond the data range with confidence, either to more extreme events or to other areas.

Fournier produced four regression equations relating sediment yield to the p^2/P index for specific conditions of relief and climate (***Fig. 3.11***).

Table 3.4 gives the value of p^2/P for a few areas in Mauritius.

It can be noticed that for Mauritius most values lie above 40. In fact a large number of physical parameters affect sediment yield in a river basin. ***Fig. 3.12*** shows the relative range of sediment yield based on a number of catchment characteristics. Thus the soil type, cover type and soil disturbance are other important factors which come into consideration when soil erosion is concerned.

Soil Erosion Indices

Slope (SL)	Rainfall Erosiuity (R)		Soil Erodibility (ST)		Cover Type (C)		Soil Disturbance (D)	
0 - 2 ....) 1	Temperature $\frac{P^2}{P}$ Arid (05...(30)	1	Clay	1	Virgin Forest	1	(1) In 100 Years	1
2 - 4 ....) 2	Sub $\frac{P^2}{P}$ Arid (30 <..<50)	2	Coarse Sand	2	Woodland	2	(1) In 50 Years	2
4 - 6 ....) 3	Semi $\frac{P^2}{P}$ Arid (50 <..<70)	3	Medium Sand	3	Pasture	3	Grazing	3
6 - 8 ....) 4	Sub $\frac{P^2}{P}$ Tropic (70 ...< 50)	4	Fine Sand	4	Agricultural	4	Annual Crops	4
7 - 8 ....) 5	$\frac{P^2}{20}$ Tropic (...< 90)	5	Silt	5	Bare Fallow	5	Multiple Annual	5

$\frac{P^2}{P}$ = Fournier Ration in (mm) where: P^2 = max. monthly rainfall

P = Annual rainfall

(1) In (100) Years Plantations

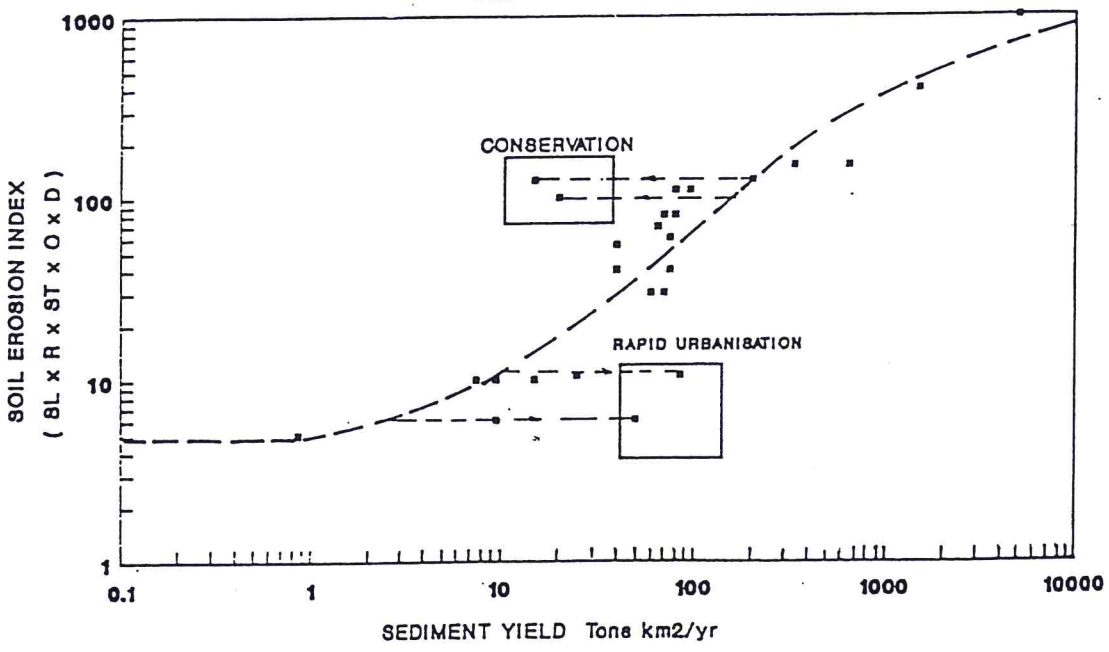


Fig. 3.12. Sediment Yield and Erosion Indices

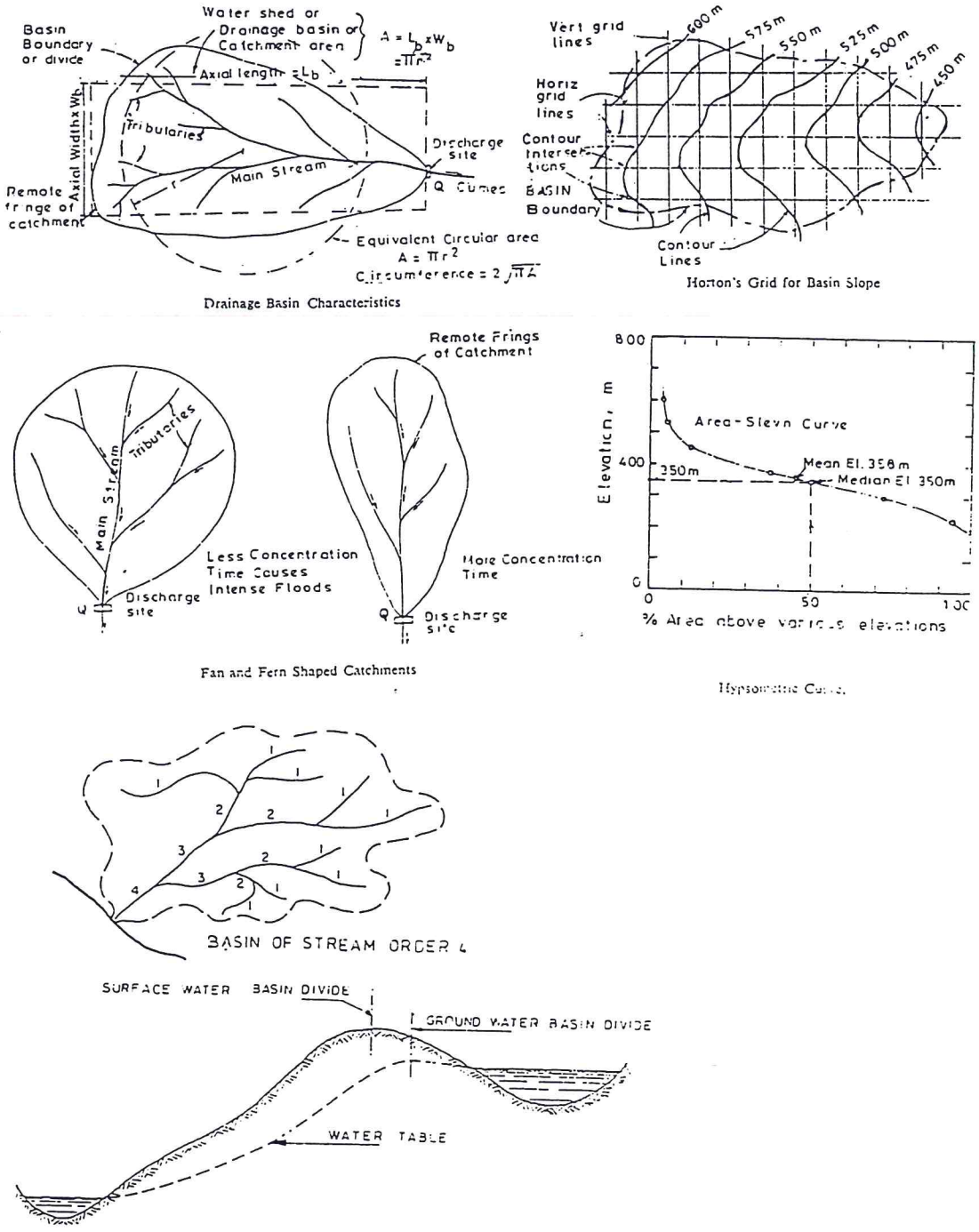


Fig. 4.1. Morphometric characteristics of drainage basins

All types of streams should be included in the computation of D_d, since this factor may be used in connection with flood flows. An accurate computation of D_d would be cumber some and in most cases, knowledge of the order of magnitude of D_d, varying from less than 0.6 km/sq. km for a poorly drained basin to about 3 km/sq. km for well drained basins, is satisfactory.

The main morphometric characteristics of the basins of Mauritius are given in ***Table 4.1***. This table indicates the surface area (km^2), stream order, basin length (km), mean basin width (km), maximum basin width (km), length of main stream (km), basin shape and basin geometry, drainage density (km^{-1}), mean slope of basin, mean basin elevation (m) and the mean slope of the river. It may be noticed that the drainage density indicates the whole range from poorly drained to well-drained basins.

Fig. 4.1 explains the meaning of the different parameters that are normally used for the comparison of drainage basins.

4.2 HYDROGRAPHS

4.2.1 Definition

The hydrograph is the plot of discharge versus time from a hydraulic or hydrologic unit or system such as a river, drainage basin, or runoff component of storm. The duration for which the distribution of flow is sought varies from a few hours for a storm hydrograph to a year for the hydrograph of annual flow of a river (see ***fig. 4.2***). The study of the hydrograph of a river before, during, and after its drainage basin is hit by a storm is particularly helpful in determining the amount of precipitation that reaches the river as direct runoff (surface or storm runoff). The same analysis of a series of storms of various durations and under different conditions is therefore a first step inn establishing a precipitation runoff relation for a given basin. It may be noticed in this particular one that there are about occurrences of heavy rainfall.

4.3 HYDROGRAPH COMPOSITION

When the drainage basin of a perennial stream is hit by a storm in the dry season, and when the river discharge decreases in time as indicated in ***Fig. 4.3***, the hydrograph of the stream will be disturbed from its smoothly levelling off curve and may assume various shapes according to the

- relative magnitude of rainfall intensity
- rate of infiltration
- volume of infiltrated water
- soil moisture deficiency
- rainfall duration
- other characteristics of the storm and the basin.

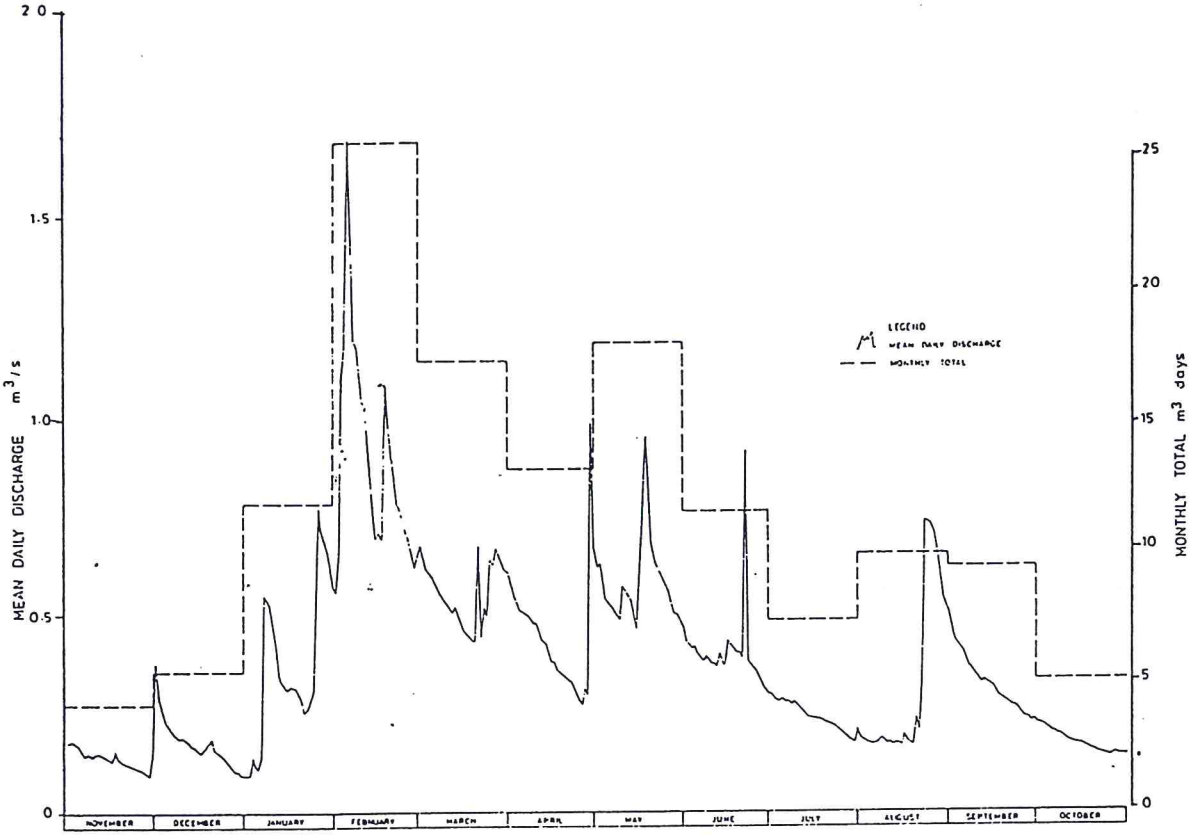


Fig. 4.2 Typical Hydrograph

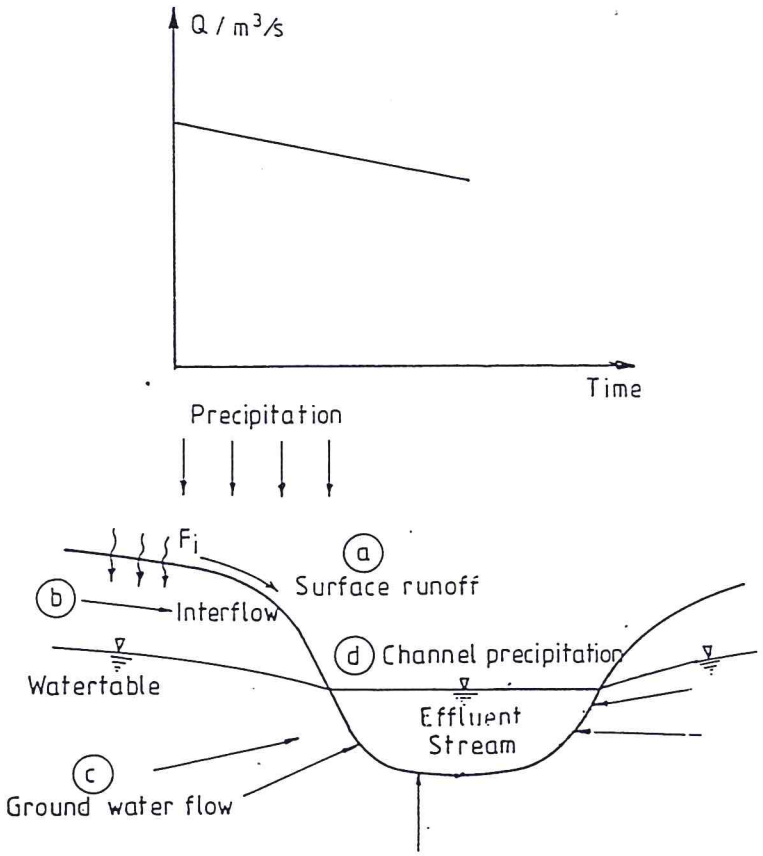


Fig. 4.3. Effluent stream hydrograph before storm and runoff contribution

The most relevant parameters and this influence on the four components of runoff (surface runoff, interflow, ground-water flow, and channel precipitation) are briefly compared here. Four different hydrograph pictures result from the following possibilities.

4.3.1 Case 1

Rainfall intensity i < rate of infiltration fi
Volume of infiltrated water Fi < soil moisture deficiency

In order to have contributions from interflow and ground-water flow due to the storm, Fi must be larger than the soil moisture deficiency which is the volume of water required to bring the moisture content of the soil up to field capacity.

There can be surface runoff only when i > fi, and therefore the only addition to stream flow is due to channel precipitation, which leads to a slight increase of discharge Q with time over the prolonged curve (***Fig. 4.4 a***).

4.3.2 Case 2

Rainfall intensity i < rate of infiltration fi
Volume of infiltrated water Fi > soil moisture deficiency

After the moisture content of the soil reaches field capacity, inter flow and groundwater flow accretion due to the storm occur. Added to channel precipitation, these flow components give the hydrograph picture of Fig. ***4.4b***.

4.3.3 Case 3

Rainfall intensity i > rate of infiltration fi
Volume of infiltrated water Fi < soil moisture deficiency

In this case there are contributions from surface runoff and channel precipitation but no additional (i.e. due to storm) ground-water flow on top of the existing base flow sustained by the groundwater basin of the river (the river is called effluent). The hydrograph is shown in ***Fig. 4.4c.***

4.3.4 Case 4

Rainfall intensity i > rate of infiltration fi

Volume of infiltrated water Fi > soil moisture deficiency
This is what usually happens during a big storm. There is additional streamflow due to channel precipitation, surface runoff, interflow, and ground-water flow, although the contribution from ground-water flow may be negative when the river becomes influent and the groundwater flow is reversed in direction (***Fig. 4.5***). The hydrograph is given on ***Fig. 4.4d***.

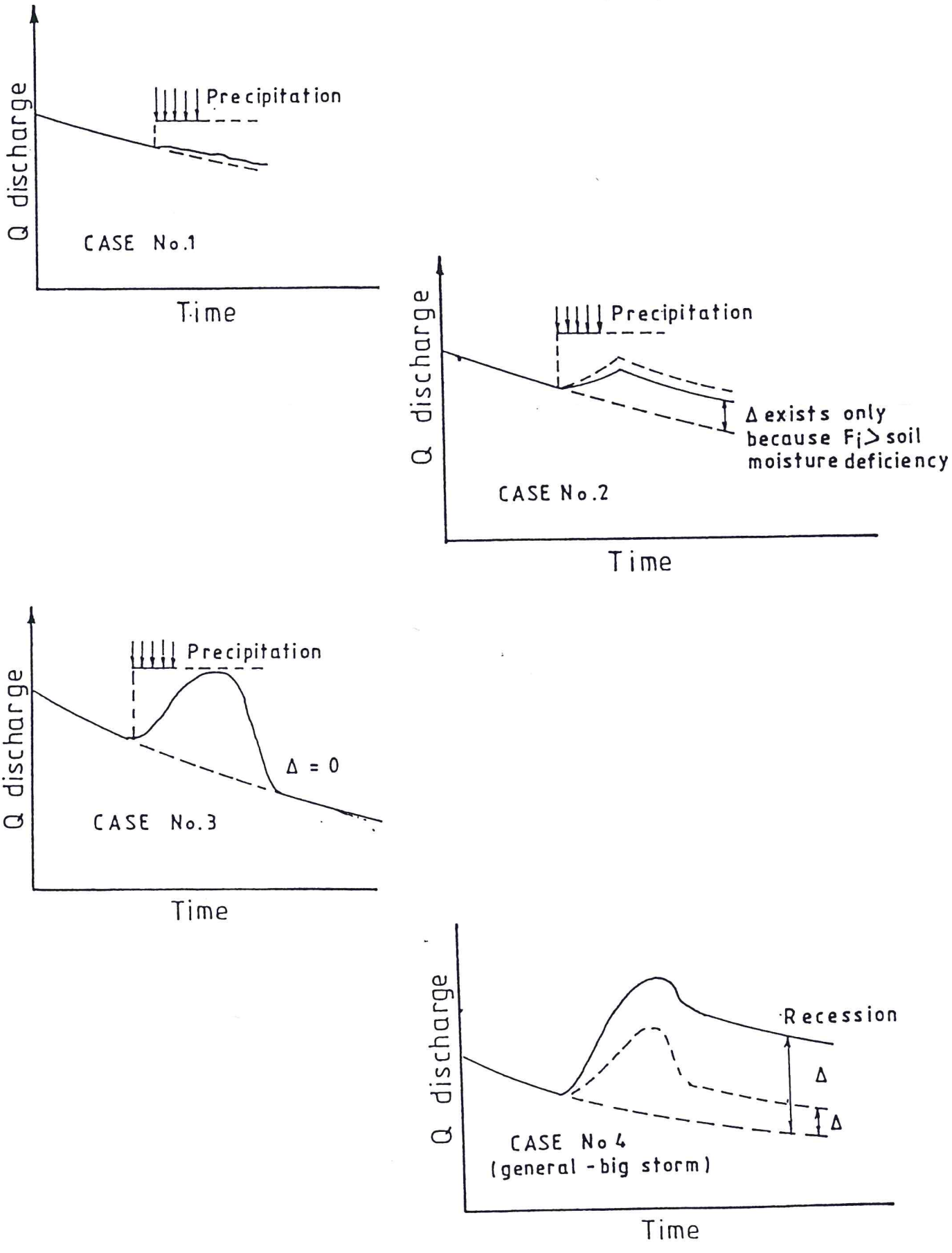


Fig. 4.4. Hydrograph composition

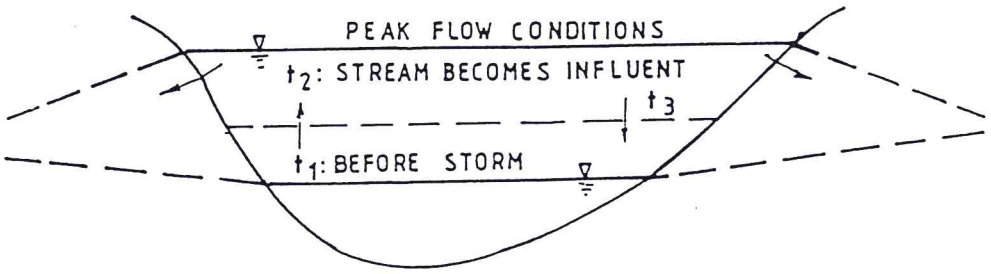


Fig. 4.5. Hydrograph for influent stream condition

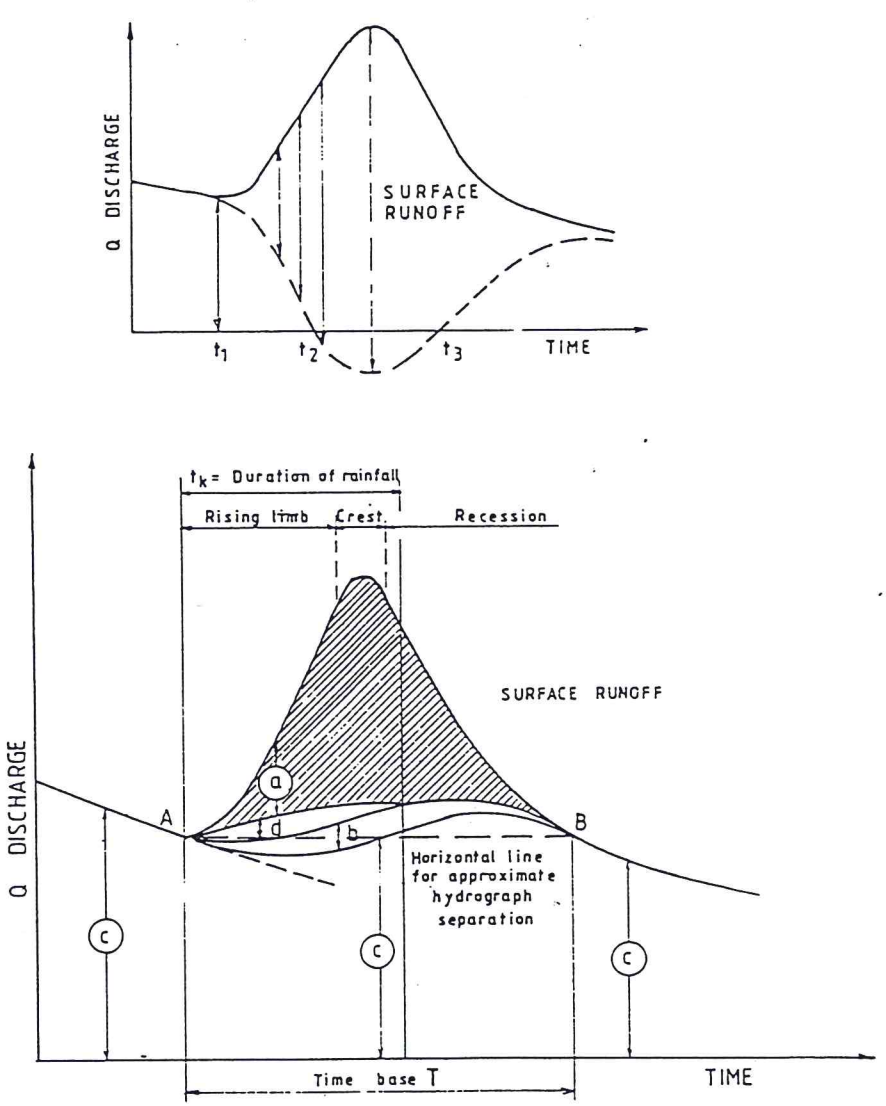


Fig. 4.6. Hydrograph parts and flow contributions

4.4 SEPARATION OF HYDROGRAPH COMPONENTS

An enlarged and idealised picture of ***Fig. 4.4(d)*** is given in ***Fig. 4.6*** and shows the contributions of the various components:

1. Surface runoff
2. Interflow
3. Ground-water flow
4. Channel precipitation.

Channel precipitation ends, of course, with the rainfall. The curve indicating the ground-water component may assume a variety of positions between those of ***Fig. 4.5*** and ***Fig. 4.6***. In these extreme cases the surface runoff contribution differs significantly in magnitude for the same total hydrograph.

In practice the problem is not to compose a hydrograph, because the hydrograph is given by measurements in a gauging station, but rather to separate, its components. For reasons of simplicity, channel precipitation and interflow are included in surface runoff as a single item, designated as direct or storm runoff. The problem is to separate this item from the ground-water flow component, also called base flow. The parts of a hydrograph (***Fig. 4.6***), are commonly designated as

- rising limb, or concentration curve
- crest segment
- recession or falling limb.

The time base of the hydrograph may be obtained by drawing a horizontal line ***Fig. 4.6*** through point A where the rising limb starts and by finding its points of intersection B with the recession curve. This horizontal line may also be considered, as a first approximation, to be the boundary between direct runoff and base flow.

A more sophisticated method of separation, however, is based on an analysis of the recession curve. The recession curve for a given basin, may be represented by an equation which does not change in form for different storms, but only varies in the value of the recession constant K_r of

$$q_1 = q_o K_r \qquad (4.1)$$

$$q_t = q_o K_r^t \qquad (4.2)$$

in which t is the time between the occurrence of discharge q_o and q_t. Variations in K_r are due to differences in areal rainfall distribution and in relative magnitude of the components of flow (direct runoff versus groundwater flow), each component contributing to the final shape of the overall recession curve. A simple method devised for filtering out the ground-water component from the total recession is illustrated in ***Fig. 4.7***, where the mean daily flows of one day, say qn, are plotted versus those of the following day, say qn + 1 (n assumes values from 0 to t -1 in Eqs. 4.1 and 4.2).

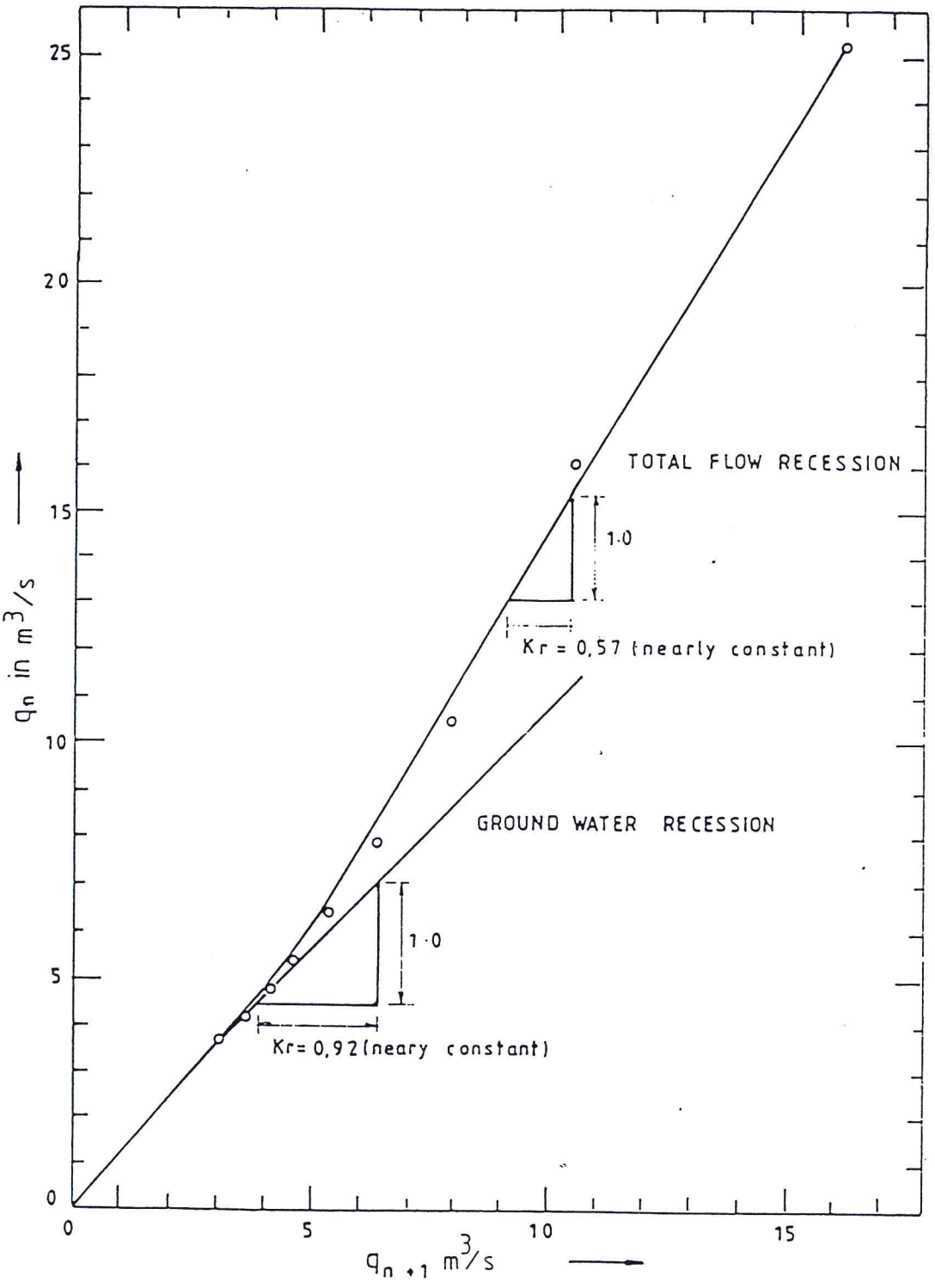


Fig. 4.7. Groundwater and total recession curves

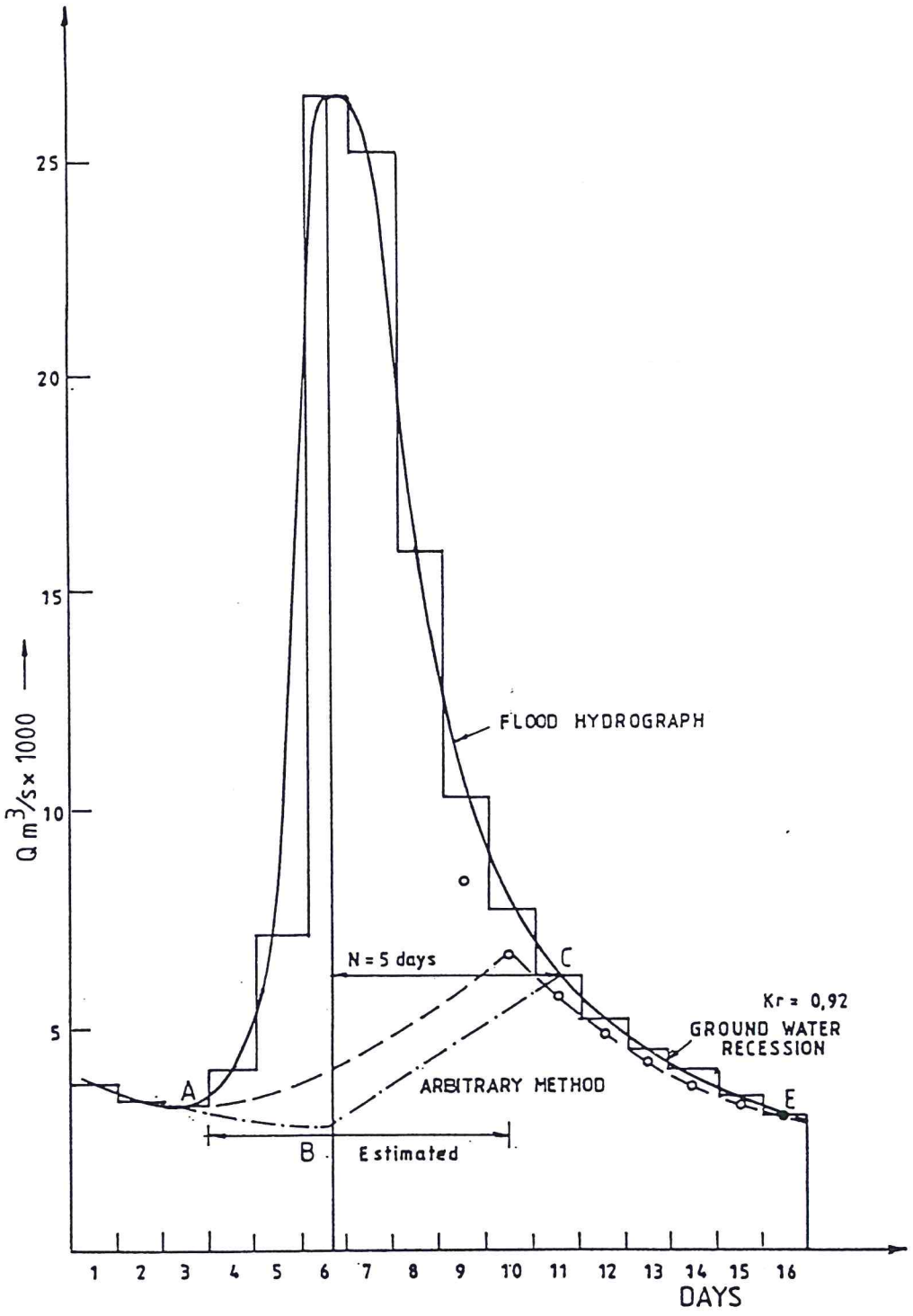


Fig. 4.8. Hydrograph separation

For high flows, the data plot as a straight line, from which a constant K_r for the total flow recession may be determined according to Eq. 4. 1. The value of Kr may be checked by plotting log qt versus t. From Eq. 4.2 it follows that

$$\log q_t = \log q_o + t \log K_r \qquad (4.3)$$

which is the equation of a straight line for constant K_r.

For low flows, when the flood has clearly subsided, the q_n and q_{n+1} data again plot as a straight line from which the constant K_r, this time for the ground-water constant K_r = 0.92 has been used in ***Fig. 4.8*** to construct the ground-water recession curve, prepared from data at the end of the flood when the recession is known to represent only groundwater flow. Successive earlier ordinates of the ground-water recession curve are computed starting from the point E of the flood hydrograph of ***Fig. 4.8***, taken as the end of direct runoff. The time of the peak of the ground-water recession curve and the shape of the rising limb are selected arbitrarily. Although this method is classified as analytical, it is only semi analytical.

The following method is often used as a variant to the simple method of separating direct runoff and base flow by a horizontal line through the starting point of the rising limb, leading to a very long time base for the direct runoff hydrograph. The dry weather recession curve Fig. 4.8 is extended from A to B at the time of peak flow. From this time, a value of N (days) is laid out to give the point C on the hydrograph, B and C are then joined by a straight line. This method is completely arbitrary, while for N a formula of the following form may be used:

$$N = 0.83 \text{ X } (A_d)0.2 \qquad (4.4)$$

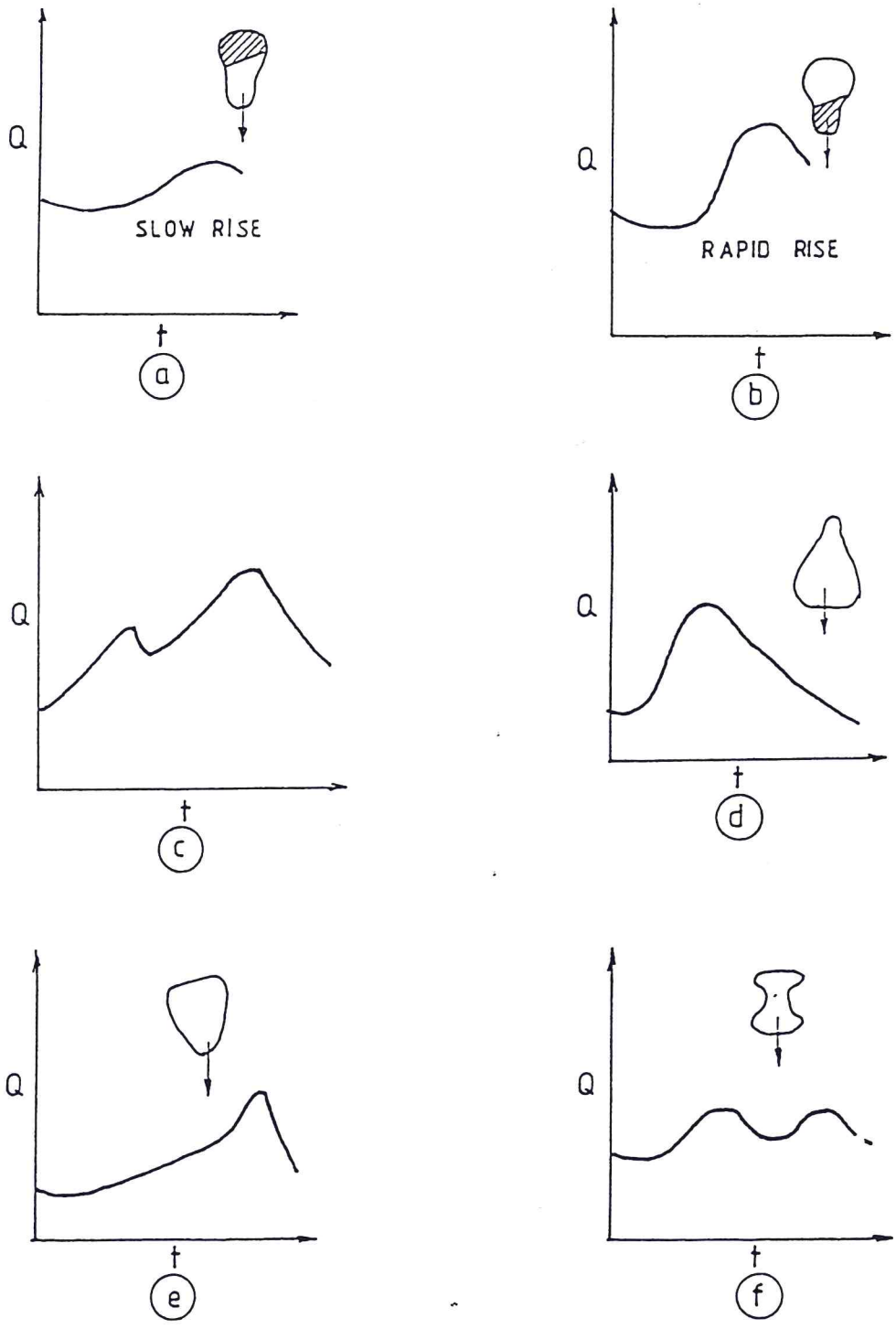
in which N is the time in days and A_d is the drainage area in square kilometres.

From these considerations it may be seen that hydrograph separation is a rather arbitrary procedure, mainly because of the multitude of shapes which are acceptable for the ground-water hydrograph as a result of the possible combinations of effluent and influent conditions of the stream.

4.5 HYDROGRAPH SHAPE

The shape of the hydrograph, in particular the rising limb, crest segment and early recession, are determined by surface runoff. This portion of the hydrograph may be identified with the direct runoff hydrograph, and its shape depends on such storm characteristics as the duration, areal distribution, intensity variation of rainfall, and also on the shape of the basin.

The time base of the hydrograph spans the period between the beginning of the rising limb and the time on the hydrograph when direct runoff is practically zero. The principle used is that for a given basin the time bases of all floods caused by rainfalls of equal duration are the same, from which followed the concept of the unit hydrograph. The time base may be defined by the equation



a and b: Nonuniform areal rainfall distribution
c: Varying rainfall intensity
d, e, and f: Influence of shape of basin on hydrograph

Fig. 4.9. Different Hydrograph Shapes

$$\text{Time base} = t_R + t_C \qquad (4.5)$$

in which

- t_R is the duration of the storm
- t_c the time of concentration for the drainage basin.

In the definition t_c is the time required for water to travel from the most remote portion of the basin to the outlet and may be estimated for a drainage channel by means of either Manning's or Chezy's formula.

The influence of nonuniform areal distribution of rainfall on the hydrograph is marked by a flat slope of the rising limb when most of the rainfall is concentrated in the region most remote from the basin outflow, and by a steep, rapid rise of the concentration curve when, most of the rainfall precipitates near the outflow ***Fig. 4.9a, b***. The shape of the basin for a uniform areal distribution is reflected in the various shapes of ***Fig. 4.9c, d and e***, while the double peak of ***Fig. 4.9f*** indicates a varying intensity.

4.6 RAINFALL-RUNOFF RELATIONS

The relation of runoff to rainfall is affected by many factors characteristic of rainfall, drainage basin, temperature, and season, and it is therefore obvious that no single relationship can be established to predict the runoff from a storm with known total precipitation and duration.

Nevertheless, for many years the rational approach to runoff was the use of dimensionless runoff coefficients to estimate runoff as certain percentage of storm rainfall. Recorded runoff was plotted versus precipitation as observed in a nearby station for a number of storms, and a curve was fitted to the data, possibly a straight line (***Fig. 4.10***), rendering the equation

$$\begin{aligned} Q &= K(p-b) && P > b \\ &= 0 && P < b \end{aligned}$$

in which

Q is the direct runoff in mm
P is the amount of storm rainfall in mm
b is a threshold of precipitation below which there is no runoff
K is the runoff coefficient.

If streamflow records are available, the ground-water flow must be extracted from the stream flow hydrograph to give the storm hydrograph.

Sometimes, relations of the form

$$Q = aP^n$$

or

$$Q = a + bP + cP^2$$

are used, where a, b, c and n are constants, with Q and P being annual runoff and precipitation.

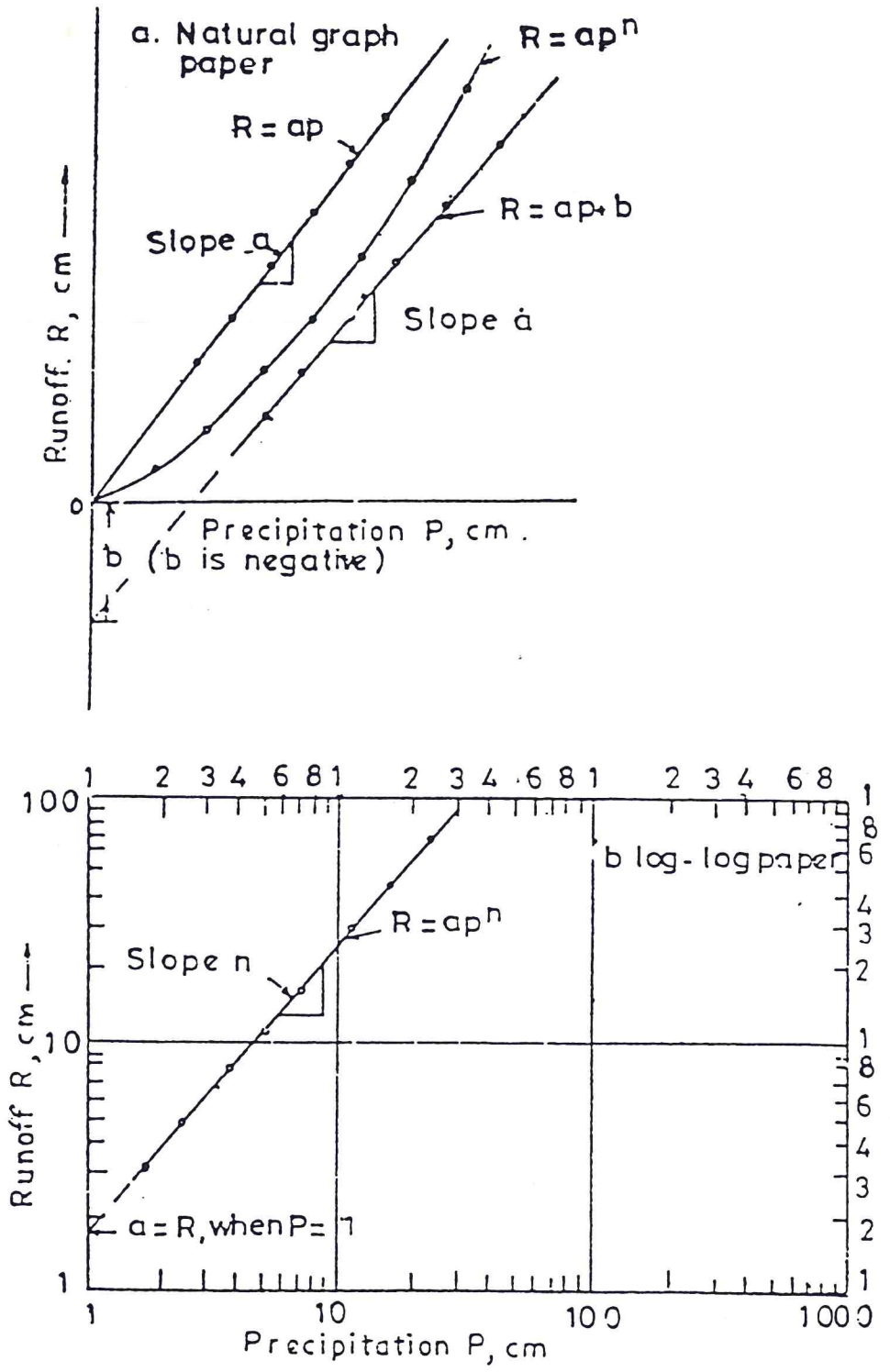


Fig. 4.10. Rainfall-runoff relationship

4.7 UNIT HYDROGRAPHS (UNIT GRAPHS)

Sherman introduced the concept of the unit hydrograph for a storm of a specific duration for any given drainage basin. It is based on the fact that the time of concentration as defined before, is constant for a basin and therefore the time base for the direct runoff hydrograph of all storms of the same duration is constant for the basin. The storm characteristics affecting the shape of the hydrograph have been discussed before. The shape of the unit hydrograph results from the average characteristics of a number of storms of the same duration. The area bounded by the unit graph and the time axis represents one millimetre of direct runoff from the basin. The usefulness of the unit hydrograph lies mainly in the forecasting of peak flows. Given a unit hydrograph of specific duration for a basin, the hydrograph for any other storm of the same duration may be constructed by multiplying the ordinates of the unit graph by the storm runoff.

Consequently if we can predict by any method the total direct runoff for a storm, we shall be able to predict the peak flow as well provided that we have the unit graph of the basin for the duration of the storm.

In the absence of any specific parameters for the flood hydrographs of Grand River South East, a dimensionless unit hydrograph. ***Fig. 4.11*** from a variety of unit hydrographs for different watersheds was used. The recession limb of this hydrograph plots as a straight line on semi-logarithmic paper. Using this unit hydrograph in conjunction with the runoff volumes determined elsewhere. S-hydrographs were contructed for the probable maximum precipitation storms with durations longer than the time of concentration of 2 hours.

The hydrographs are illustrated on ***Fig. 4.12*** while the total flood volumes are given below.

Table 4.2: Probable Maximum Flood Volumes

PMP duration (hours)	PMP depth (mm)	Loss (mm)	Run-off coefficient	Flood volume (Mm^3)
2	520	20	0.96	8.6
6	910	30	0.97	15.1
12	1300	45	0.97	21.5
24	1860	75	0.96	30.7

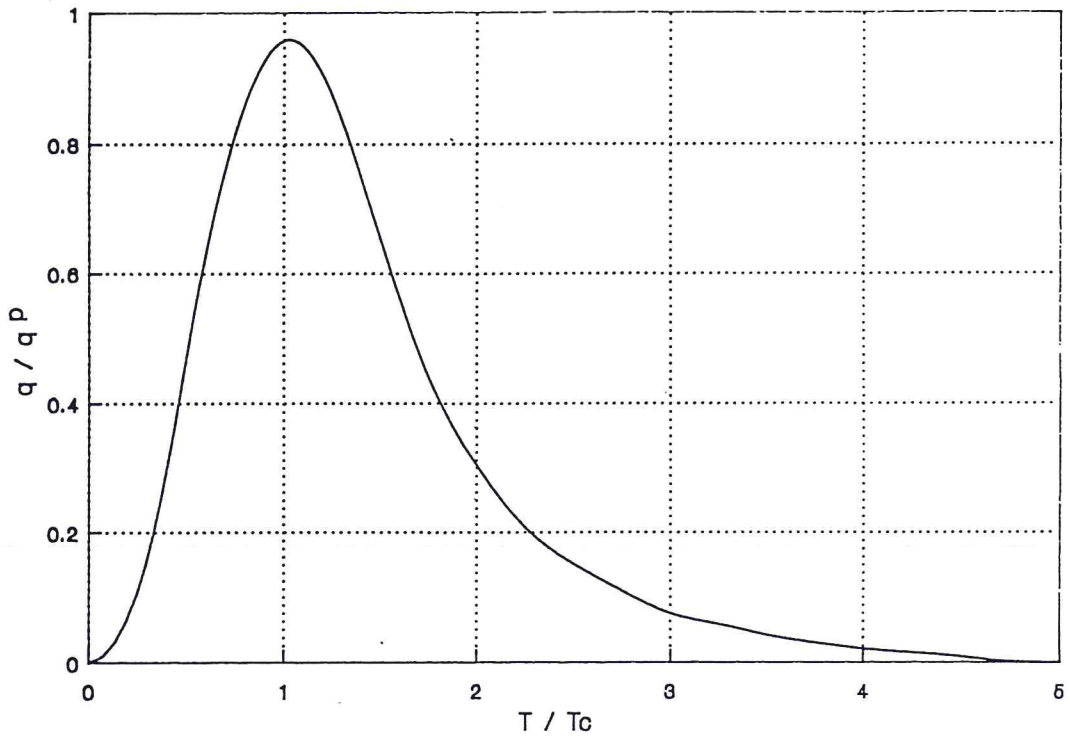


Fig. 4.11. Dimensionless hydrograph for Midlands catchment

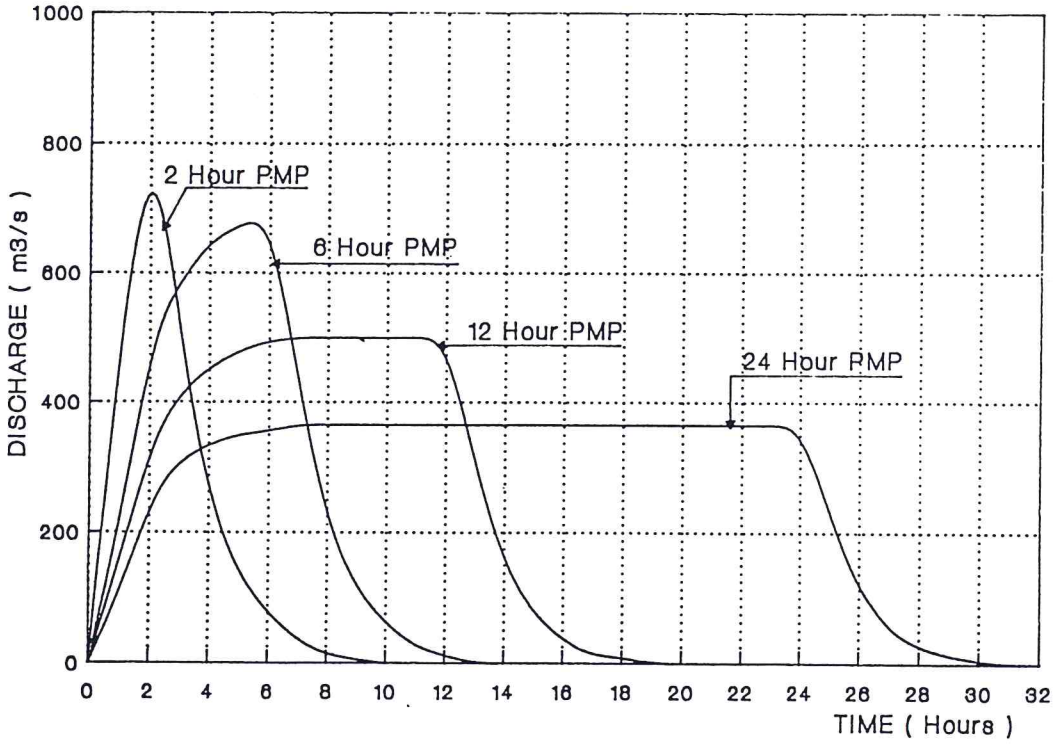


Fig. 4.12. Midlands catchment - probable maximum flood hydrographs

CHAPTER 5

RIVER DYNAMICS

5.1 INTRODUCTION

A River System is a network of connection channels through which water precipitates on the surface is collected and funneled back to the ocean.

At any given time about 1300 km^3 of water flows in the world's river. As it moves it picks up weathered debris and carries it to the ocean.

5.2 GEOLOGIC IMPORTANCE OF RUNNING WATER

Running water is part of earth's hydraulic system and is the most important agent of erosion. Streams' valleys are the most abundant and widespread land forms in continent.

5.3 THE MAJOR CHARACTERISTICS OF A RIVER SYSTEM

Although rivers and the valleys through which they flow are the most familiar of all nature's phenomena it is difficult to define the word river precisely because of the great variety of physical characteristics river exhibits. There are big river such as the *Mississippi, Amazon, Nile* and there are little rivers sometimes referred to as *streams, creeks, or brooks.* Some rivers in hot and dry regions flows only after a heavy rain and then dries up, whereas rivers in the Arctic are frozen two-third of the year.

It may be useful not to consider as a natural channel through which water flows, but as a system.

The river system can be divided into 3 subsystems.

[1] A collecting system.
[2] A transporting system.
[3] A dispersing system.

5.3.1 The Collecting System

The collecting system of a river, consist of a network of tributaries in the head water region, collects and funnels water and sediments to the main stream. It commonly has a branching stream pattern, with numerous branches that extend up slope towards the ridge.

5.3.2 The Transporting System

The transporting system is the main trunk stream, which functions as a channeling trough which water and sediment move from the collecting area towards the ocean. Although the major process is transportation this subsystem also collects additional water and forth at times when the river overflows its banks during a flood stage.

Erosion, deposition and transportation thus occur in the transporting subsystem of a river.

5.3.3 The Dispersing System

The dispersing subsystem consist of a network of distributaries at the mouth of a river, where sediment and water are dispersed into an ocean, a lake or a dry basin. The major process are the disposal of the fine grained material and river waters into the basin.

5.4 ORDER IN STREAM SYSTEMS

Every stream, every river, every gully and ravine are part of a drainage system, with each tributary intimately related to the streams that flow into it.

Every stream has tributaries and every tributary has smaller tributaries, extending down to the smallest gully. Studies of the drainage system showed that when a stream system develops freely on a homogeneous surface, definite mathematical ratios characterize the relationships between the size, the gradient of the stream and of the stream valley, some of the more important relationship and generalization are as follows:-

[1] The number of tributaries decreases down stream in mathematical progression.

[2] The length of tributaries becomes progressively greater down stream.

[3] The slope of tributaries decreases exponentially down stream.

[4] The stream channels becomes progressively deeper and wider downstream.

[5] The size of the valley is proportional to the size of the stream and increases downstream.

These relationships comprises the basic assumptions that streams erode the valley through which they flow

Stream erosion has been studied in the great detail over the last 100 years, and geologists have been able to observe and measure many aspects of stream development and erosion by running water. The origin of valleys by erosion is well established and running water is clearly the most significant agent of erosion on Earth's surface.

5.5 THE DYNAMIC OF STREAM FLOW

Anyone who has watched the fascinating flow of water in a river realizes that the process is complex. The water moves down the stream channel through the force of gravity, and the flow increases with slope or gradient of the stream bed.

The flow however is not in a straight line down slope, but in a turbulent, with numerous secondary eddies and swirls in addition to the main down stream current. It is obvious to the observer that the energy of a river increases with increasing gradient and increasing volume of water. In most streams, however, there is a considerable load of sediment carried down stream by the flowing water. The flow in natural streams is variable, fluctuating from hour to hour from place to place.

Some of the most important variables in stream dynamics are:-

[1] *Discharge.*
[2] *Velocity.*
[3] *Gradient / Slope.*
[4] *Sediment load.*
[5] *Base level.*

These variables are initially related and a change in one will bring about a compensation change in another.

5.5.1 Discharge

Discharge is the amount of water passing a given point during a specific time interval. It is usually measured in cubic metres per seconds. The discharge of most of the world's major drainage systems have been monitored by gauging stations for years and indicates that the water for a river system comes from both surface run off and seepage from ground water into the stream channels. Ground water seepage is important because it can maintain the flow of water throughout the year. Continual seepage establishes permanent streams. If the supply of ground water is depleted seasonally, streams becomes temporarily dry. Such streams are called intermittent streams.

5.5.2 Velocity

The velocity of flowing water is not uniform through out the stream channel. It depends on the shape and roughness of the channel and on the stream pattern.

The velocity is usually greatest near the centre of the channel and above the deepest part, away from the frictional drag of the walls and floor.

The velocity of the water is proportional to the gradient of the stream channel. Steep gradients produce rapid flow, which commonly occur in high mountain streams.

Where slopes are very steep, waterfalls and rapids develops and the velocity approaches that of free fall. Low gradient produce slow sluggish flow, and where a stream enters a lake or ocean, its velocity is soon reduced to zero.

The velocity of flowing water in a given channel also depends on the volume. The greater the volume, the faster the flow.

5.5.3 Stream Gradient

One of the most obvious factors controlling stream flow is certainly the gradient of the stream channel. The gradient of a stream is steepest in the headwaters and decreases down slope. The longitudinal profile (a cross section of a stream from its headwaters to its mouth) is a smooth, concave upward curve that becomes very flat at the lower end of the stream. The gradient usually is expressed in the number of metres the streams descends for each kilometre of flow.

5.5.4 Sediment Load

Flowing water in natural streams provides a fluid medium by which loose, dis-aggregated regolith is picked up and transported to the ocean. The capacity of a stream to transport sediment increases to a third or fourth power of its velocity, that is, if the velocity is doubled, the stream can move from 8 to 10 times as much sediment. Running water is the major agent of erosion, not only because it can abrade and erode its channel, but because of its enormous power to transport loose sediments produced by weathering.

Table 1 below shows a set of names of sediments and their corresponding size ranges.

	PARTICLE SIZE
Boulders	> 300 mm
Cobbles	150 to 300 mm
Gravels	2.0 to 150 mm
Sands	0.06 to 2.0 mm
Silts	0.002 to 0.06 mm
Clays	< 0.0002 mm

Within a stream system sediment is transported in 3 ways.

[1] Fine particles are moved in suspension.*(suspended load)*
[2] Coarse particles are moved by traction along the stream bed. *(Bed load)*
[3] Dissolved material is carried in solution.*(Dissolved load)*

5.5.4.1 Suspended Load

The suspended load is the most obvious, and generally the largest fraction of material moved by a river. In most major streams, silt and clay size particles remains in suspension most of the time and move down stream at the velocity of the flowing water, to be deposited in an ocean, in a lake or on a flood plain.

5.5.4.2 Bed Load

Particles of sediment too large to remain in suspension collect on the stream bottom and form bed load, or traction load. These particles moves by sliding, rolling and saltation (short leaps). The bed loads moves only if there is sufficient force to move the large particles. It thus differs fundamentally from the suspended load, which moves constantly. There is not always a sharp distinction between the largest particle of the suspended load and the smallest particle of bed
load because the velocity of the stream fluctuates constantly. Part of the bed load can suddenly move in suspension, or part of the suspended load can settle.

The movement of the bed load is one of the major tools of streams abrasion because, as the sand and the gravel moves, they abrade (wear away) the sides and bottom of the stream channel.

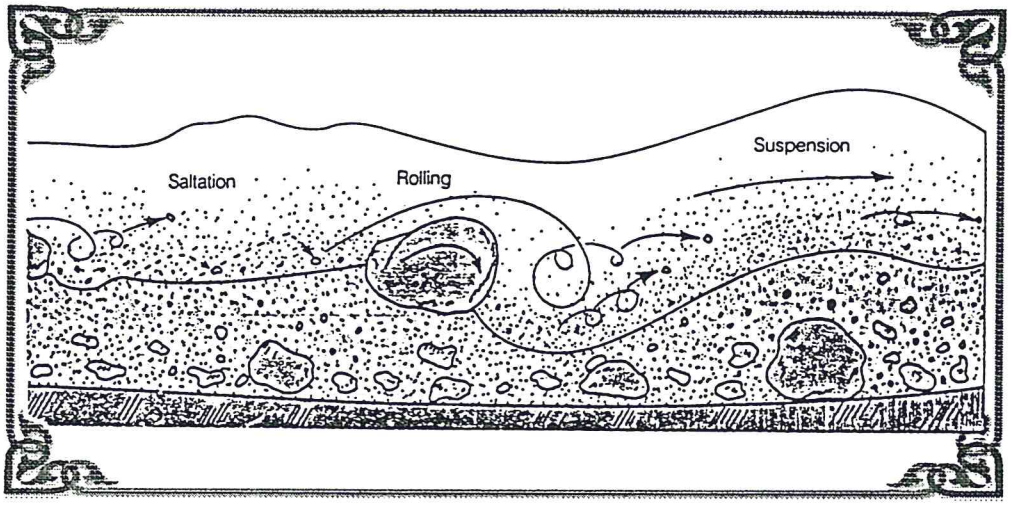


Fig 5.1

Fig 5.1 shows the movement of sediment load in a stream is accomplished in a variety of ways. Mud and silt are carried in suspension. Particles that are too large to remain in suspension are moved by sliding, rolling and saltation. Increases in discharge due to heavy rainfall can flush out all the loose sand and gravel, so the bed is eroded by abrasion.

5.5.4.3 Dissolved Load

The dissolved load is matter transported in the form of chemical ions and is essentially invisible. All streams carry some dissolved material which is derived principally from the ground water that emerges from seeps and springs along the river banks. The most abundant materials in solution are calcium and bicarbonate ions, but sodium, magnesium, chloride, ferric and sulphate ions are also common. Various amount of organic matter are present and some streams are brown with organic acids derived from the decay of plant materials.

Flow velocity, which is so important to the transportation of the suspended and traction loads, has little effect on a river's capacity to carry dissolved materials. Once mineral matter is dissolved it remains in solution, regardless of velocity, and is precipitated and deposited only if the chemistry of the water changes.

5.6 BASE LEVEL

The base level of a stream is the lowest level to which the stream can erode its channel. It is a key feature in the study of stream activity. The base level is, in effect, the evaluation of the stream's mouth, where the stream enters an ocean, a lake or another stream. A tributary cannot erode lower than the level of the stream into which it flows. Similarly, a lake controls the level of erosion for the entire course of the river that drains into it. The levels of tributary junctions and lakes are temporary base levels.

5.7 THRESHOLD VELOCITY FOR SEDIMENT TRANSPORT

Erosional velocities vary with the depth and density of the water. Small particles, such as fine silt and clay require a relatively high velocity to lift them into suspension because they tend to stick together when they are deposited. Once in suspension however, fine particles remains with a minimum velocity.

Sediment particles are deposited according to size, if the velocity of the water decreases below the particle's critical settling velocity, (*e.*g. on gentle slope) where the stream's velocity is reduced, a significant part of the sediment load is thus deposited along the channel or on the flood plains.

Most of the remaining sediment is deposited where the river enters a lake or the ocean because the velocity is reduced there.

The time of greatest erosion and transpiration of sediment is during floods. The increase in discharge results in an increase in both the maximum size of transported material and the size of the total load.

5.8 EQUILIBRIUM IN RIVER SYSTEM

The major factors that determine stream flow (discharge, velocity, channel slope, base level and load) constantly change towards a balance, or equilibrium, so eventually the gradient of the stream is adjusted to accommodate the volume of water available, the channel's characteristics, and the velocity necessary to transport the sediment load.

A change in any of these factors causes compensating adjustments to restore equilibrium within the entire drainage system. A river is in equilibrium, if its channel form and gradient are balanced, so that neither erosion nor deposition occur. Rivers are constantly adjusting to approach this ideal condition.

This adjustment is important to an understanding of the natural evolution of the landscape. It also has practical considerations. If we continually

modify rivers to suit our needs we should know how river system responds to artificial modifications.

5.9 PROCESSES OF STREAM EROSION

Erosion of the landscape by running water and the evolution of a river system is accomplished by the basic processes.

[1] Removal of regolith.

[2] Down cutting of the river channel by abrasion.

5.9.1 Removal Of Regolith

One of the most important processes of erosion is the removal and transport of rock debris (regolith) produced by weathering. The process is simple but important.

Loose rock debris is washed down slope into the drainage system and is transported as sediment load in streams and rivers. In addition, soluble material is carried in solution.

The net results is that the blanket of regolith over Earth's surface is continually removed and transported to the sea by stream action. As it is removed, it is also continually being regenerated by weathering of the fresh bed rock below.

5.9.2 Down Cutting Of River Channels

Down cutting is a fundamental process of erosion in all streams channels, whether small hillsides, gullies or great canyons of major rivers.

An effective and interesting type of abrasion of the channel floor is the drilling action of pebbles and cobbles trapped in a depression and swirled around by currents. The rotational movement of the sand, gravel and boulders acts like a drill and cuts deep holes called potholes.

5.10 PROCESS OF STREAM DEPOSITION

Rivers transport huge volumes of sediments. Most large rivers are always muddy; in some rivers the amount of sediment may sometimes exceeds the amount of water.

There are three main types of deposition in water. These are velocity reduction, solubility decrease and electrolyte increase.

Sediments are deposited when the velocity of the current falls below the minimum velocity required to keep the particles of a particular size in motion. Thus, if a river carrying silt, sand and gravel is slowed by a more gentle gradient, or by entering a lake or the sea, the coarsest particles of the load are deposited first, and progressively finer particles are deposited as the velocity of the current continues to decrease.

Deposition of the sediment load in the lower transporting and disposal segments of a river creates prominent and distinctive land forms, such as:

[1] Floods plains.
[2] Alluvial valleys.
[3] Deltas.
[4] Alluvial fans.

5.10.1 Flood Plains

On the gentle slopes of the shields and stable platform, most stream valleys are covered with large quantities of sediment that make up a flat surface over which the stream flows. This surface is called the flood plain, and during high floods it may be completely covered with water. Rivers that flows across flood plains are characterized by channels that either meander in sinuous loops or braid in interweaving multiple channels.

5.10.2 Alluvial Valleys

Many streams fills part of their valleys with sediment during one part of their history and then cut through the sediment fill during a subsequent period.

This fluctuation in stream processes commonly produces stream terraces. Deposition can be initiated by any change that reduces a stream's capacity to transport sediment.

These changes includes:-

[1] A reduction in discharge (as a result of climatic change or of a loss of water volume to stream piracy).
[2] Change in gradient (caused by a rise in base level or by regional tilting).
[3] An increase in sediment load.

5.10.3 Deltas

As a river enters a lake or the ocean, its velocity suddenly diminishes and most of its sediment load is deposited to form a delta. The growth of a delta can be complex, especially for large rivers depositing large volumes of sediment.

Two major process for the formation and growth of deltas are:-

[1] The splitting of a stream into a distributary channel system, which extends into the open water in a branching pattern.
[2] The development of local breaks, called "crevasses", in natural levees through which sediment is diverted and deposited as splays in the area between the distributaries.

5.10.4 Alluvial Fans

Alluvial fans are stream deposits that accumulate in dry basins at the base of a mountain front. Such areas usually have large quantity of loose, weathered rocks debris on the surface, so when rain falls, the streams transport huge volumes of sediments. Deposition results from sudden decrease in velocity as a stream emerges from steep slopes of the upland and flows across the adjacent basin with its gentle gradient.

The channel soon becomes clogged with sediment and the stream is forced to seek a new course. In this way the stream shifts from side to side and builds up an accurate, fan shaped deposit.

The data on the following pages which where obtained from the C.W.A. Shows the amounts of materials that are being carried out in forms of dissolved and suspended solids in some of the rivers of Mauritius.

CHEMICAL ANALYSIS OF WATER

TABLE 5.1

SAMPLE NUMBER	2523/92	25/16/92	---
LOCATION	Riv. Rempart	Riv. Francoise @ Constance	Riv. du Poste at Providence Bridge
TYPE OF WATER	Raw	Raw	L.23
DATE OF SAMPLING	12/11/92	26/11/92	30/11/89
RESIDUAL CHLORINE	---	---	---
APPEARANCE	Clear	Clear	Clear
FLOW RATE cfs	2.5	2.11	2.45
TASTE AND ODOUR	None	None	None
COLOUR (HAZEN)	5	5	10
TURBIDITY (FTU UNITS)	0	0	0
pH	7.8	7.5	7.0
ELECTRICAL CONDUCTIVITY	308.0	162.9	200
TEMPERATURE / °C	24.7	24	---

RESULTS IN MILLIGRAM PER LITRE / PART PER MILLION

FREE CARBON DIOXIDE AS CO_2	2.6	0.9	3.5
ACIDITY (AS $CaCO_3$)	6	2	8.0
ALKALINITY (TOTAL AS $CaCO_3$)	98	50	68
ALKALINITY ($CaCO_3$) PHENOLPHTHALEIN	---	---	---
TOTAL HARDNESS (AS $CaCO_3$)	113	51	76
CALCIUM HARDNESS (AS $CaCO_3$)	38	27	32
MAGNESIUM HARDNESS (AS $CaCO_3$)	75	24	44
CARBONATE HARDNESS (AS $CaCO_3$)	98	50	68
NON-CARBONATE HARDNESS (AS $CACO_3$)	15	1	8

CHLORIDE (Cl^-)	35.5	18.4	19.9
NITRATE (NO_3^-)	3.8	4.9	0
NITRITE (NO_2^-)	0	0	0
PHOSPHATE	0	---	0
SULPHATE (SO_4^{2-})	24.4	0.5	0.2
ALUMINIUM	---	---	---
AMMONIUM	---	---	---
AMMONIA	0.1	0.1	0.2
CALCIUM	15.2	10.8	12.8
CHROMIUM	---	---	---
COPPER	---	---	---
IRON	---	---	---
MAGNESIUM	18	5.8	10.6
POTASSIUM	---	---	2.2
SILICA	40	16	32
SODIUM	0	---	12
ZINC	0.1	0	---
TOTAL SOLIDS DRIED @ 105 °C	230	110	---
TOTAL SUSPENDED SOLIDS @ 105°C	90	40	---
TOTAL DISSOLVED SOLIDS	140	70	---

CHAPTER 6

EXPERIMENTAL WORK IN CHANNEL

6.1 THE SEDIMENT TRANSPORT CHANNEL

Figure 6.1 shows the Sediment Transport Channel which was used for experiments carried out.

The Sediment Transport Channel consists of :-

[1] An inlet tank.
[2] A long tilting flume bed with sediment transport channel.
[3] An overshot weir at the discharge end.
[4] A manual jacking system for increasing and decreasing the gradient of the flume.
[5] A recirculation pump. The pump consist of three settings. The approximate flow rate value for each settings, that is, setting 1, setting 2, and setting 3 are as follows.

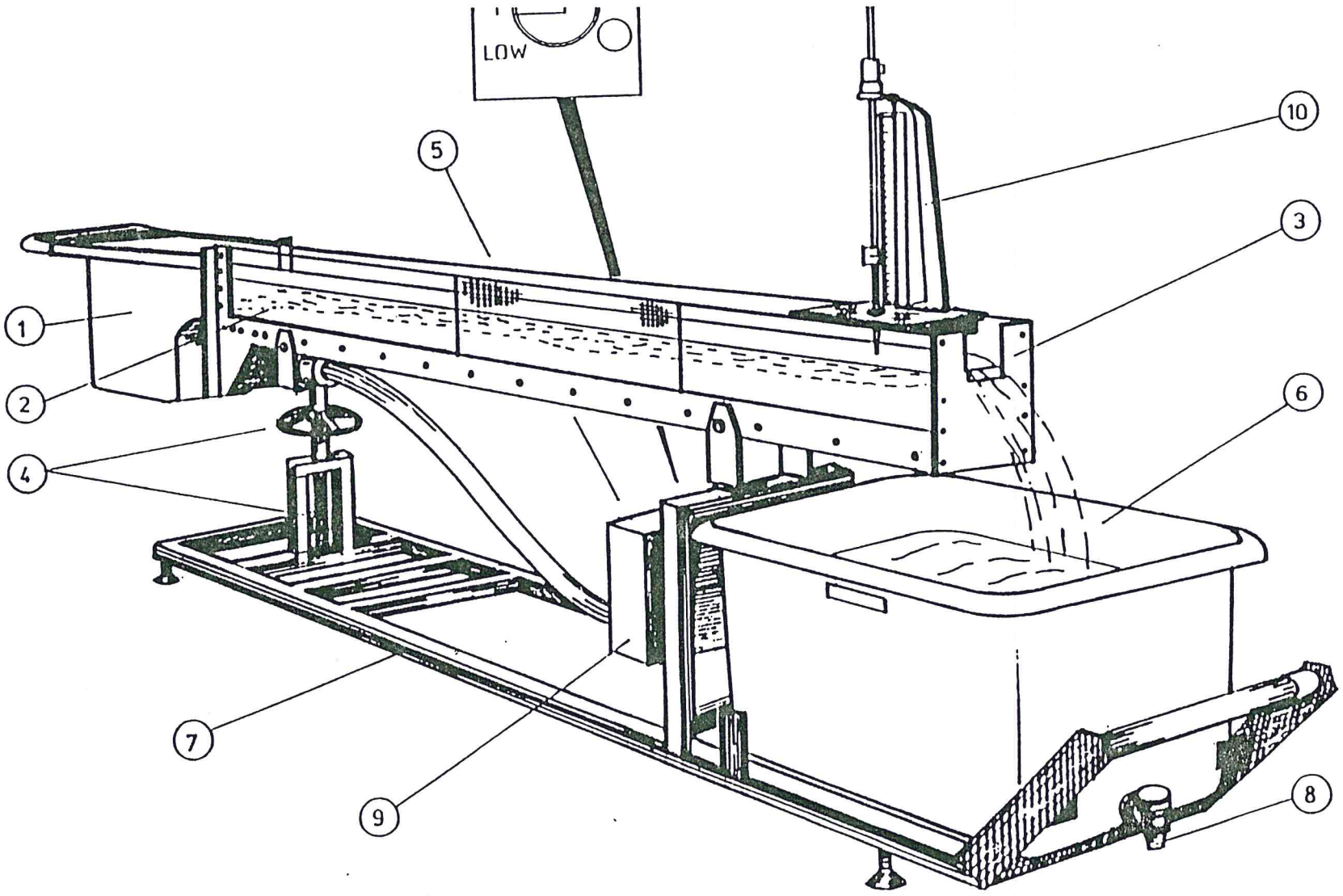
TABLE 6.1

SETTINGS	FLOW RATE	
	Litres / s	$m^3 / s \times 10^{-4}$
1	0.25	2.5
2	0.41	4.1
3	0.62	6.2

[6] A collecting and settling tank.

All are supported on a fabricated frame [7] with adjustable feet to enable leveling of the working section.

The inlet tank is supported from the tilting flume bed. Water fills the tank from the bottom and flows into the flume bed channel. Glass marbles are placed inside the inlet tank to provide stilling of the water.



SEDIMENT TRANSPORT CHANNEL

The sediment is placed into the channel. Water from the inlet tank flows along the channel over the sediment and out over the rectangular notch weir into the collecting tank.

The water then passes through the three speed recirculation pump and is returned to the inlet tank. The purpose of the collecting / settling tank is to catch the water for recirculation as well as any sediment which is carried by water, the sediment is then allowed to settle to the bottom of the tank.

A drain tap is provided on the side of the collecting tank for easy removal of water and cleaning of the tank.

An earth leakage circuit breaker is fitted to the frame near the discharge end of the flume, which acts as the on/off switch.

A point gauge is attached to the apparatus for measuring the height of water. It is provided with a vernier which is readable to 0.1 mm.

6.2 *DESCRIPTION OF THE MATERIAL USED AS SEDIMENTS FOR THE EXPERIMENTS*

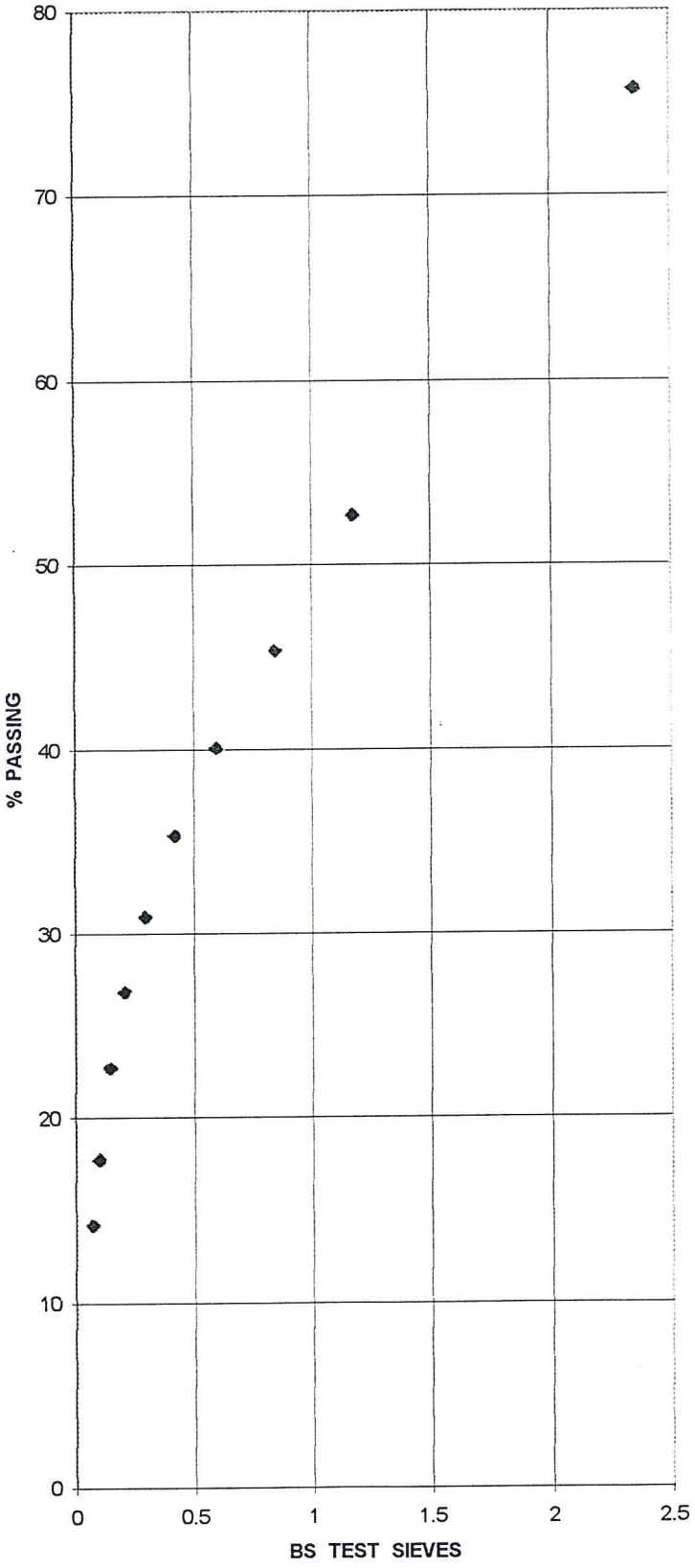
Crushed sugar size basalt rock of grading 0-5 mm and 0-6 mm were used for the experiments. A particle size distribution of the sand by sieve analysis was performed on both of the grading. The test was based on BS 812 :part 1 : 1975 and BS test sieves of 2.36 mm, 1.18 mm, 0.85 mm, 0.600 mm, 0.425 mm, 0.300 mm, 0.212 mm, 0.150 mm, 0.106 mm, 0.075 mm were used.

Table 6.2 and the graph below shows the values obtained for one of the grading.

Rock sand of 0-5 mm.

BS SIEVE SIZE (mm)	*WT OF SIEVE (g)*	*WT OF SEIVE + SAMPLE (g*	*WT OF SAMPLE (g)*	*% RETAINED*	*% PASSING*	*LOG PARTICLE SIZE*
2.36	470.80	613.70	142.90	24.27	75.73	-2.627
1.18	433.16	569.10	135.94	23.08	52.65	-2.928
0.85	417.14	460.60	43.46	7.38	45.27	-3.071
0.600	401.80	432.72	30.92	5.25	40.03	-3.222
0.425	389.64	417.90	28.26	4.80	35.23	-3.372
0.300	315.83	341.39	25.56	4.34	30.88	-3.523
0.212	299.35	323.59	24.24	4.12	26.77	-3.674
0.150	297.30	321.42	24.12	4.10	22.67	-3.824
0.106	310.35	339.24	28.89	4.91	17.76	-3.975
0.075	298.40	319.80	21.40	3.63	14.13	-4.125
RECEIVER	296.00	379.21	83.21	14.13	0.00	
			588.90	100.00		

THE CHART SHOWS THE PARTICLE SIZE DISTRIBUTION OF O-5 mm ROCKSAND



The specific gravity of the material was determined. The test was performed as per BS 1377 : 1775.

The value of Gs was found to be 2.93. The density of the material was performed as per BS 1377 :1975 and found to be 1526.63 kg/m^3

Porosity of the material was also determined. The results are as follows:

TABLE 6.3

PARTICLE SIZE (mm)	0.212	0.300	0.425	0.600	0.850	1.18	1.70
VOID (e)	0.4665	0.4917	0.5034	0.5049	0.5117	0.5062	0.4921
POROSITY (e/ 1+e)	0.3181	0.3296	0.3348	0.3355	0.3385	0.3361	0.3298

6.3 THE EXPERIMENTAL PROCEDURE

[1] Rock sand of a uniform size was properly washed to remove all the fine particles present.

[2] The rock sand was placed in the flume to a uniform thickness of 30 mm. It was then leveled with the top of the overspilled weir by using a "T" shaped leveling tool.

[3] The surface of the rock sand was tamped down so that it is uniformly packed, lightly compacted and remains as flat as possible.

[4] The catch tank was then filled with clean water up to the "full" mark.

[5] The flume slope was set to zero and the pump set to speed 1, which is the lowest speed.

[6] The pump was turned on and the bed was then observed to see if there was any movement of the sediment.

[7] To bring the sediment to the threshold of motion, the bed shear stress was increased slowly by increasing the slope of the flume in very small increments. This was done until bed motion was identified. This was continued under uniform conditions, with odd grains occasionally moving a short distance before settling again, but without any general or continuous motion.

At this time the flume slope, the average water depth, the discharge and the grain size was noted.

[8] The slope was then increased sufficiently so that the bed load motion becomes pronounced, but there is no suspended load. A dune bed was then formed quite quickly.

Quantitative measurements begin once a dune bed has become establised along the whole length of the flume. At this stage the flume slope, the average water depth, the discharge and the grain size were recorded.

[9] The bed load transported was measured by dune tracking.

This was done by placing a translucent graph paper against the flume side in the working section and the outline of a typical dune bed was traced.

After a period of time sufficient for the dune to have migrated downstream appreciably, the outline of the dune was retraced on the translucent graph paper.

The bed load transport rate was then calculated from the equation :-

$$q_b = \frac{\{(1-\lambda) \times U_s \times A\rho\}}{2}$$

Where, q_b = Bed load transport rate per unit width (kg/s).

U_s = Average velocity of the bed forms (m/s).

A = Average height of the bed forms (m).

λ = Porosity of the bed material.

ρ = Density of the bed load material.

[10] The total load of material transported was measured by placing a sieve with a mesh size a little smaller than the grain size of the bed material being used, under the jet of water. The sediment exiting the flume was collected for a measured period of time.

The period of time was taken long enough so that a measurable weight of sand could be collected.

[11] The rate of sediment transport can be increased by steepening the slope. After allowing time for the bed forms to adjust, the total load measured at the out fall and the bed load determined by dune tracking as described previously (step 9-step 10).

[12] The experiment was repeated for different discharges, that is for pump speed 2 and speed 3, by using the same grain size of sediment.

[13] Once all the experiments using a specific grain size of sediment was completed, the same experiment was repeated from step 1 to step 12 using different grading of rock sand.

The grain size of rock sand used for the experiments were :

[1] 0.212 mm.
[2] 0.300 mm.
[3] 0.425 mm.
[4] 0.600 mm.
[5] 0.850 mm.
[6] 1.180 mm.
[7] 1.700 mm.

6.4 RESULTS

The following pages shows the results obtained from the experiments carried out on a sample of rock sand of a specific size.

The results obtained were tabulated. The results were then used to plot graphs of

[1] Total load transported versus velocity.

[2] Total load transported versus slope of the flume bed.

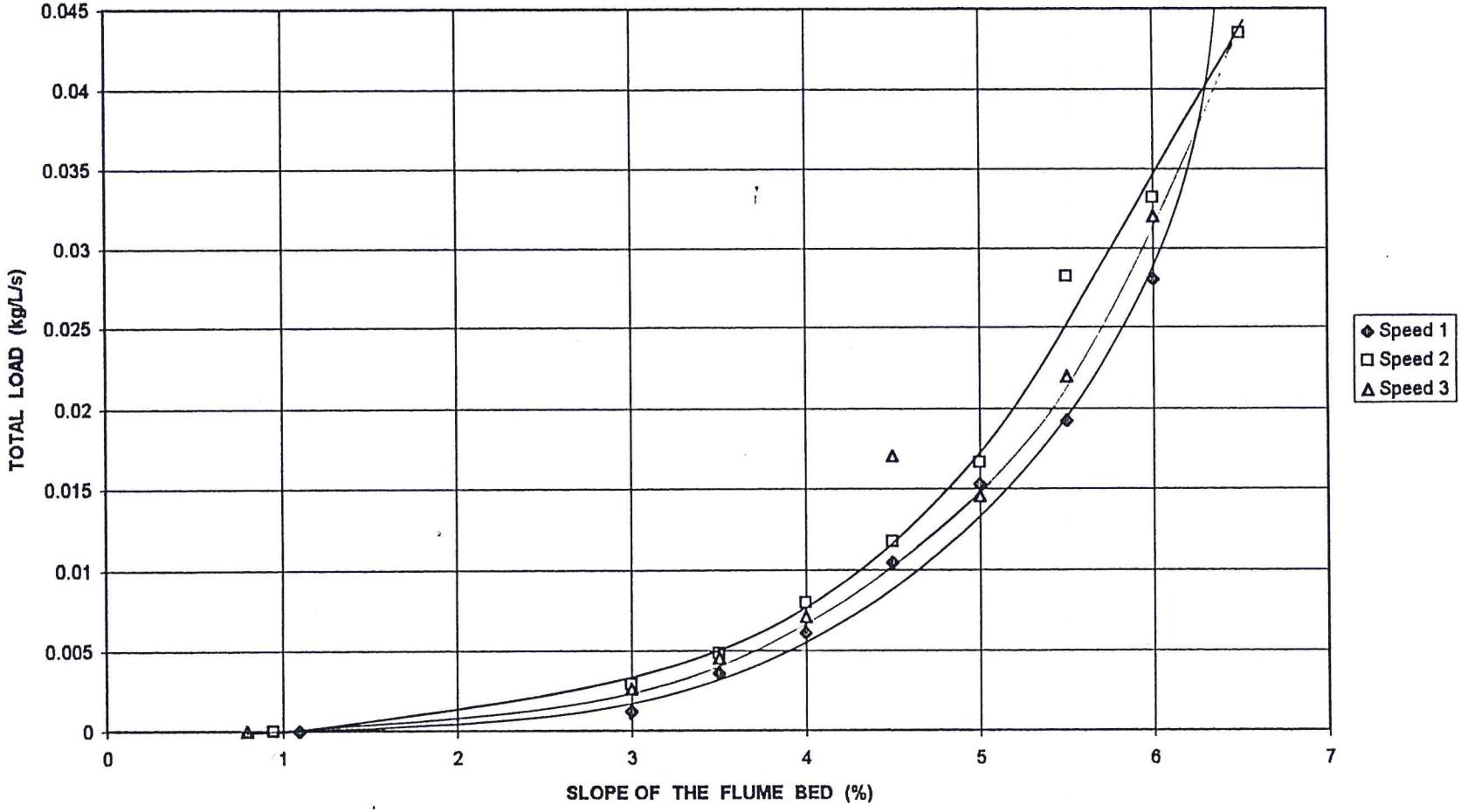
[3] Total load transported versus bed shear stress.

[4] Bed load transported versus velocity.

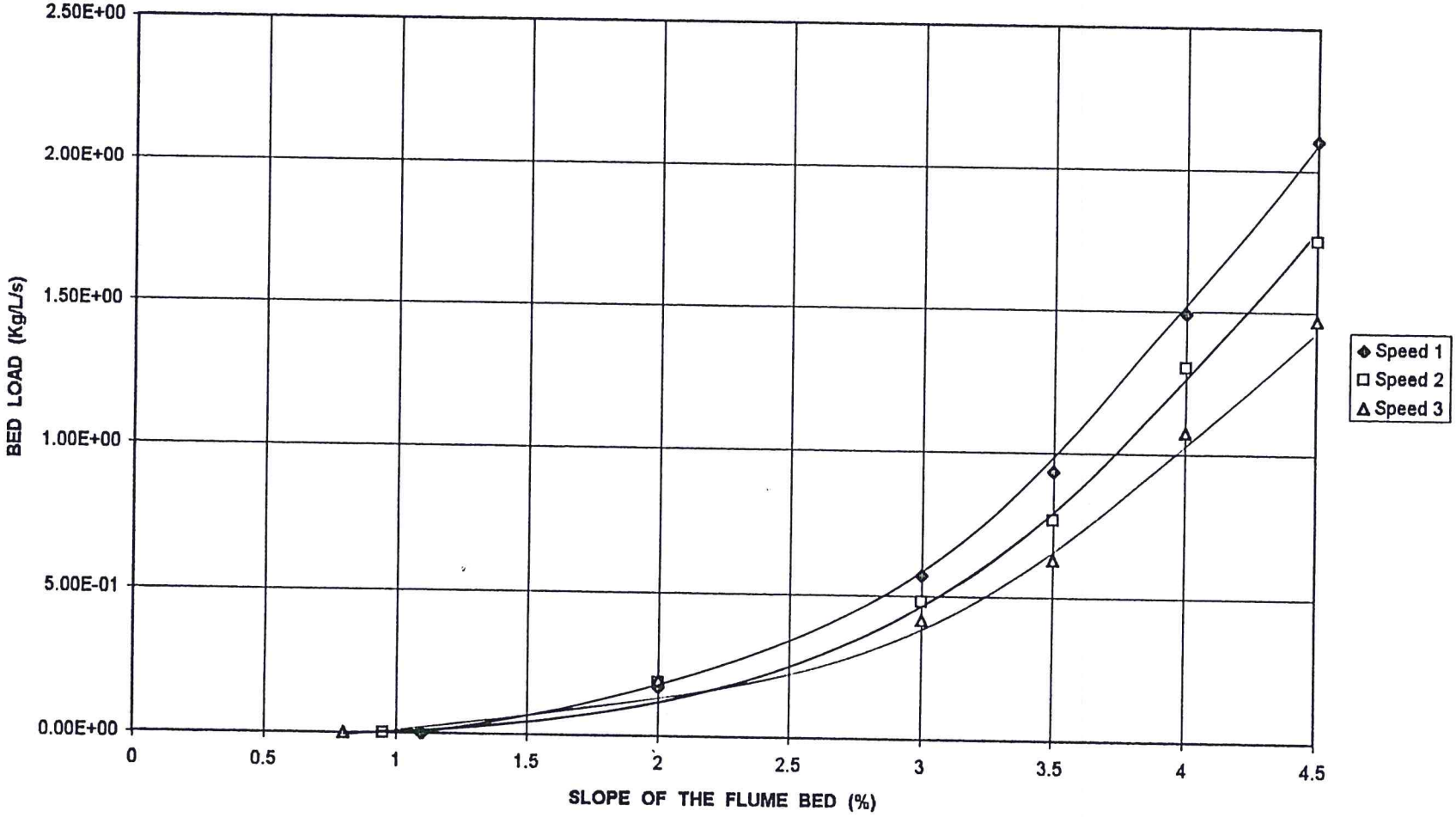
[5] Bed load transported versus slope of the flume bed.

[6] Bed load transported versus bed shear stress.

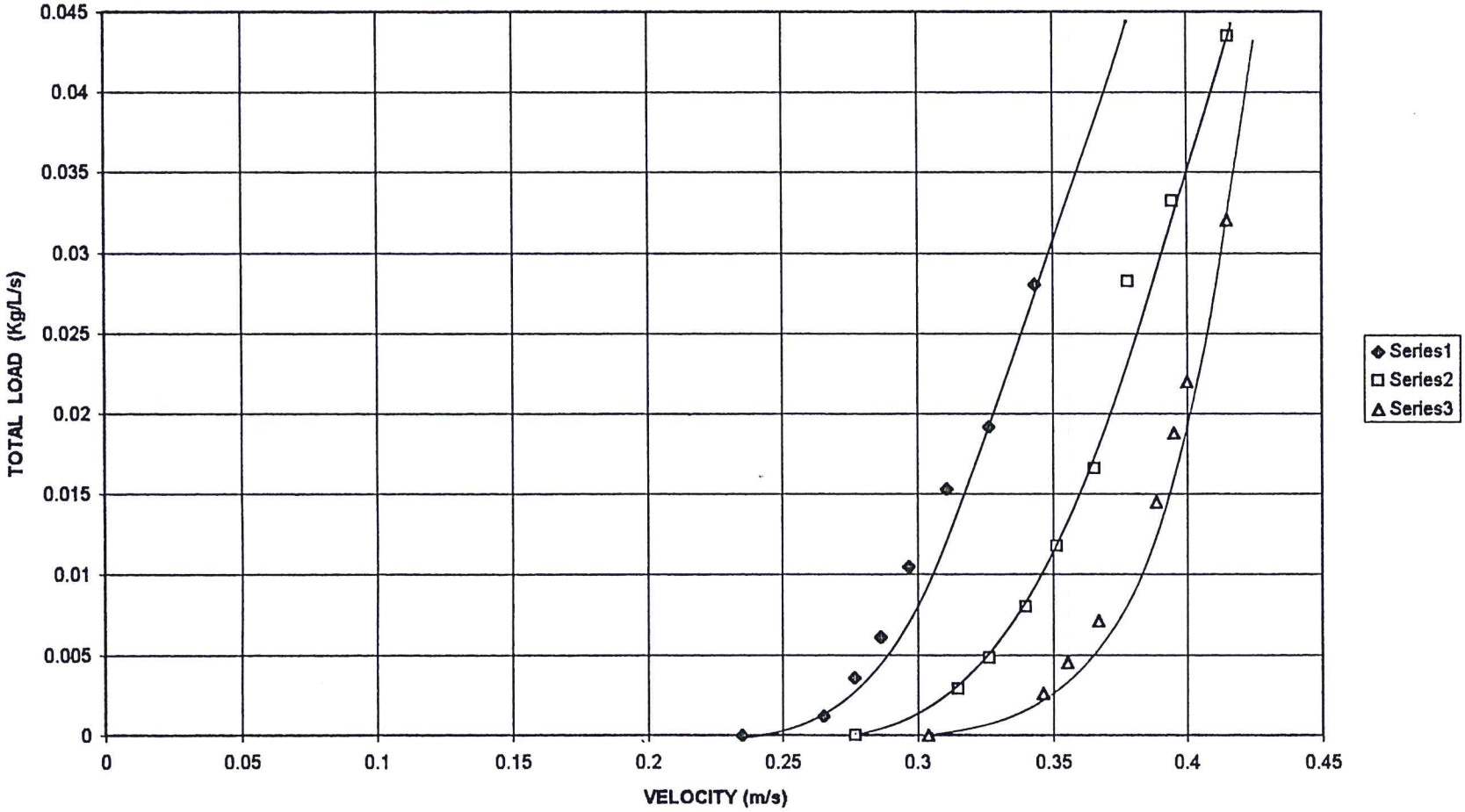
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.212 mm



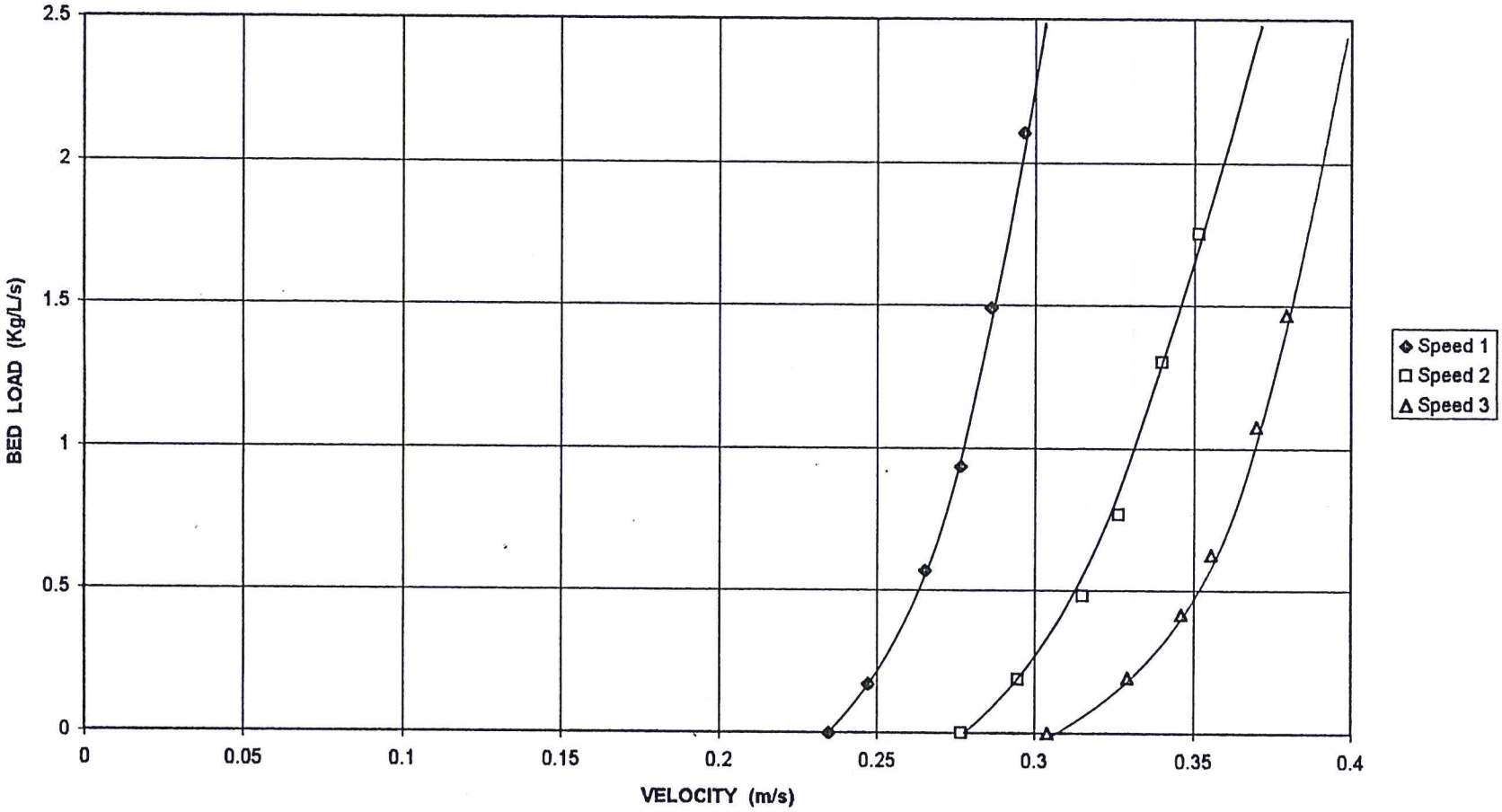
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.212 mm



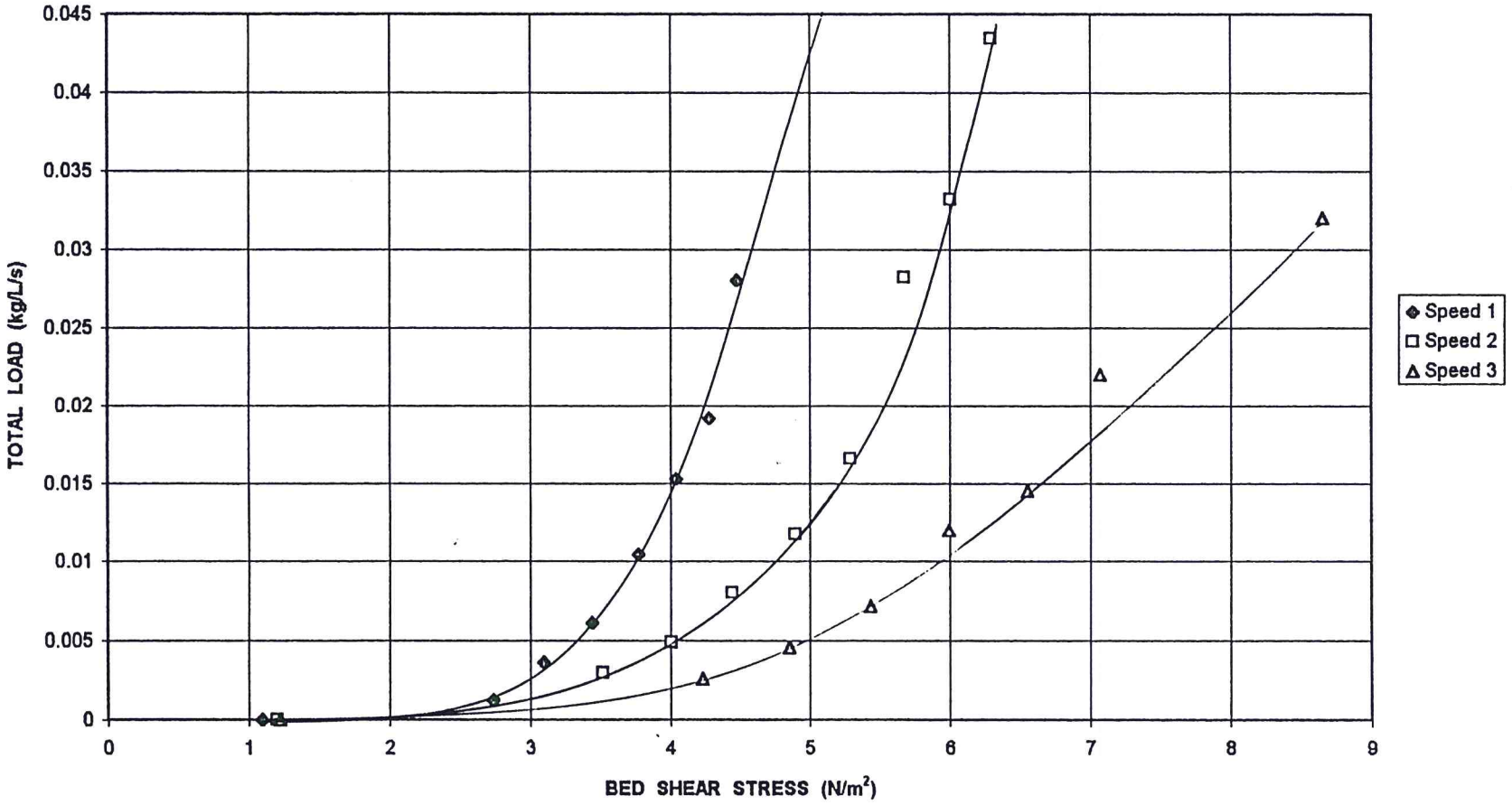
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.212 mm



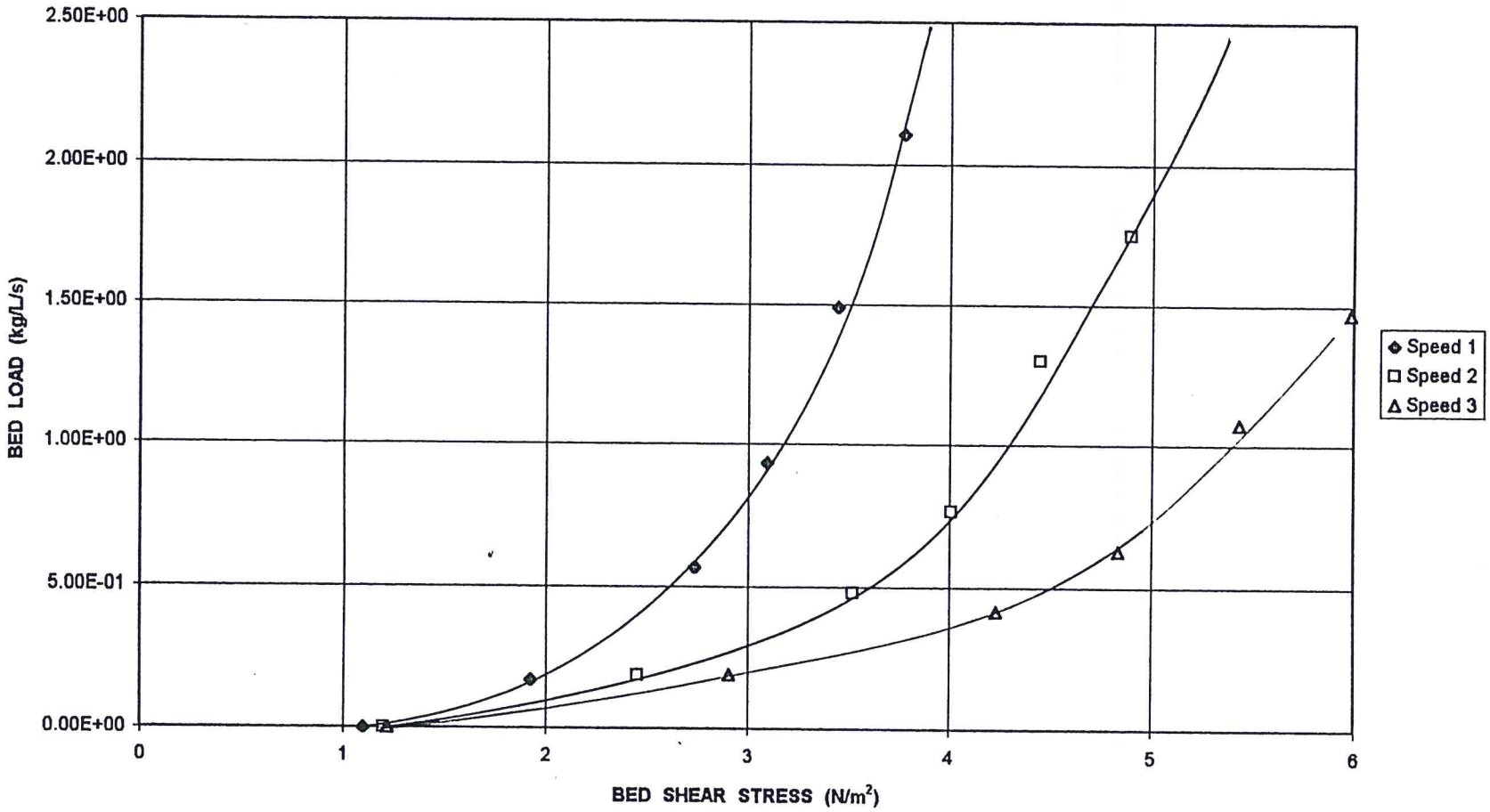
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.212 mm



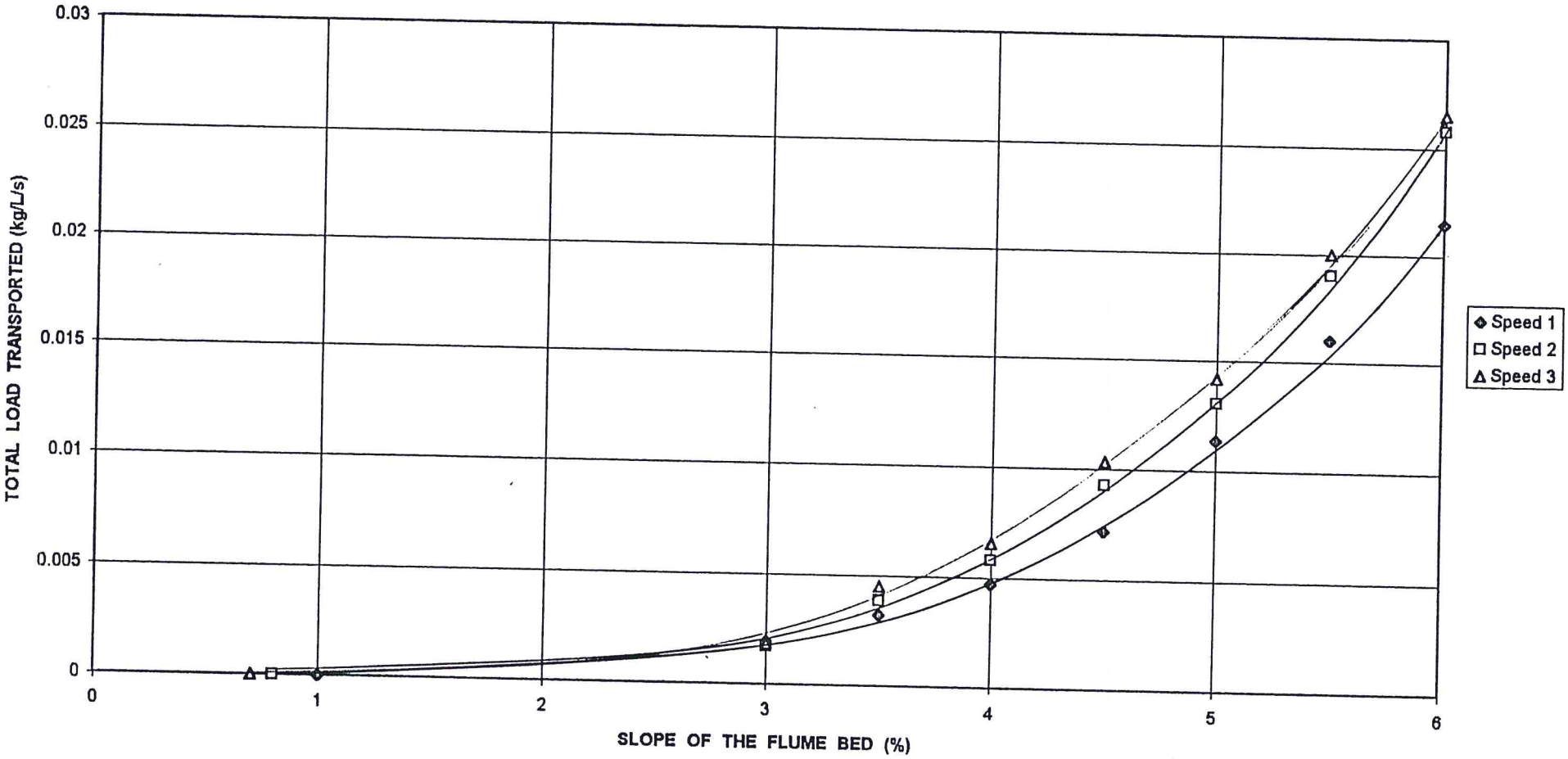
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.212 mm



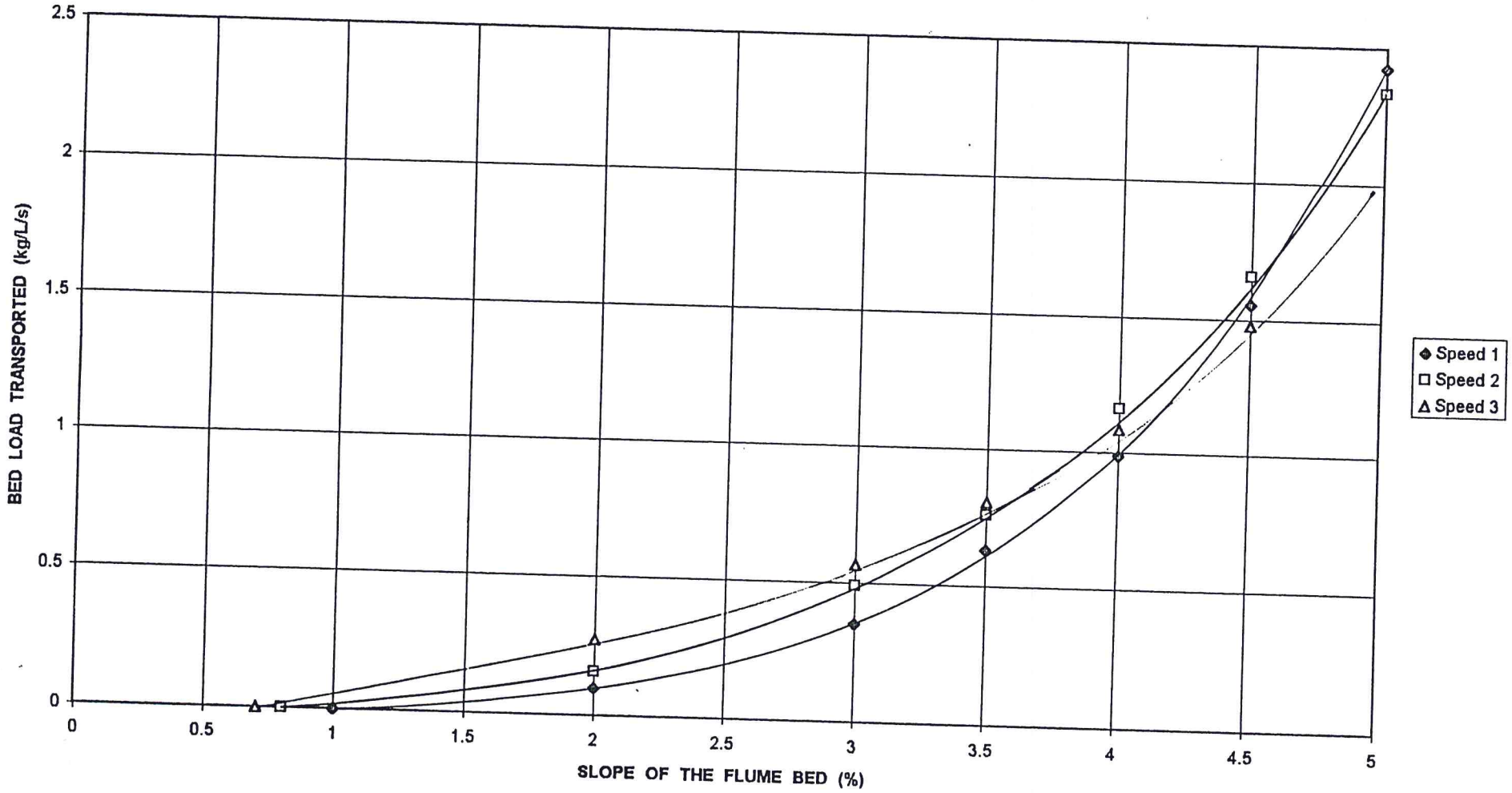
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.212 mm



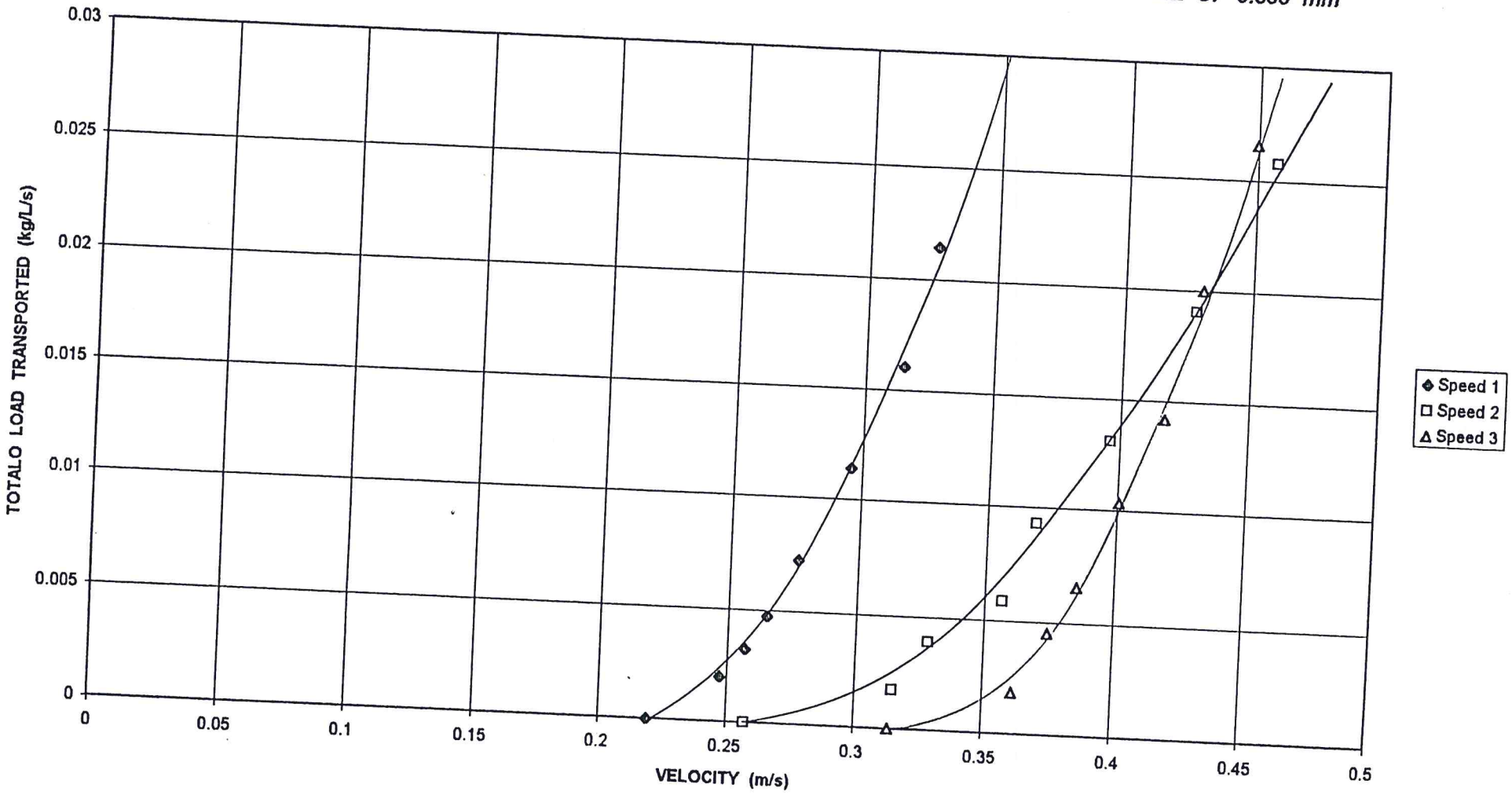
GRAPH SHOWS TOTAL LOAD TRANSPORTED AGAINST SLOPE OF FLUME BED FOR PARTICLE SIZE OF 0.300 mm



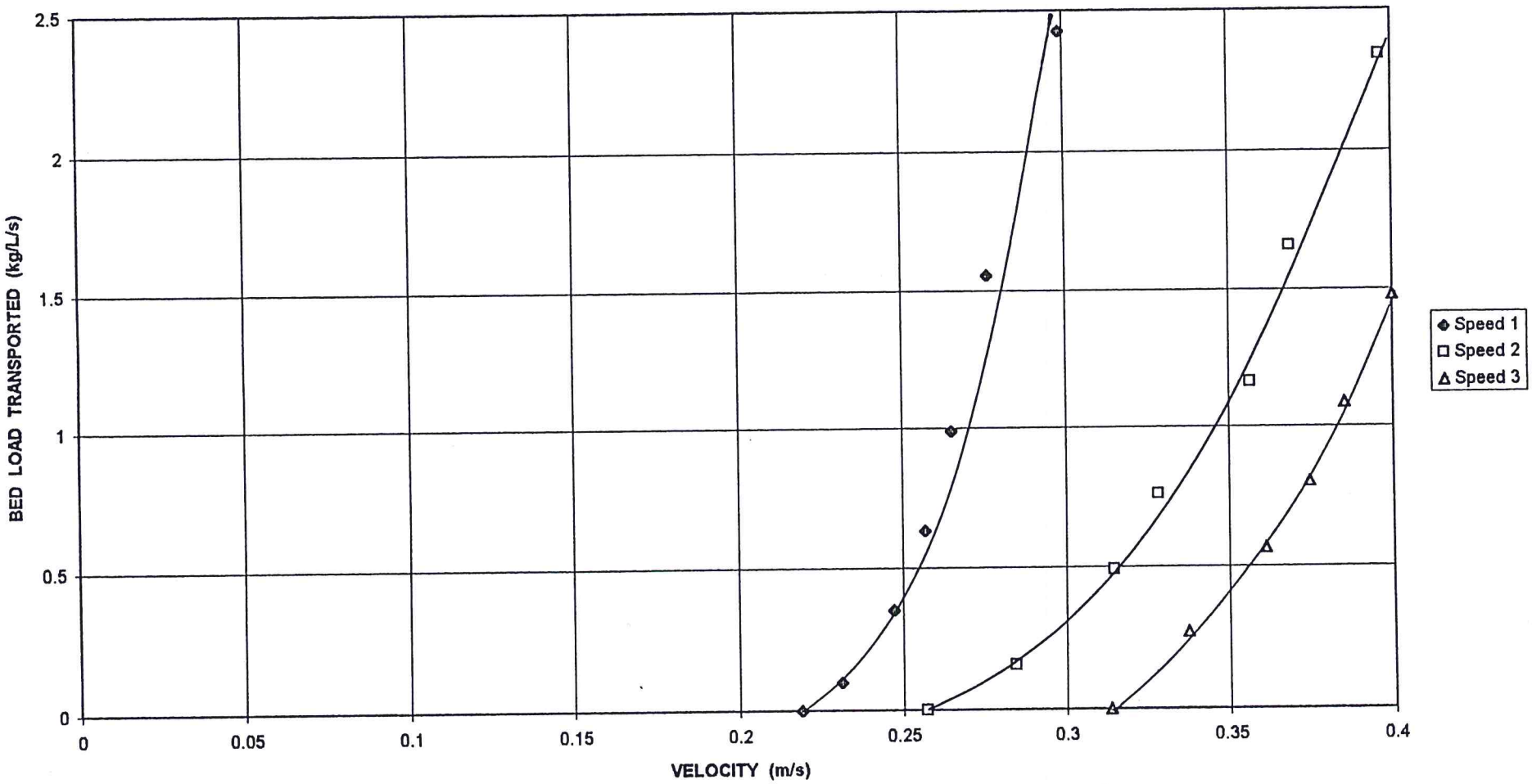
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.300 mm



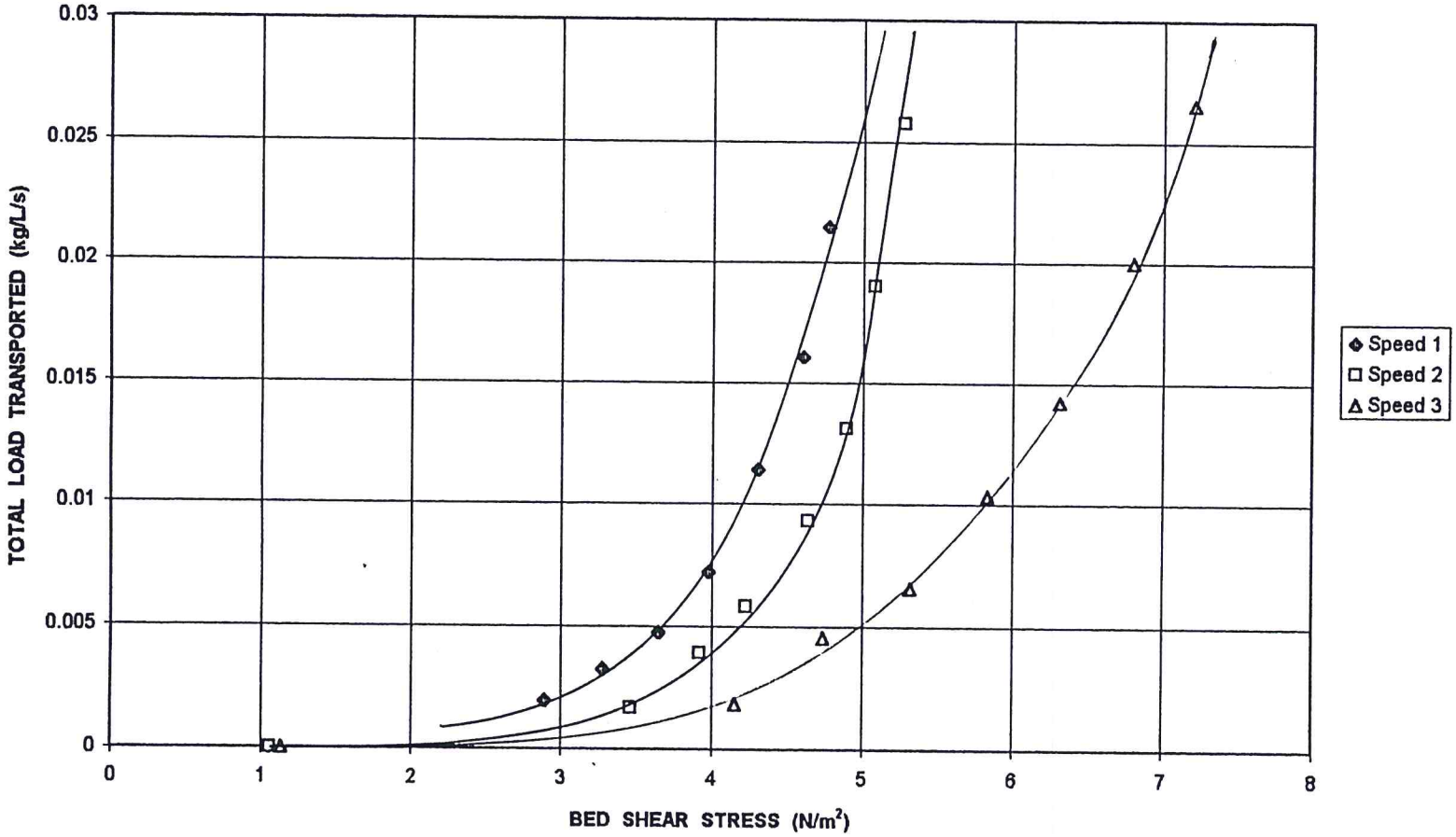
GRAPH SHOWS TOTAL LOAD TRANSORTED PLOTTED AGAINST VELOCITY FOR GRAIN SIZE OF 0.300 mm



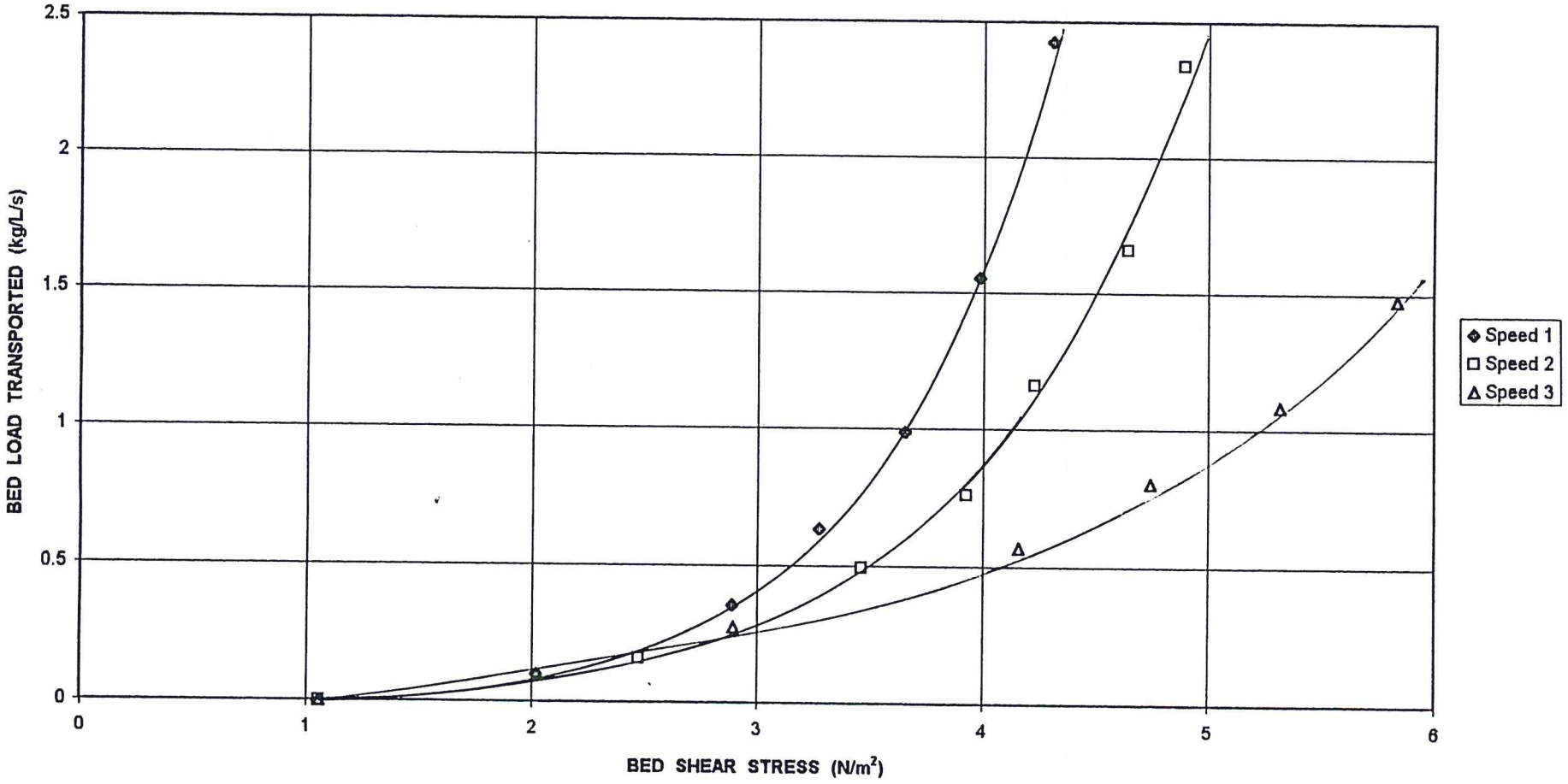
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.300 mm



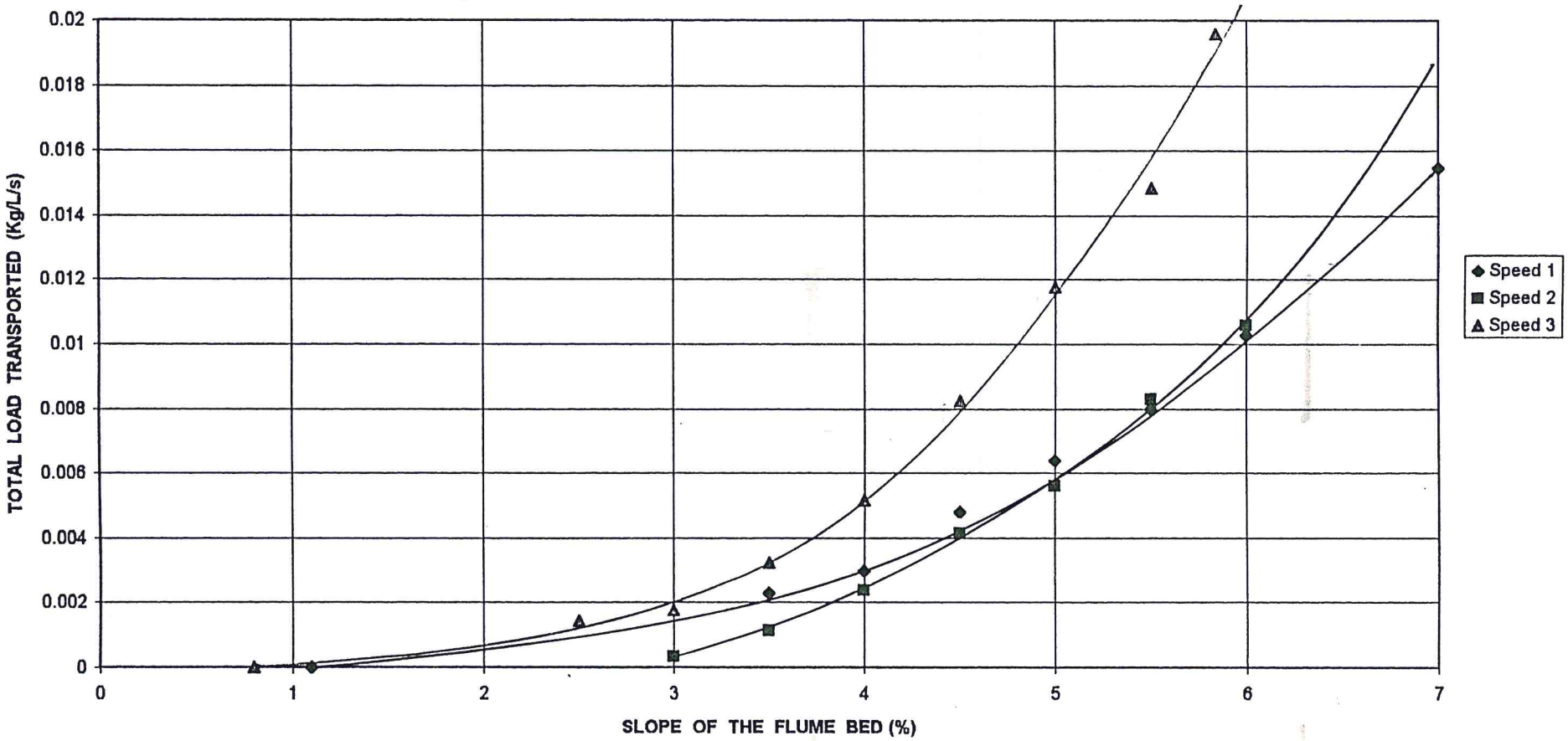
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.300 mm



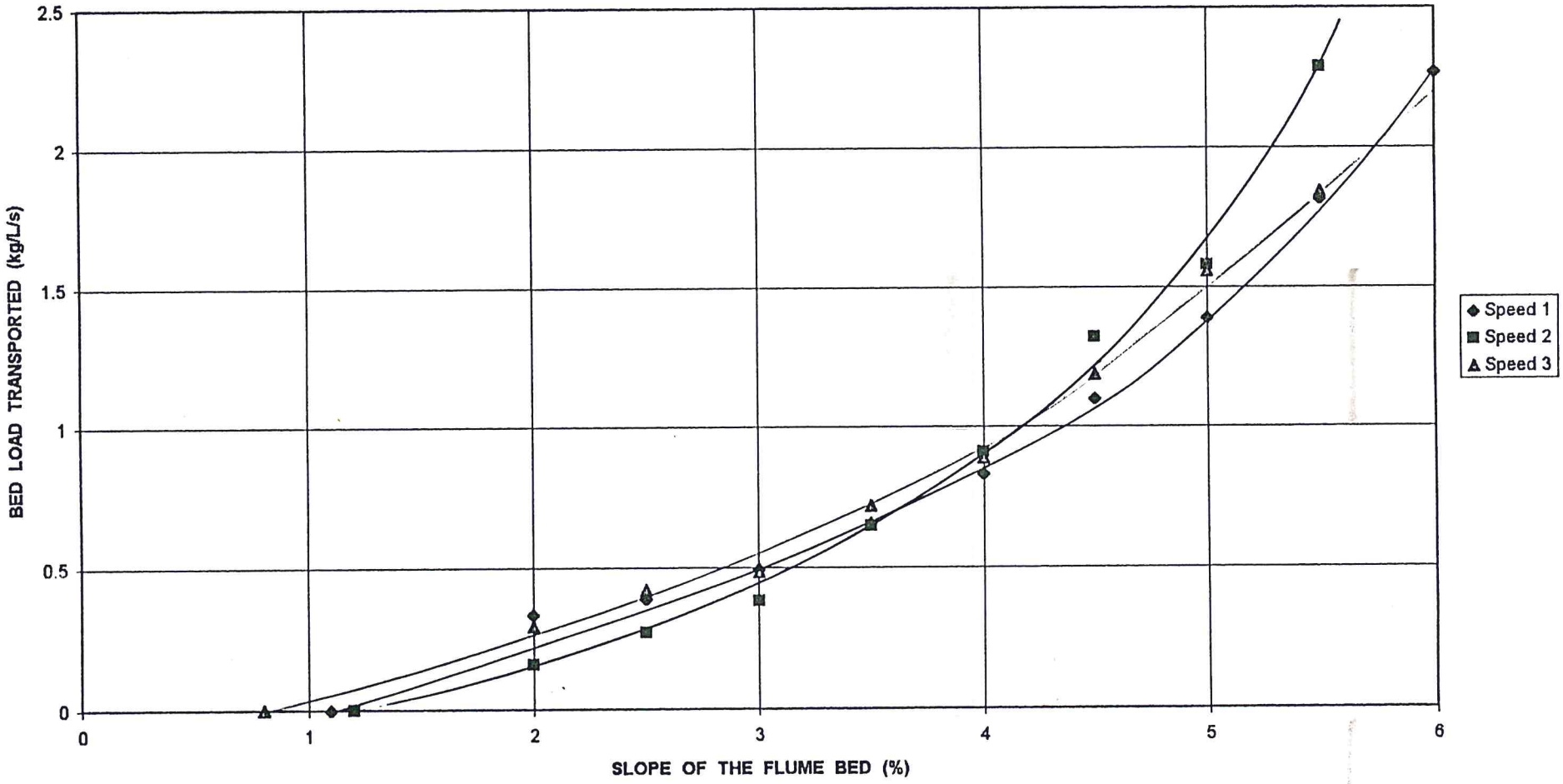
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.300 mm



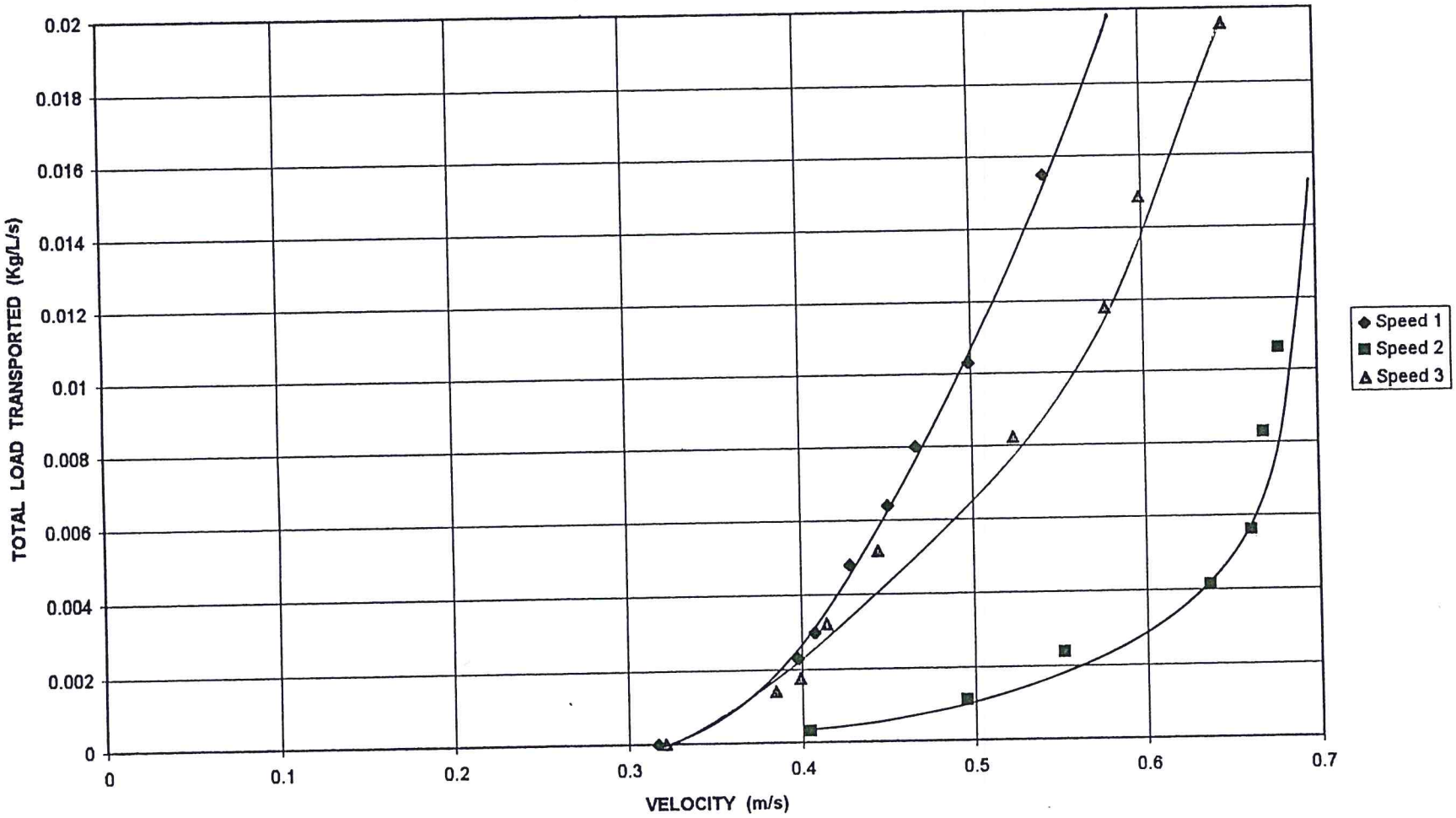
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.425 mm



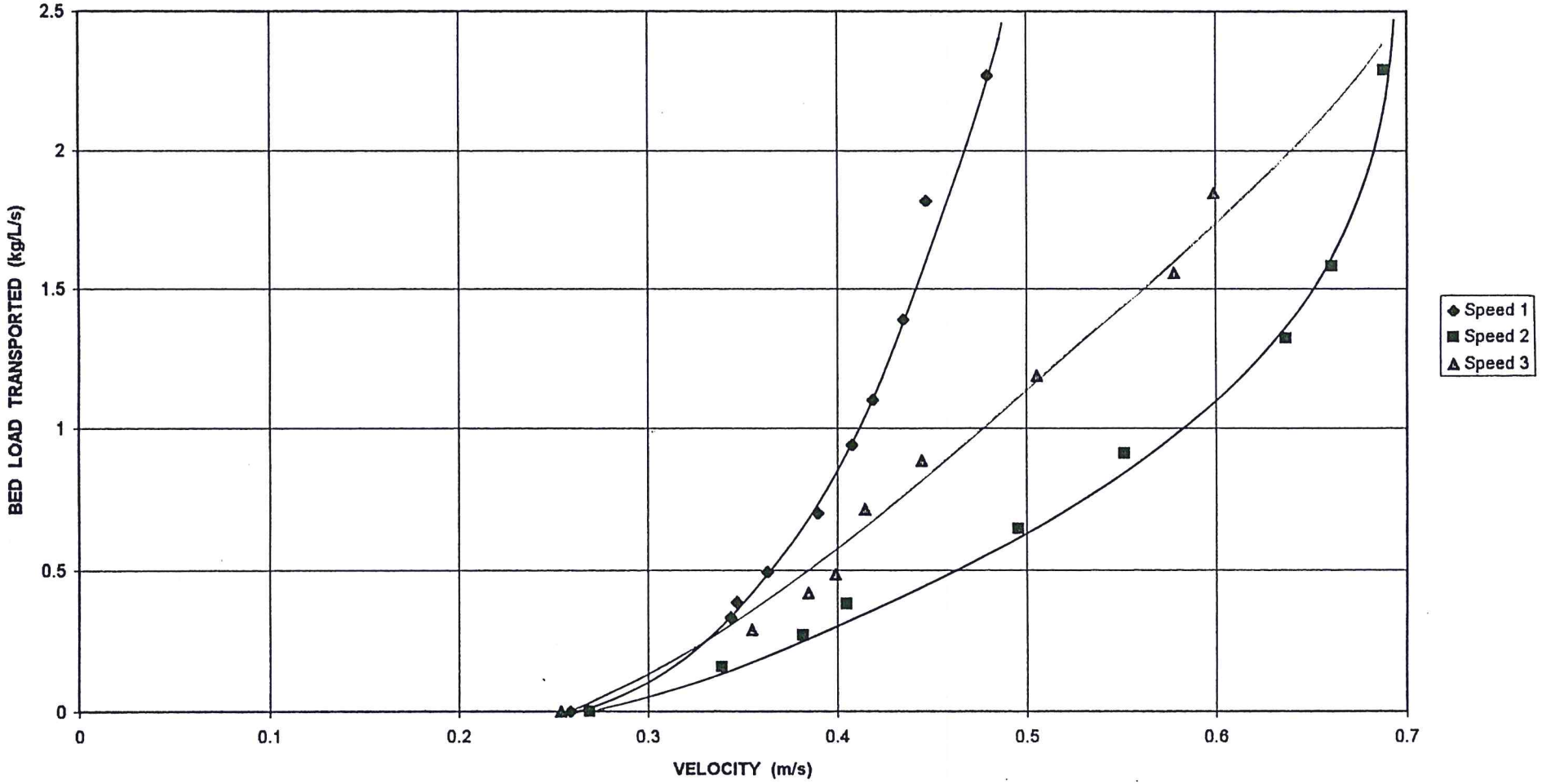
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.425 mm



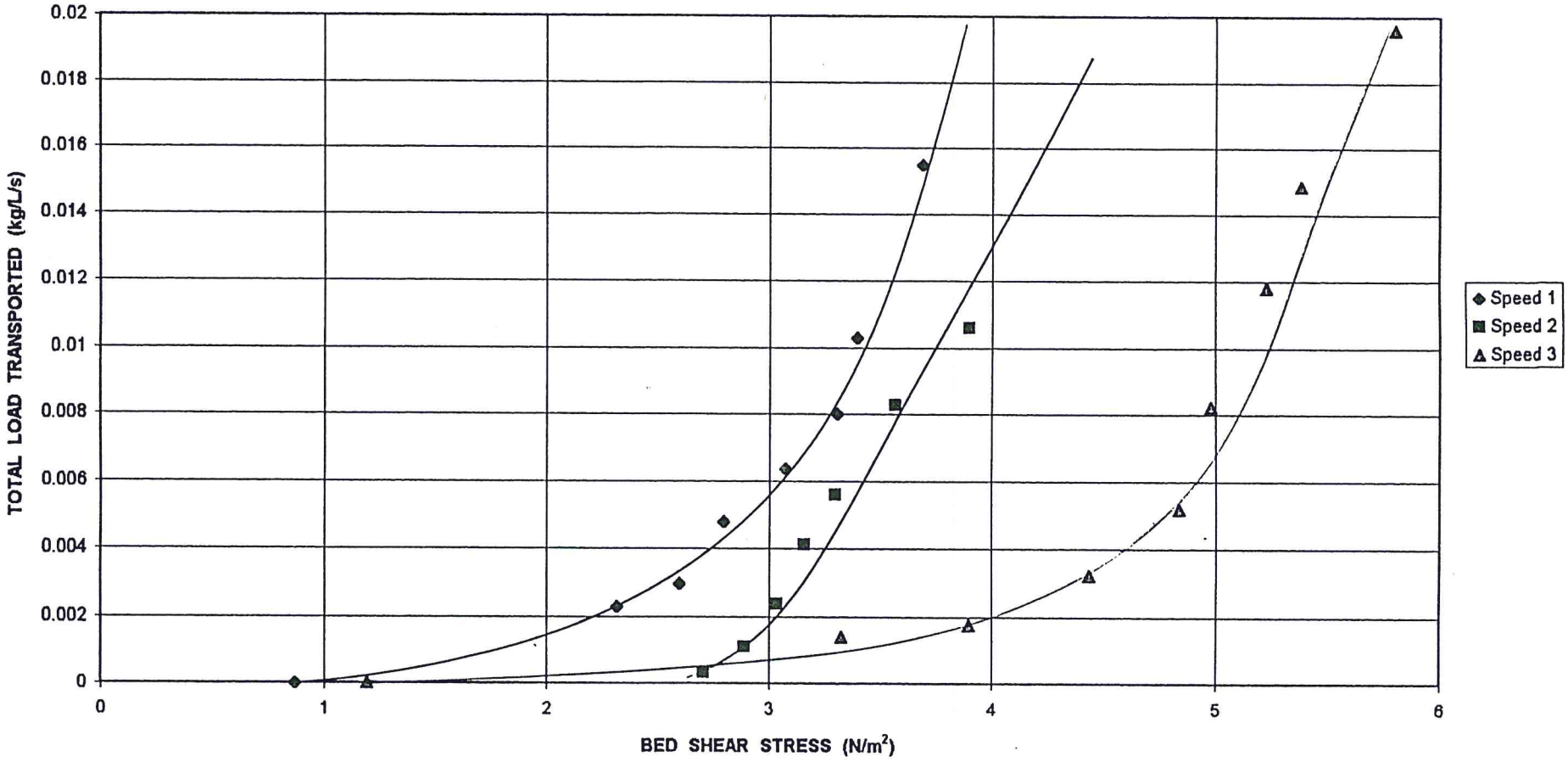
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.425 mm



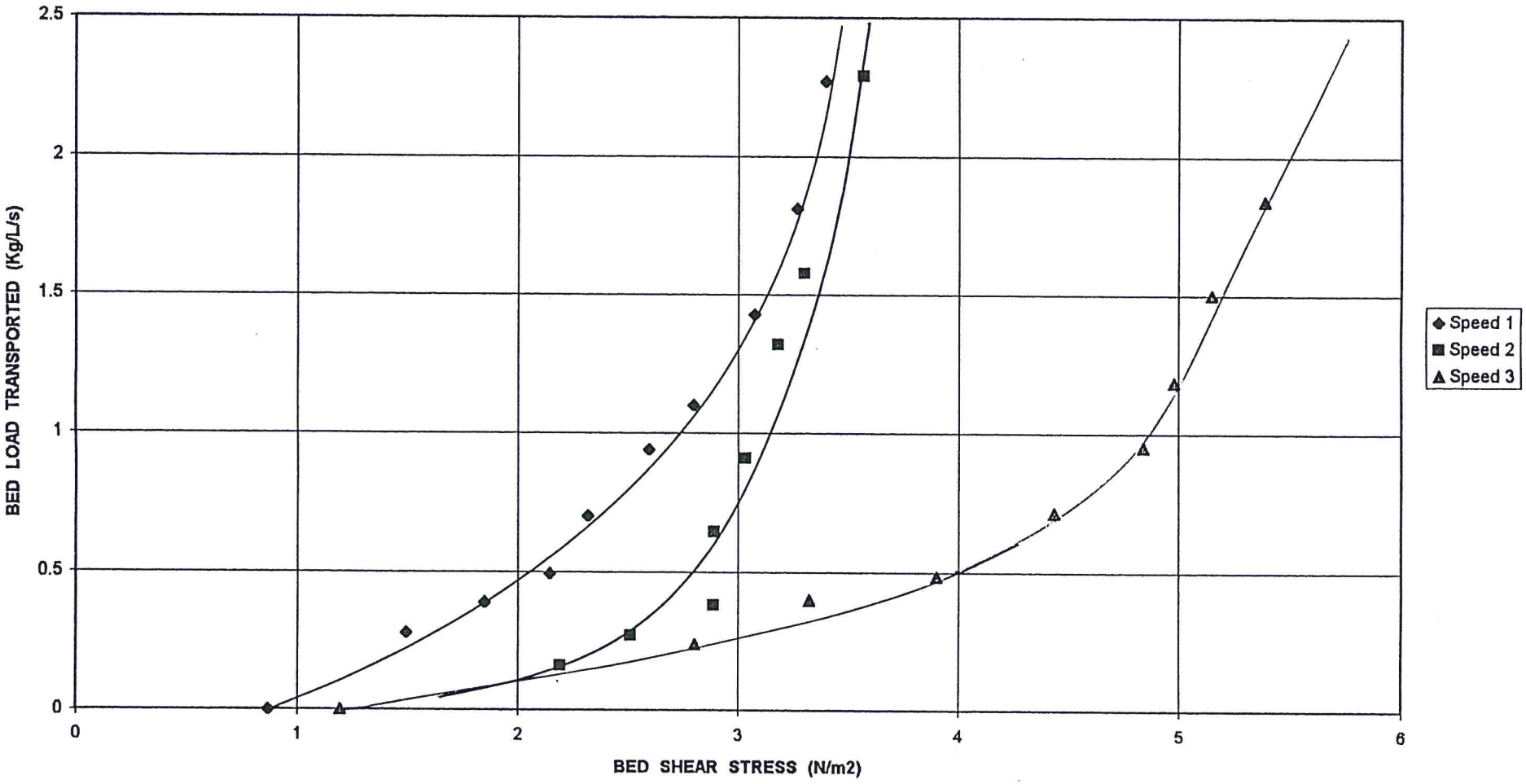
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.425 mm



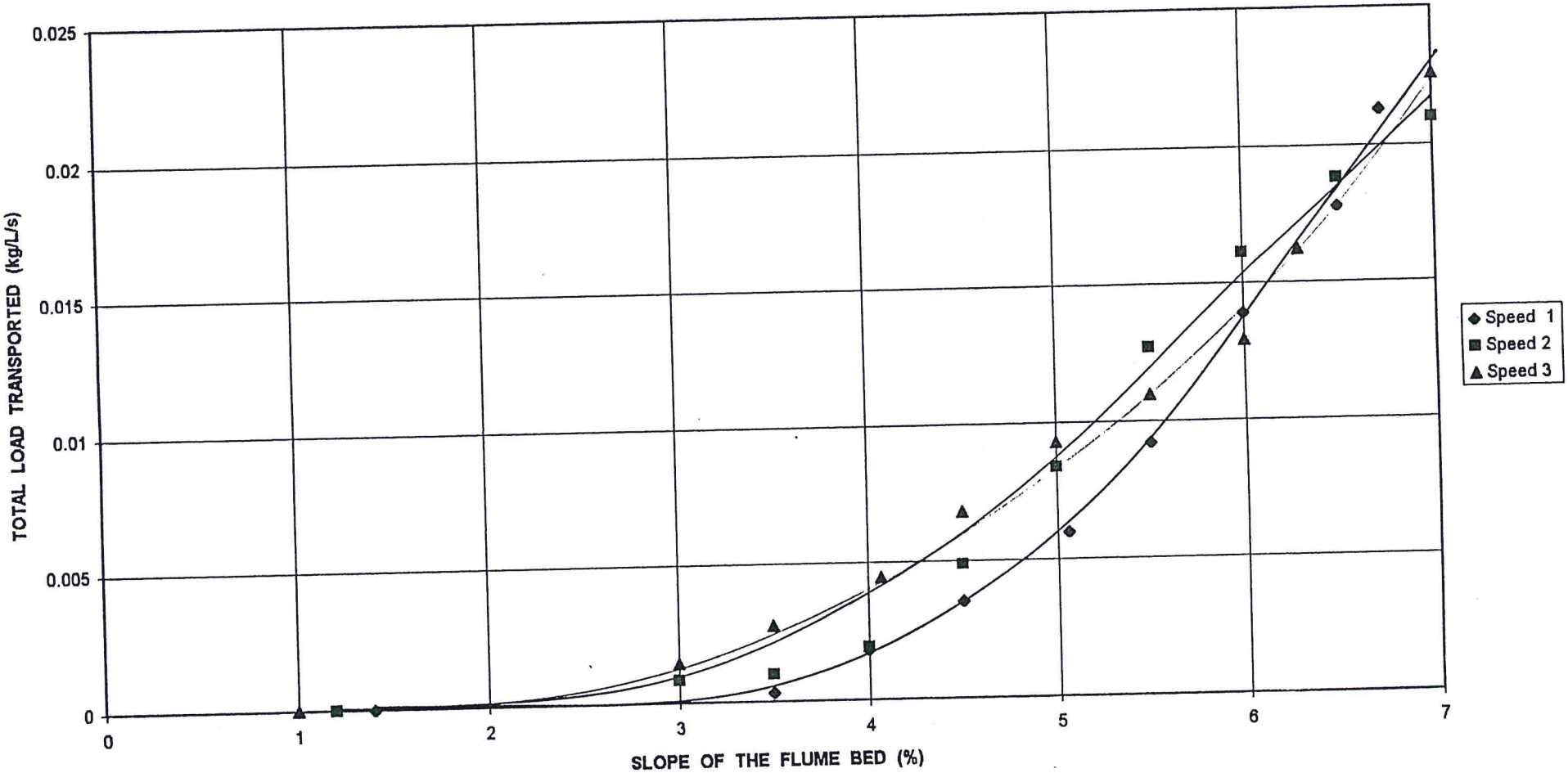
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.425 mm



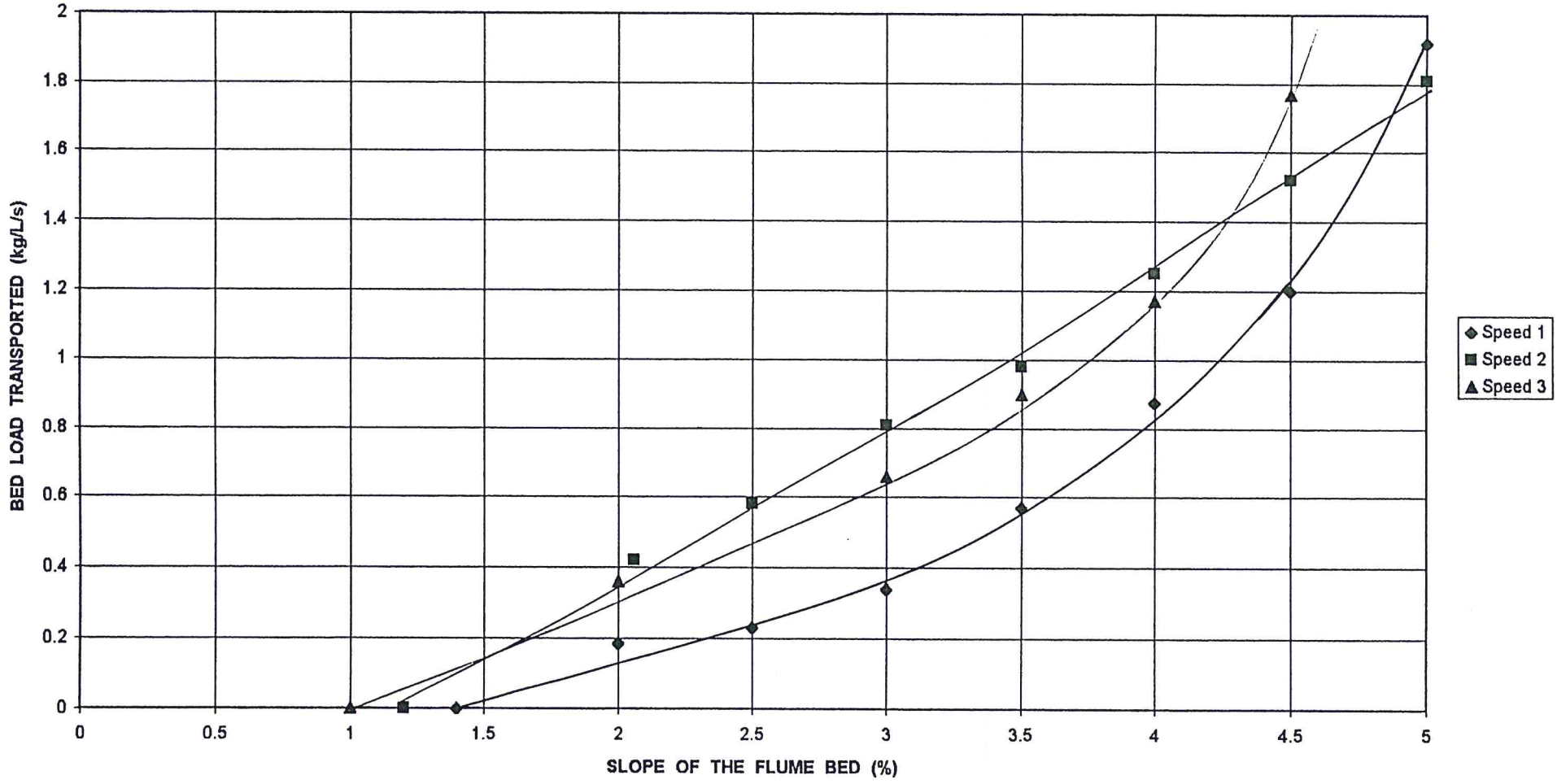
GRAPH SHOWS BED LOAD TRANSPORTED POLTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.425 mm



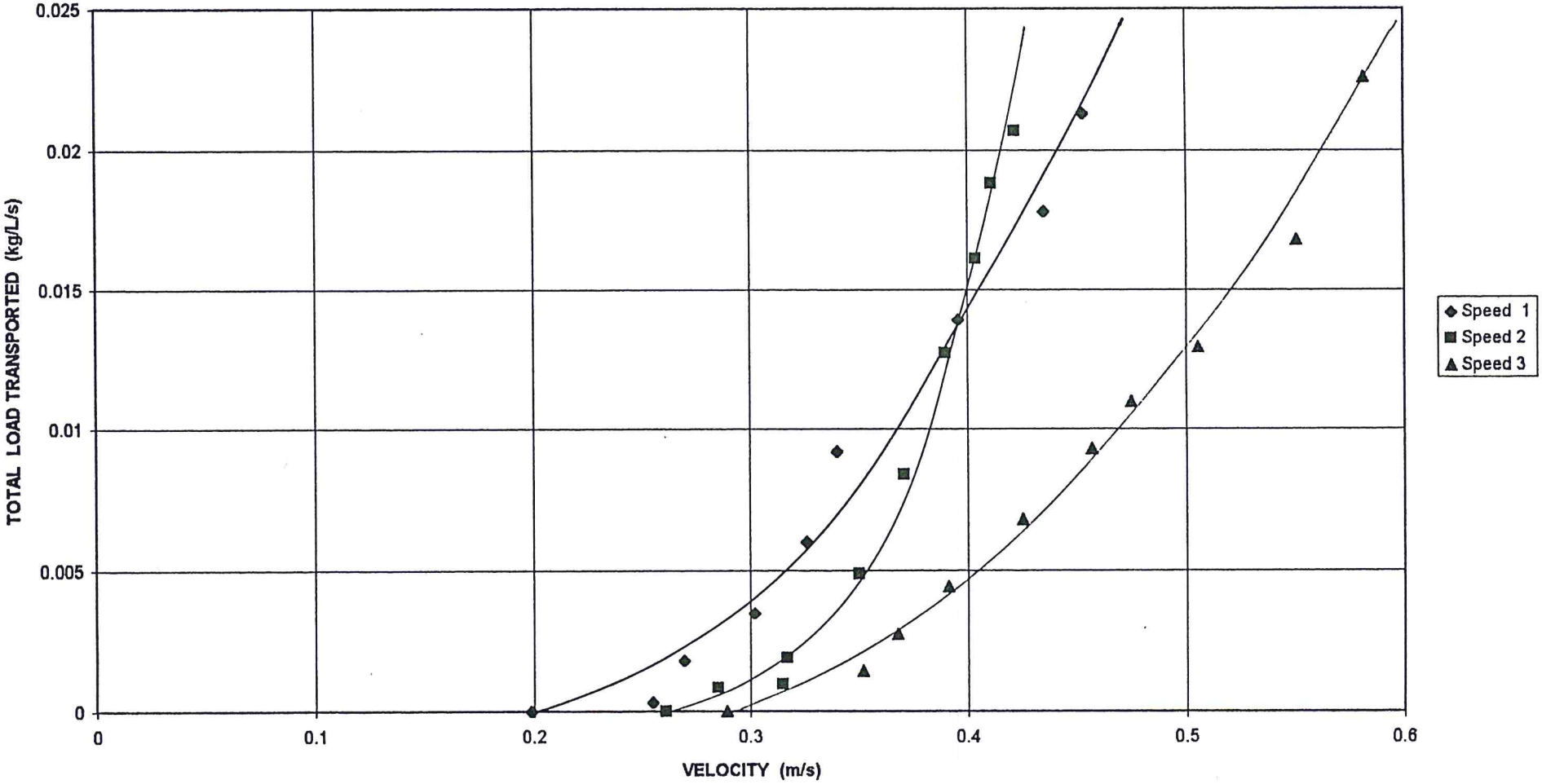
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.600mm



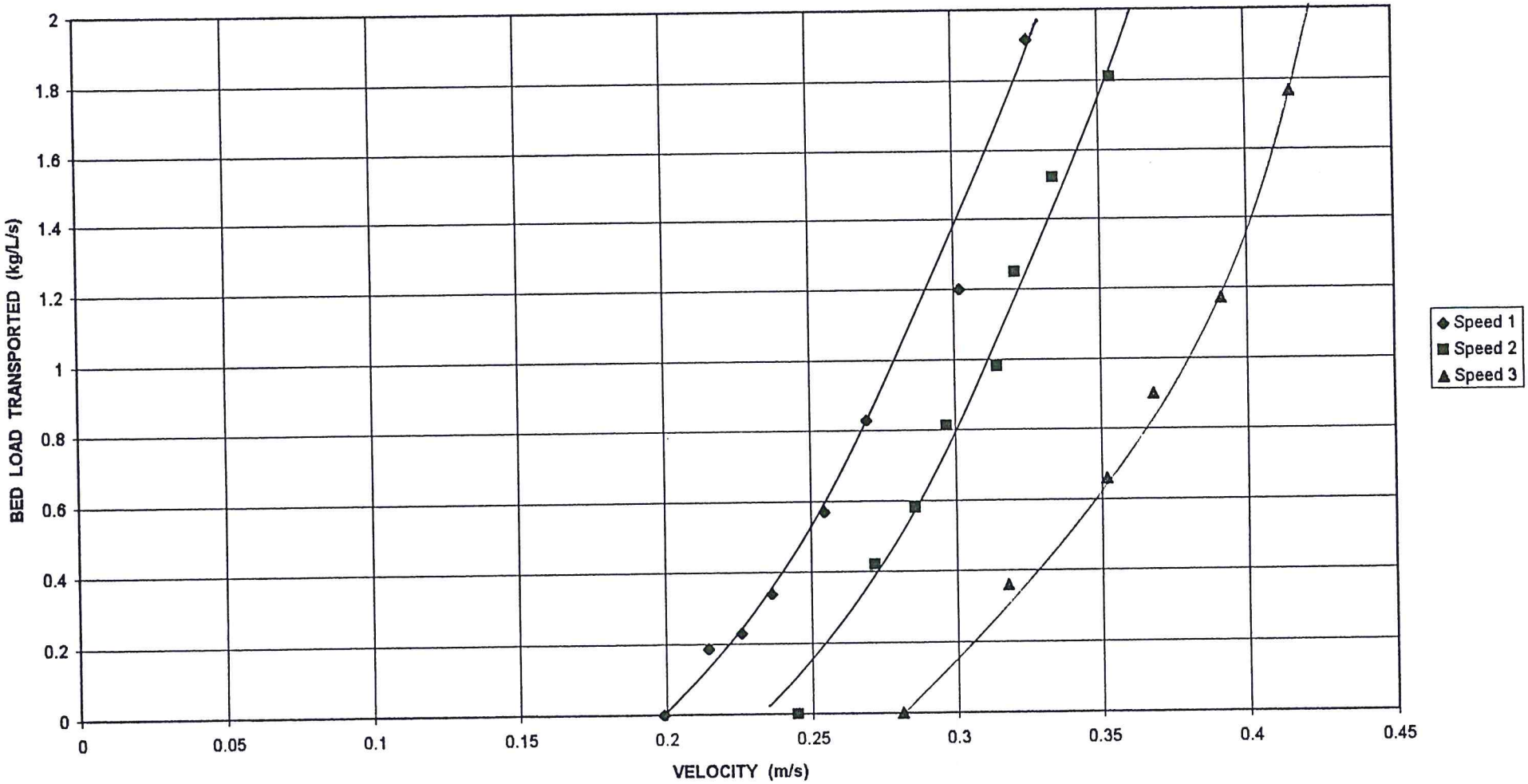
GRAPH SHOWS BED LOAD TRANSPORTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.600 mm



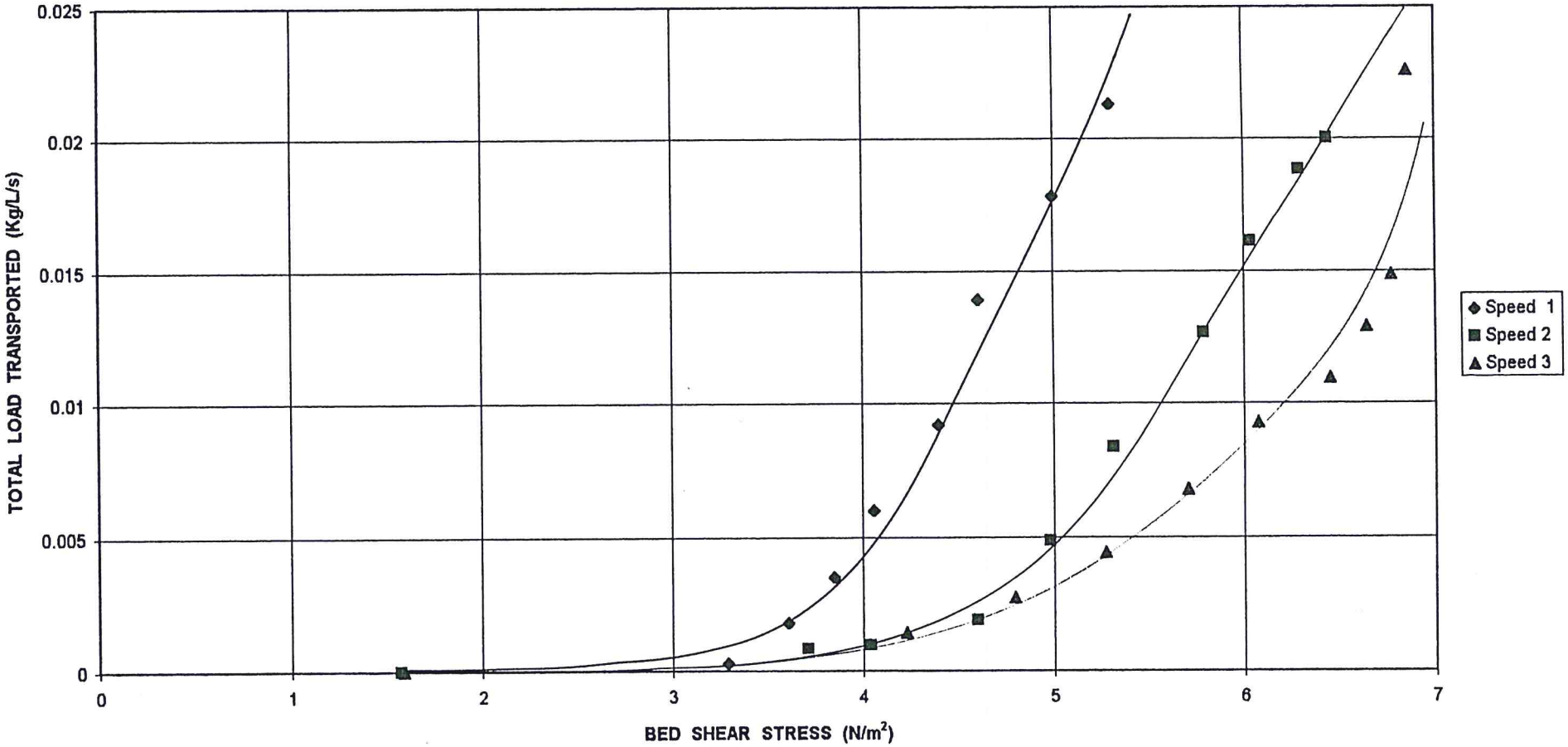
GRAPH SHOWS TOTAL LOAD TRANSPORTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.600 mm



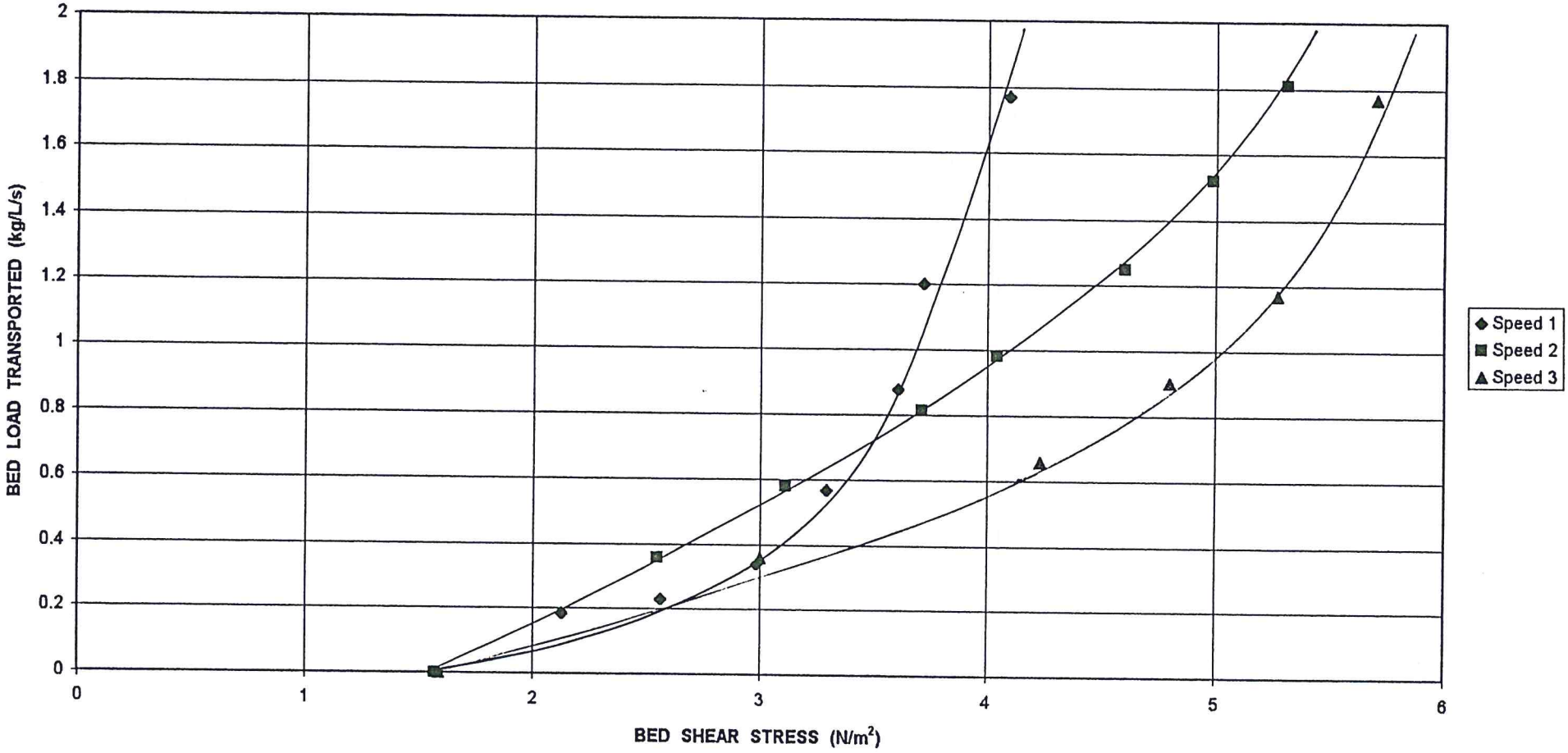
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.600 mm



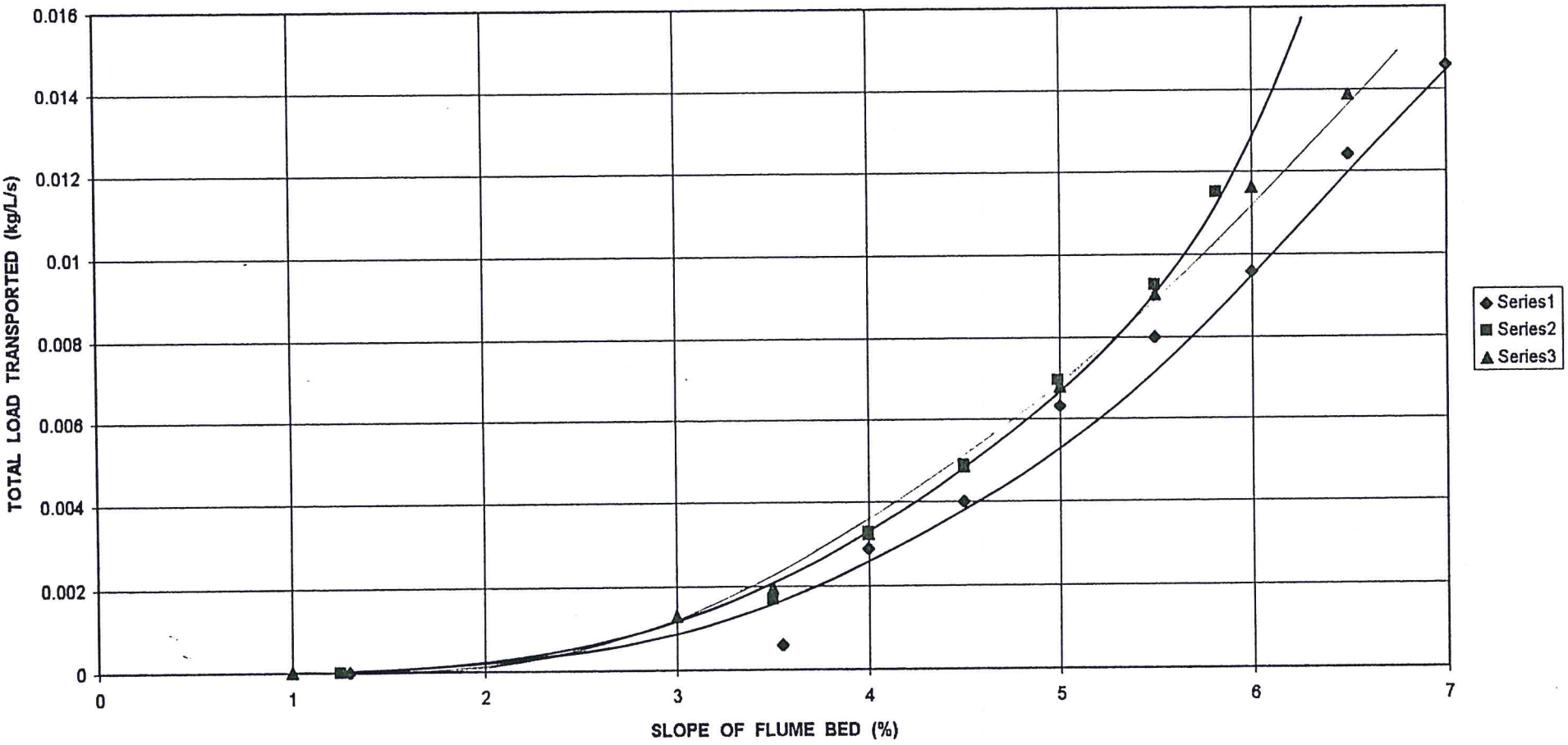
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.600 mm



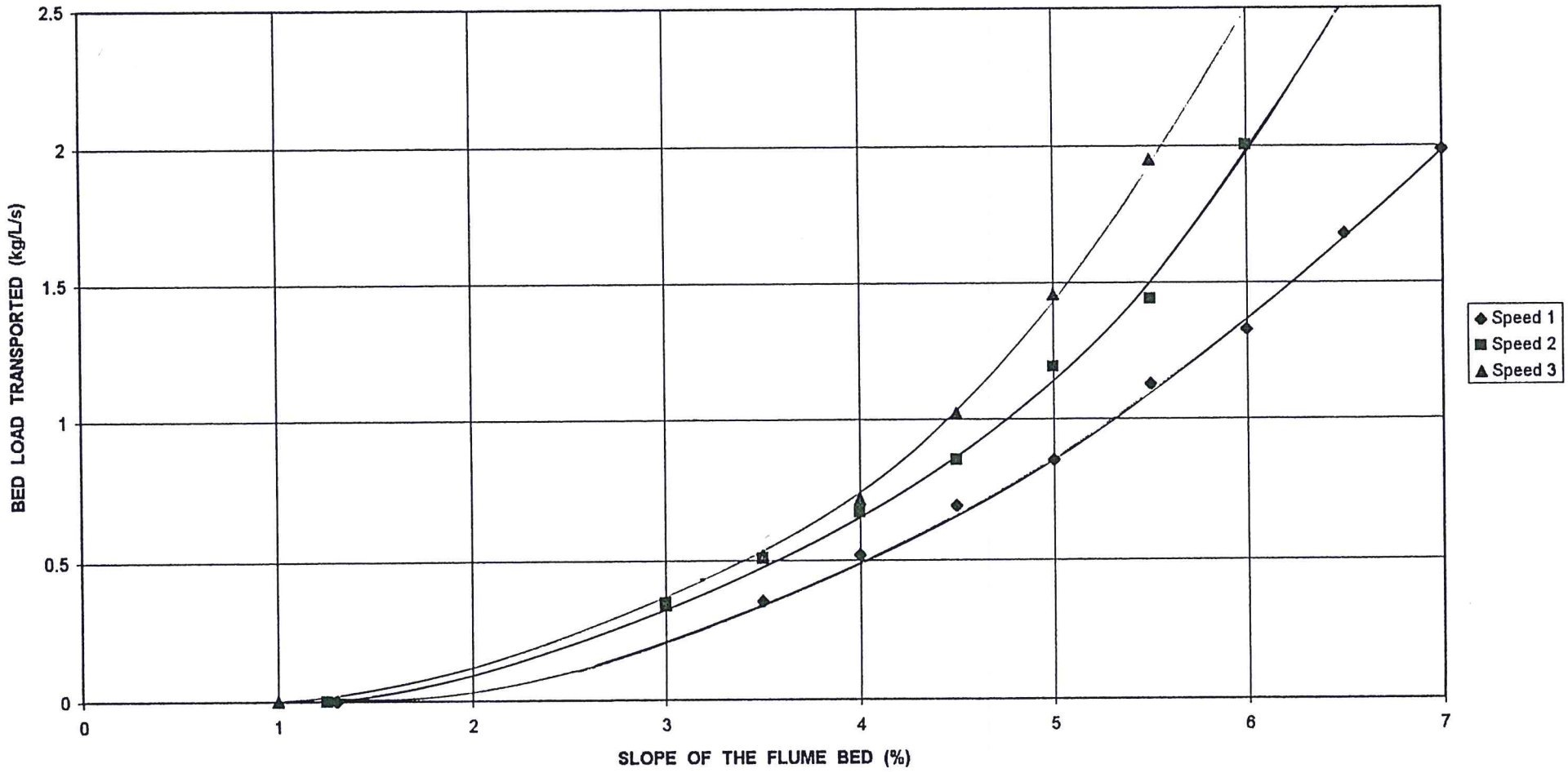
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.600 mm



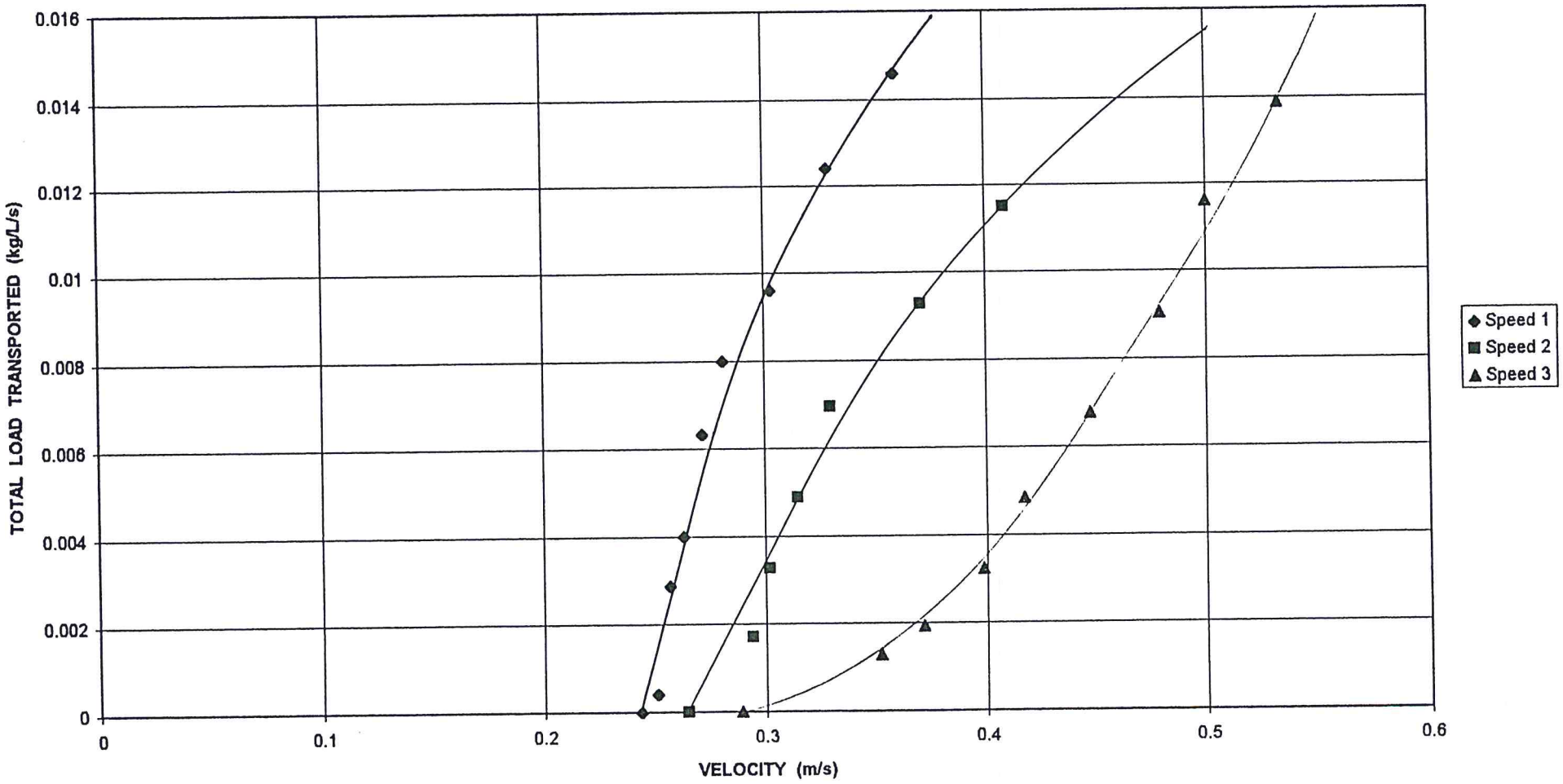
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF FLUME BED FOR PARTICLE SIZE OF 0.850 mm



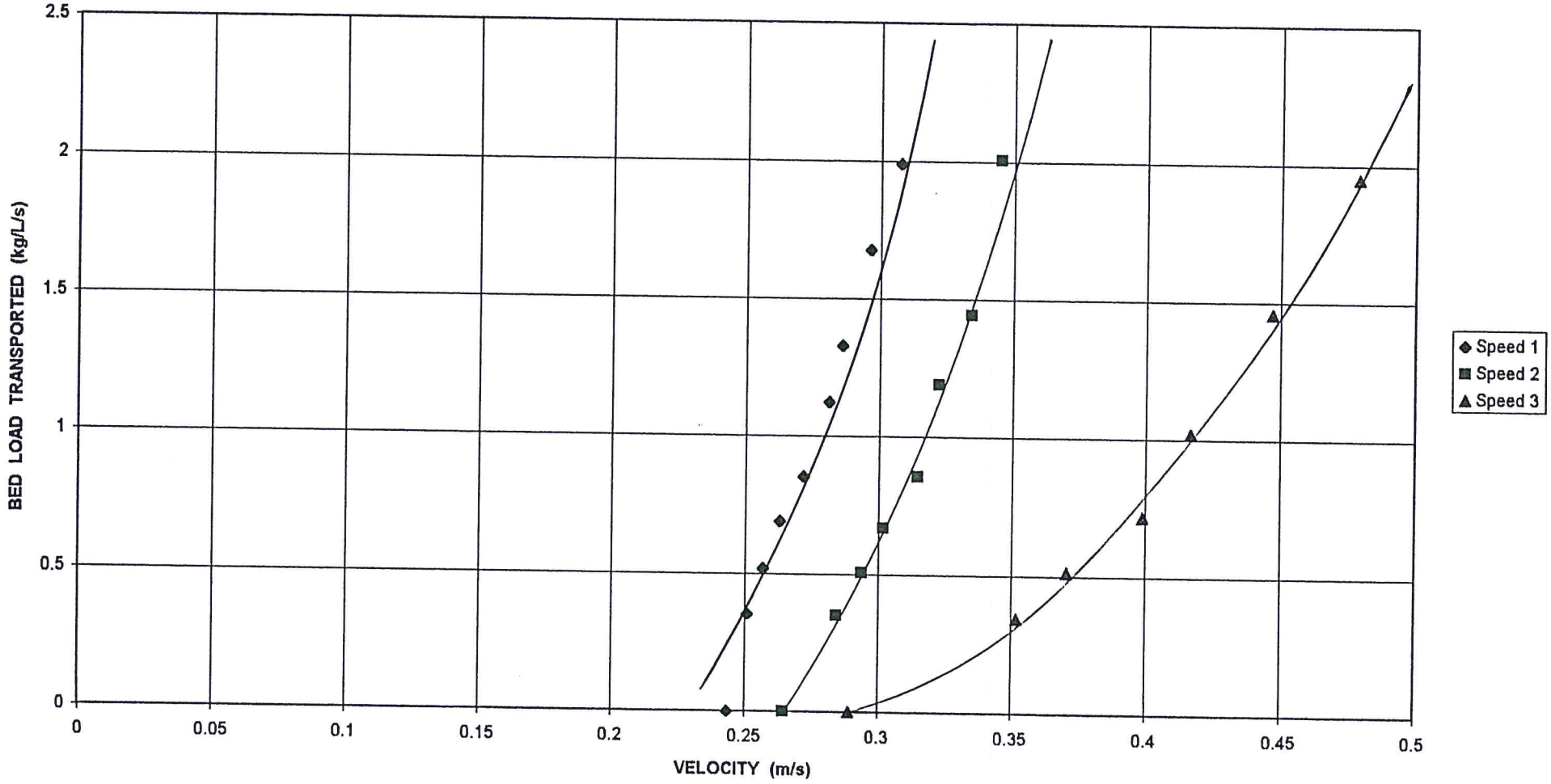
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 0.850 mm



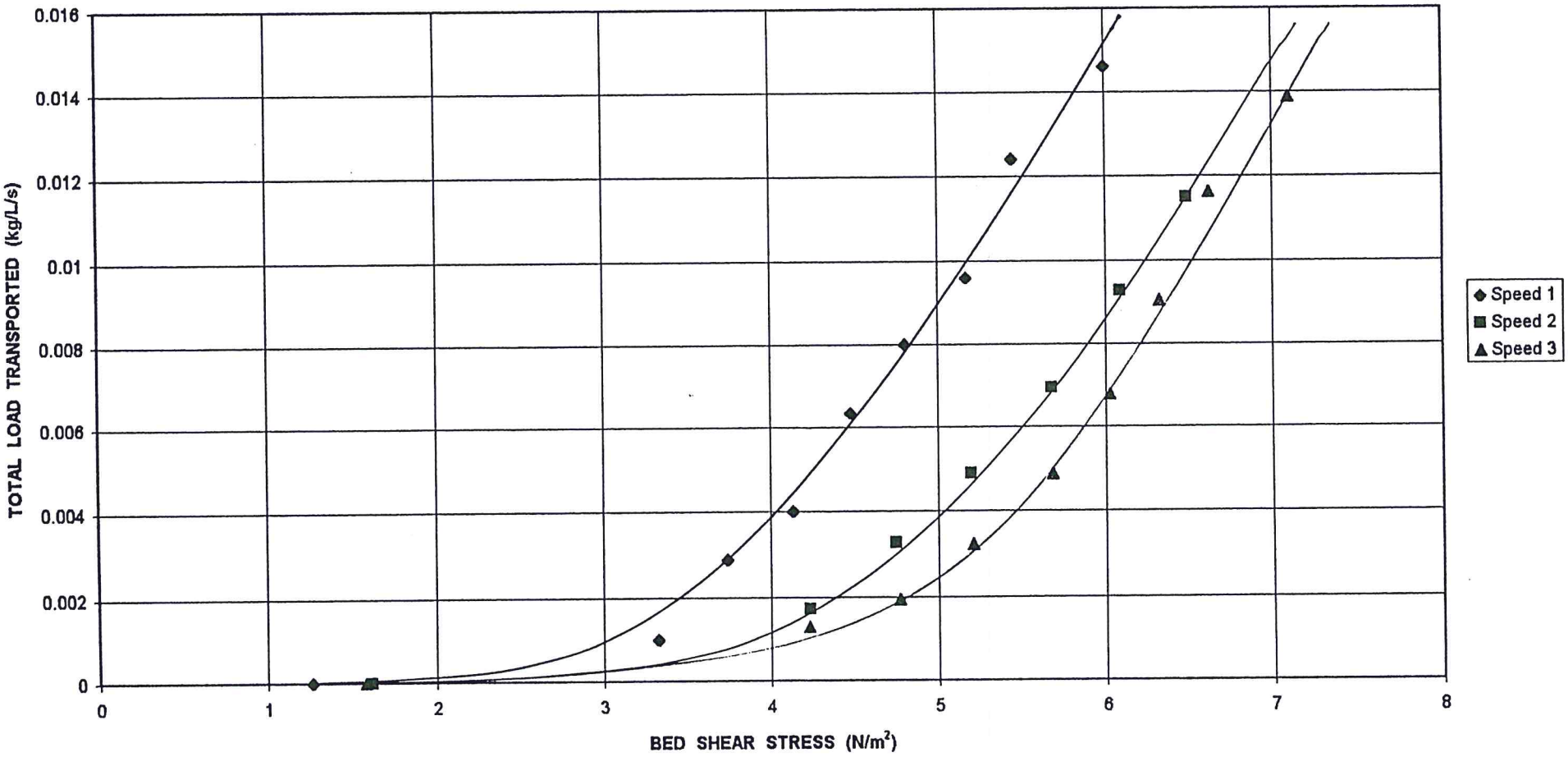
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.850 mm



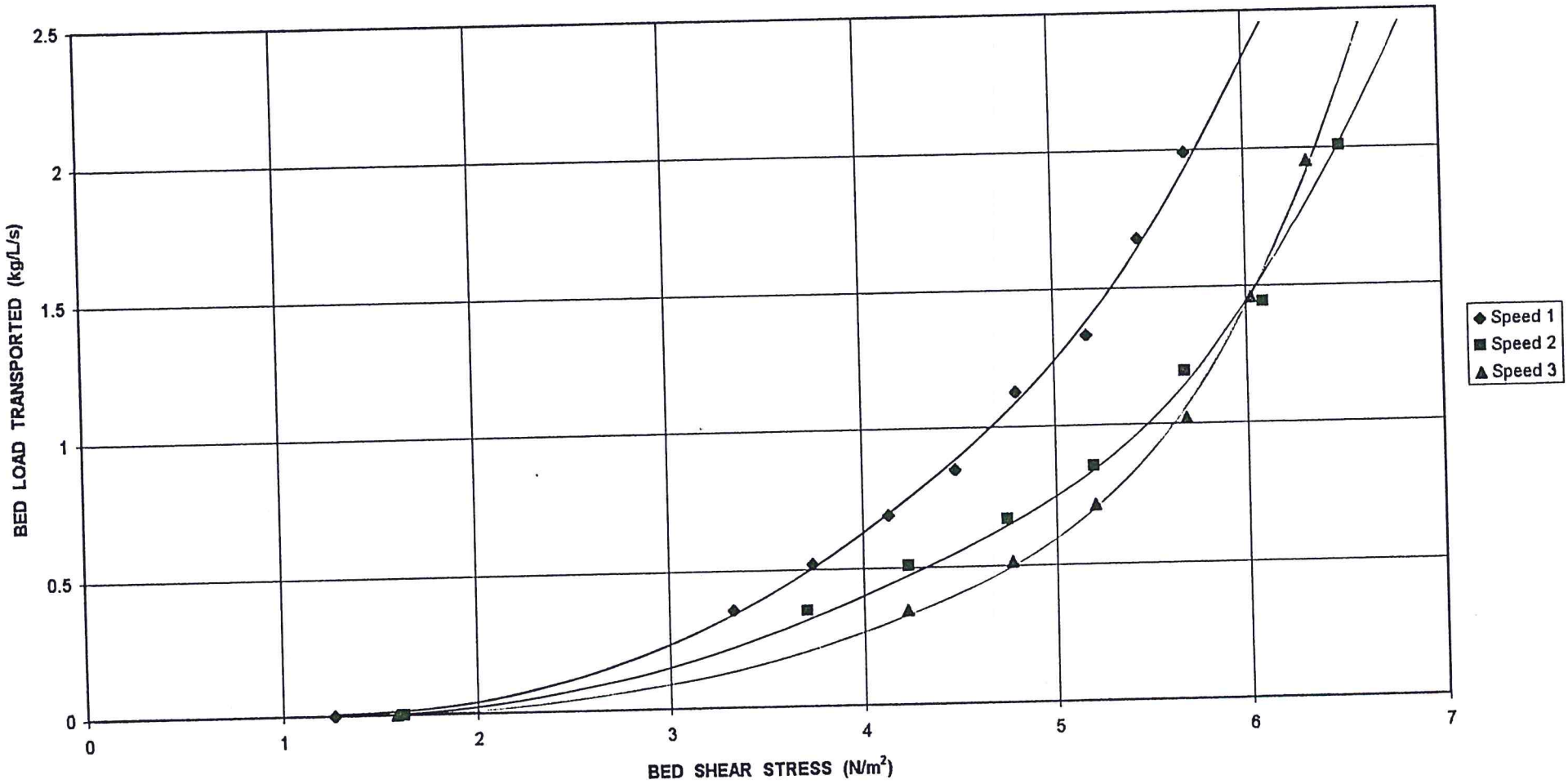
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 0.850 mm



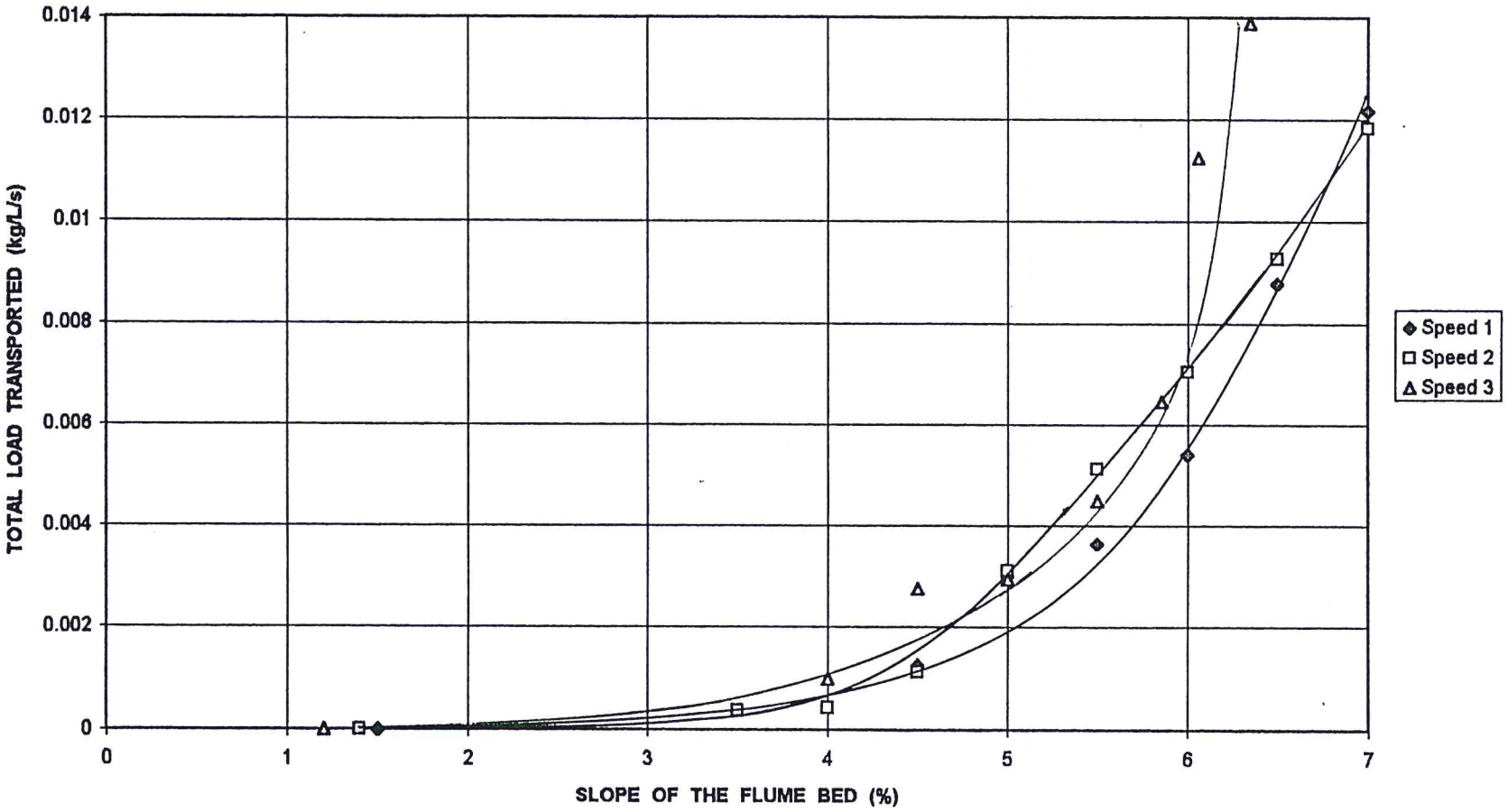
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.850 mm



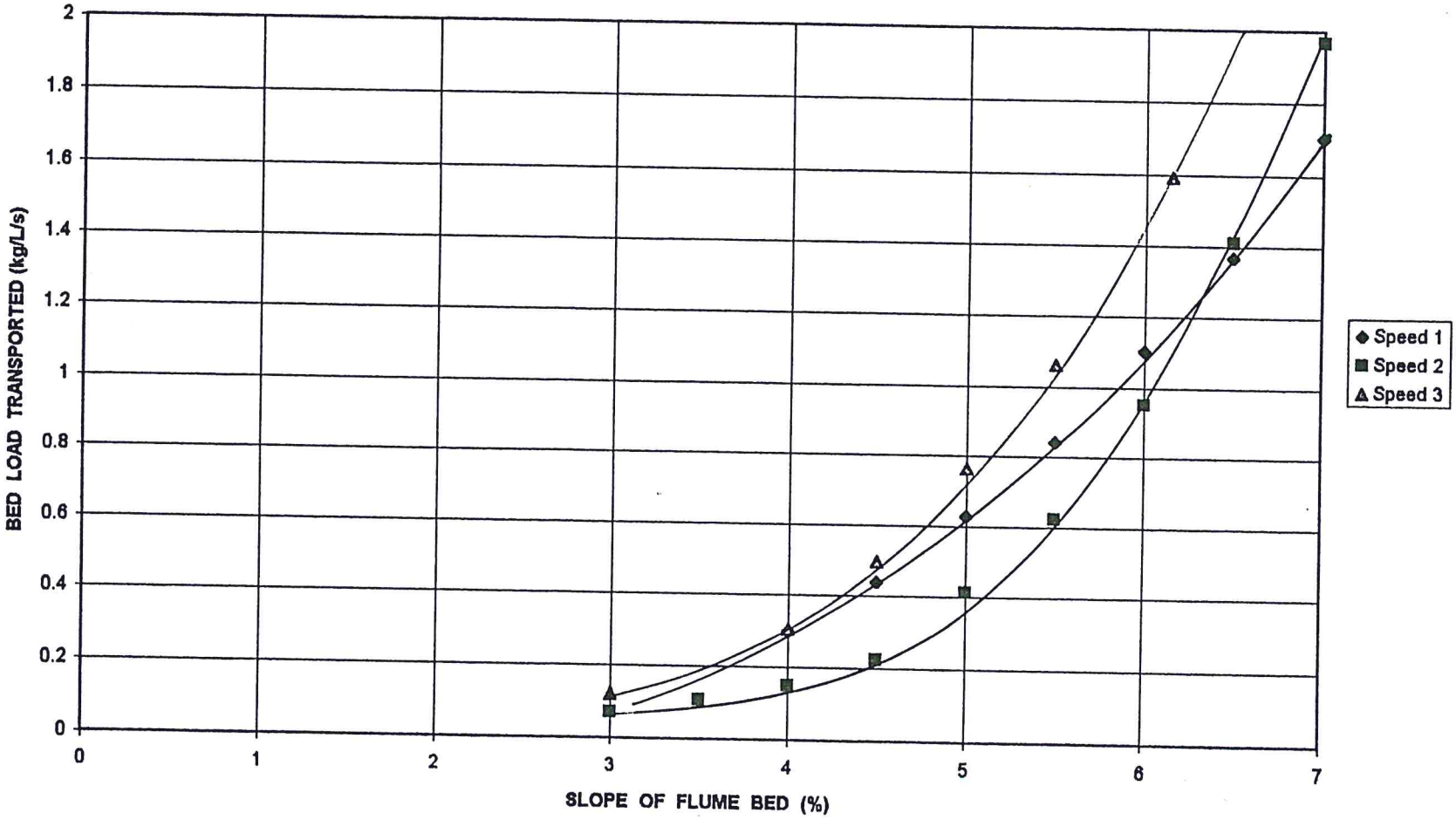
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 0.850 mm



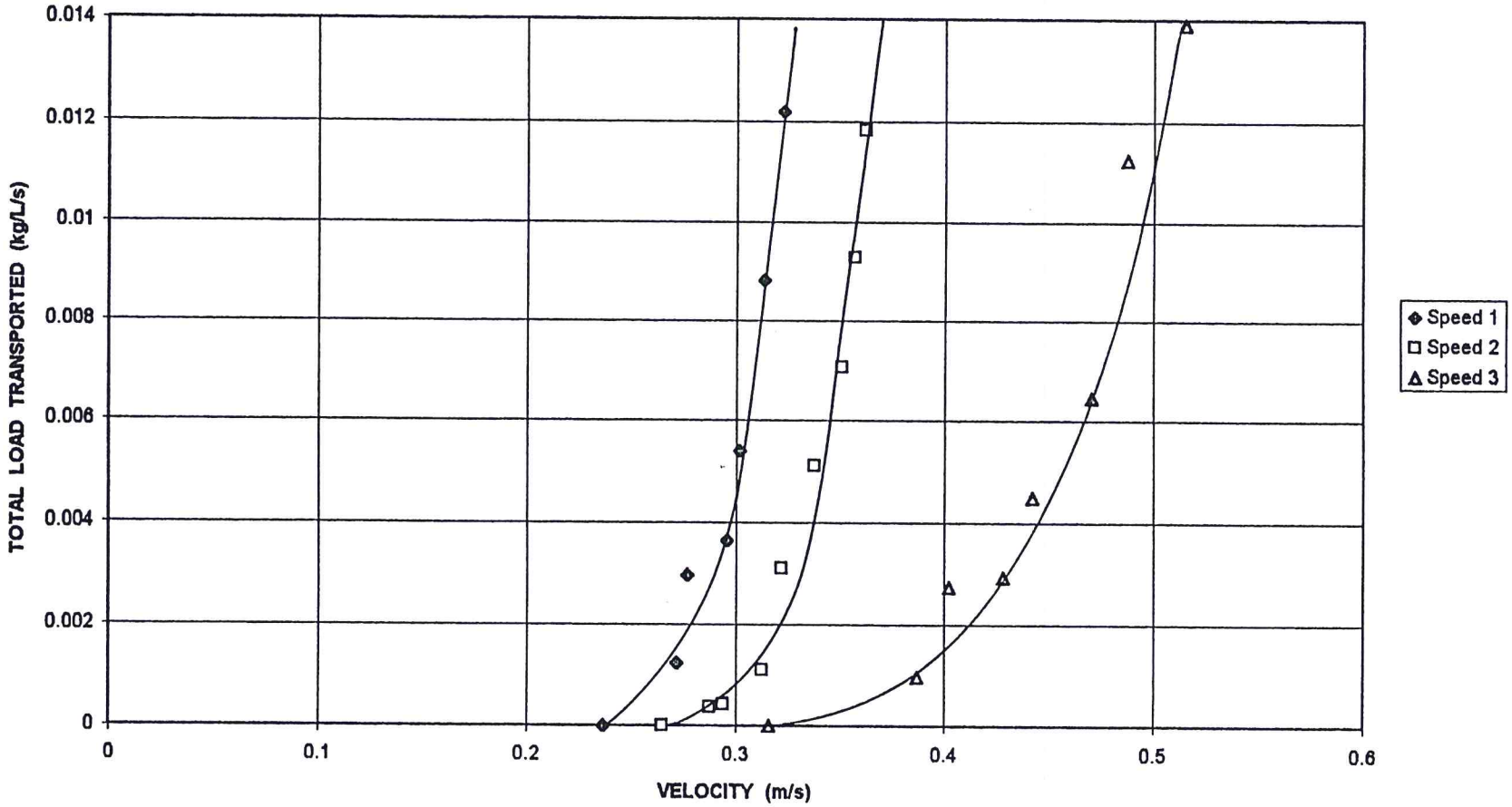
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 1.18 mm



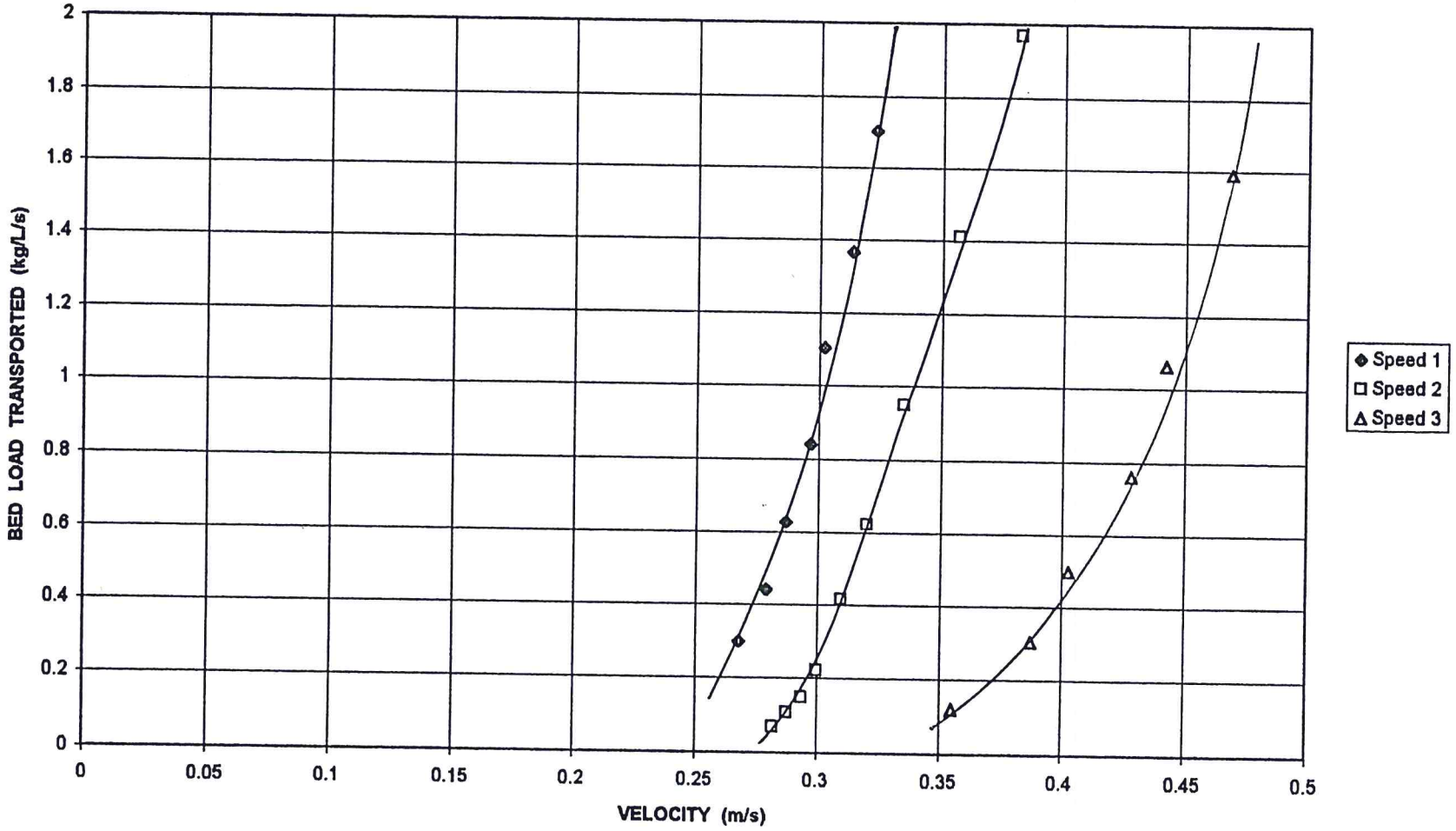
GRAPH SHOWS BED LOAD TRANSPORTED AGAINST SLOPE OF FLUME BED FOR PARTICLE SIZE OF 1.18 mm



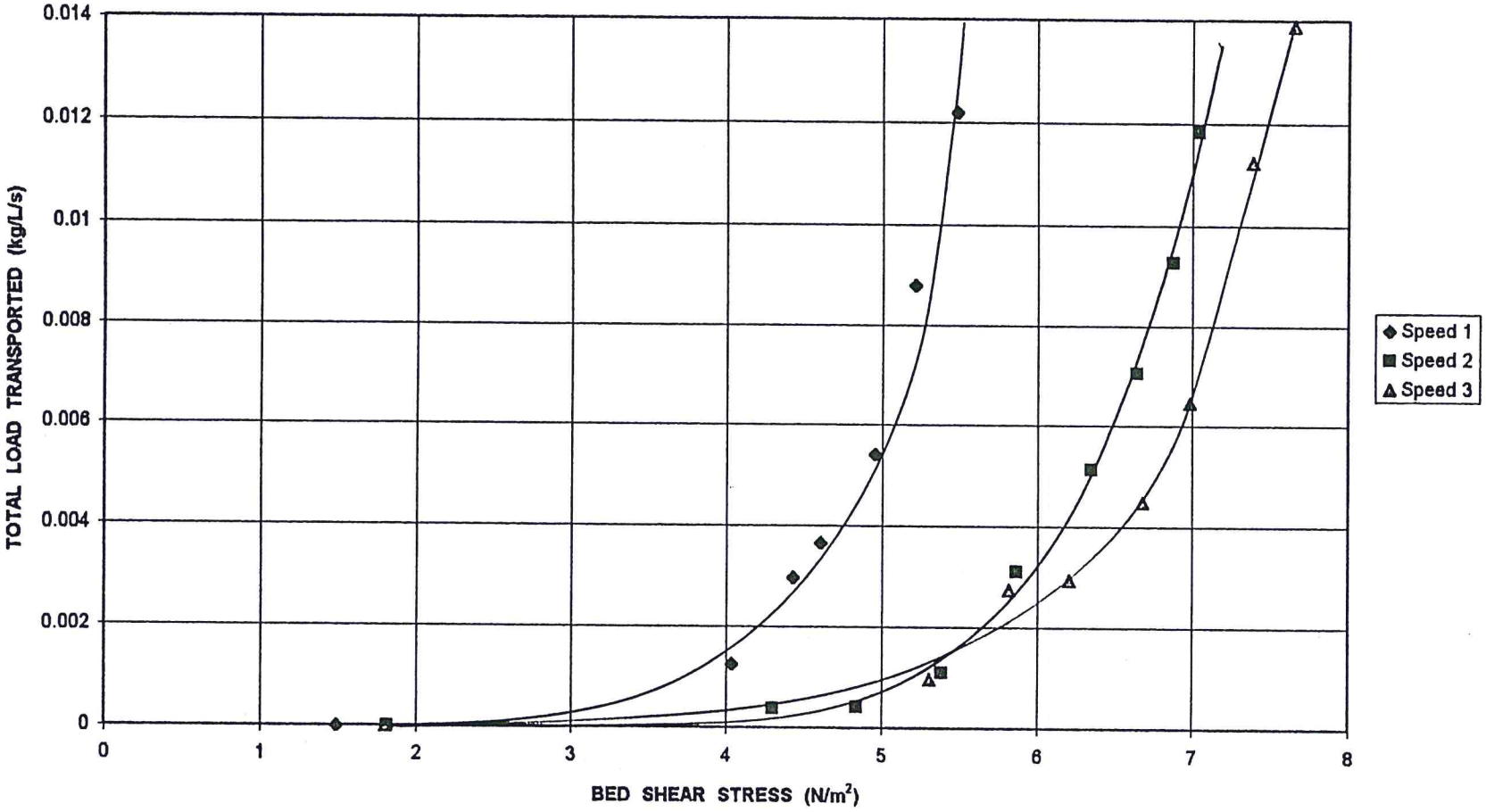
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 1.18 mm



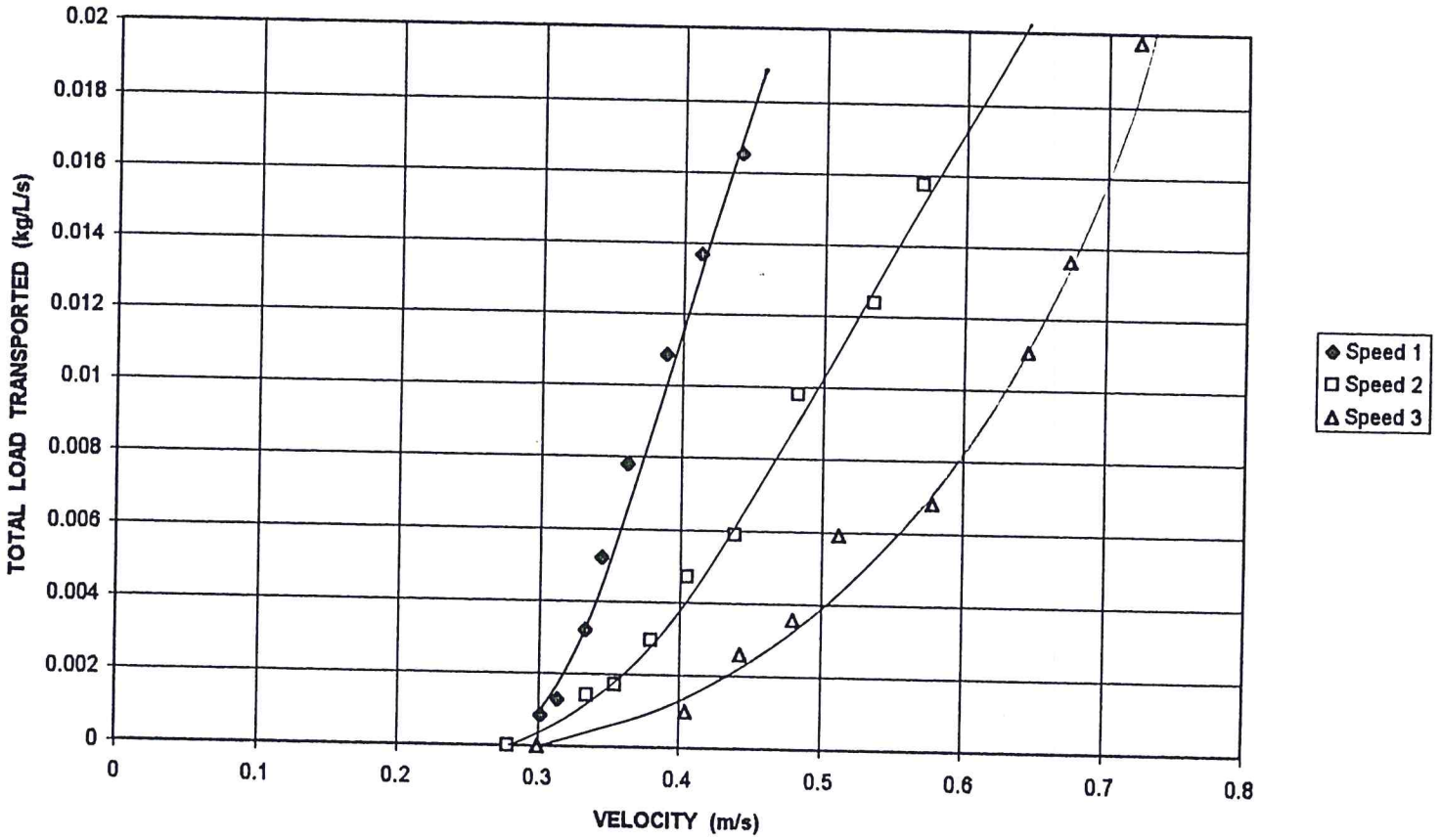
GRAPH SHOWS BED LOAD TRANSPORTED AGAINST VELOCITY FOR PARTICLE SIZE OF 1.18 mm



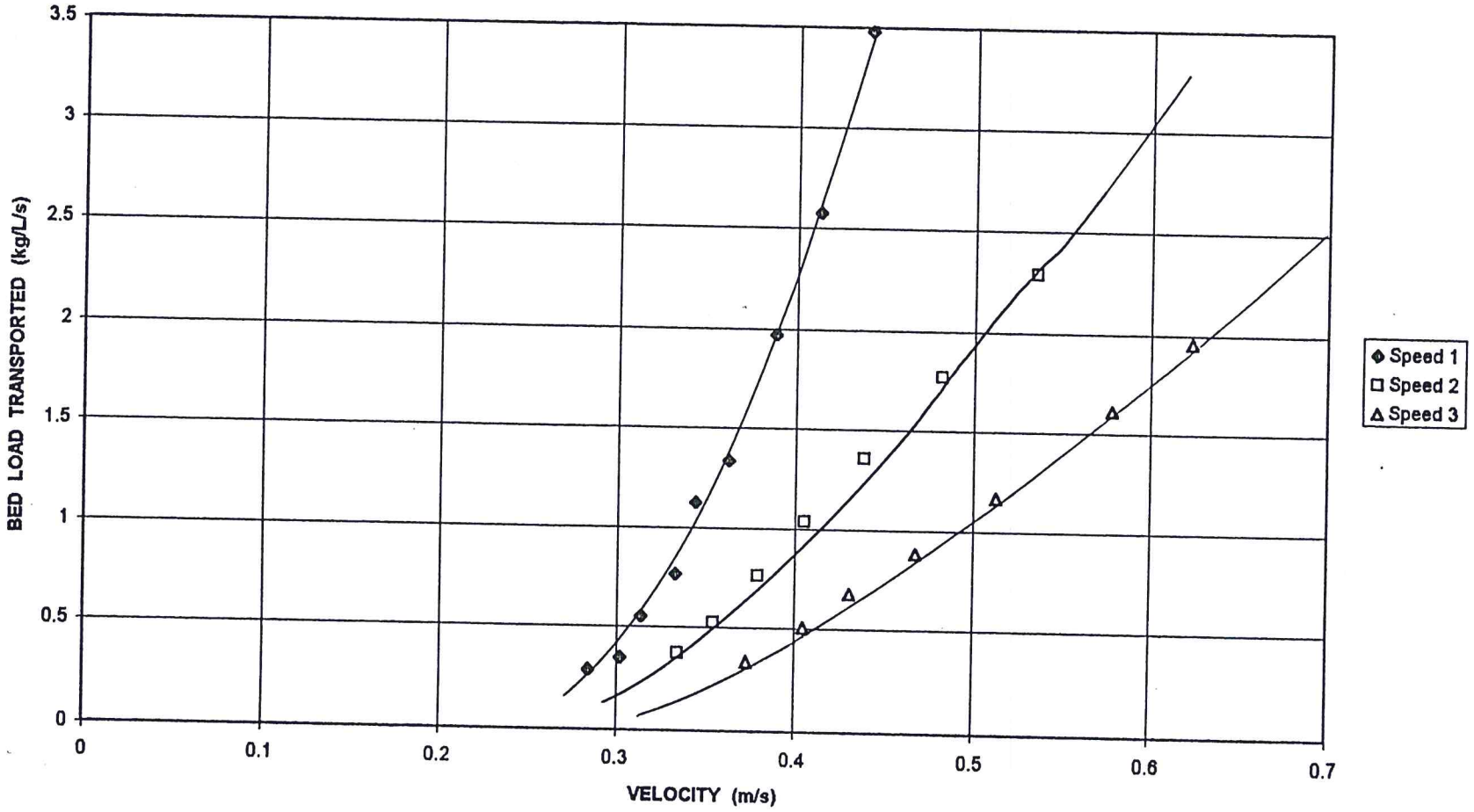
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 1.18 mm



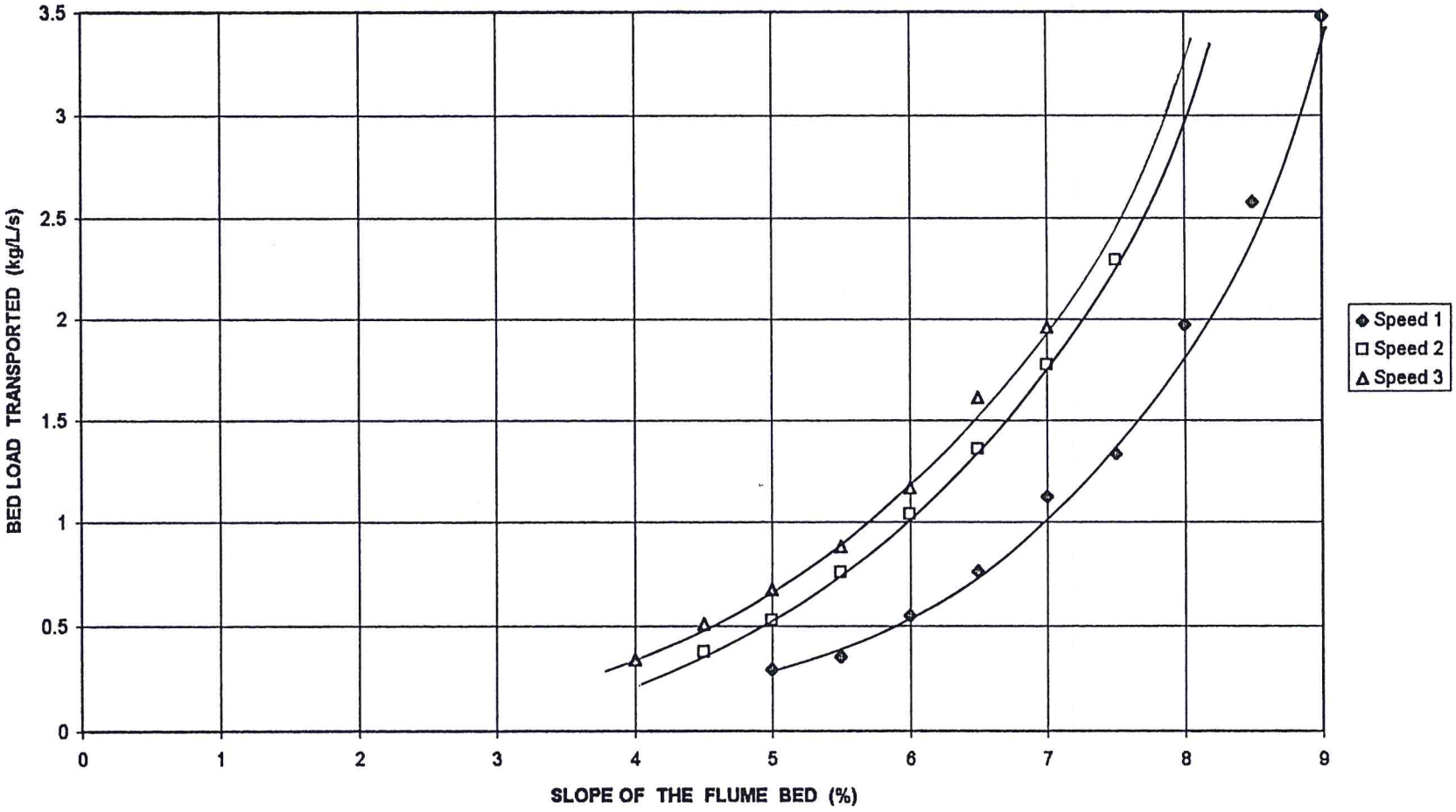
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 1.70 mm



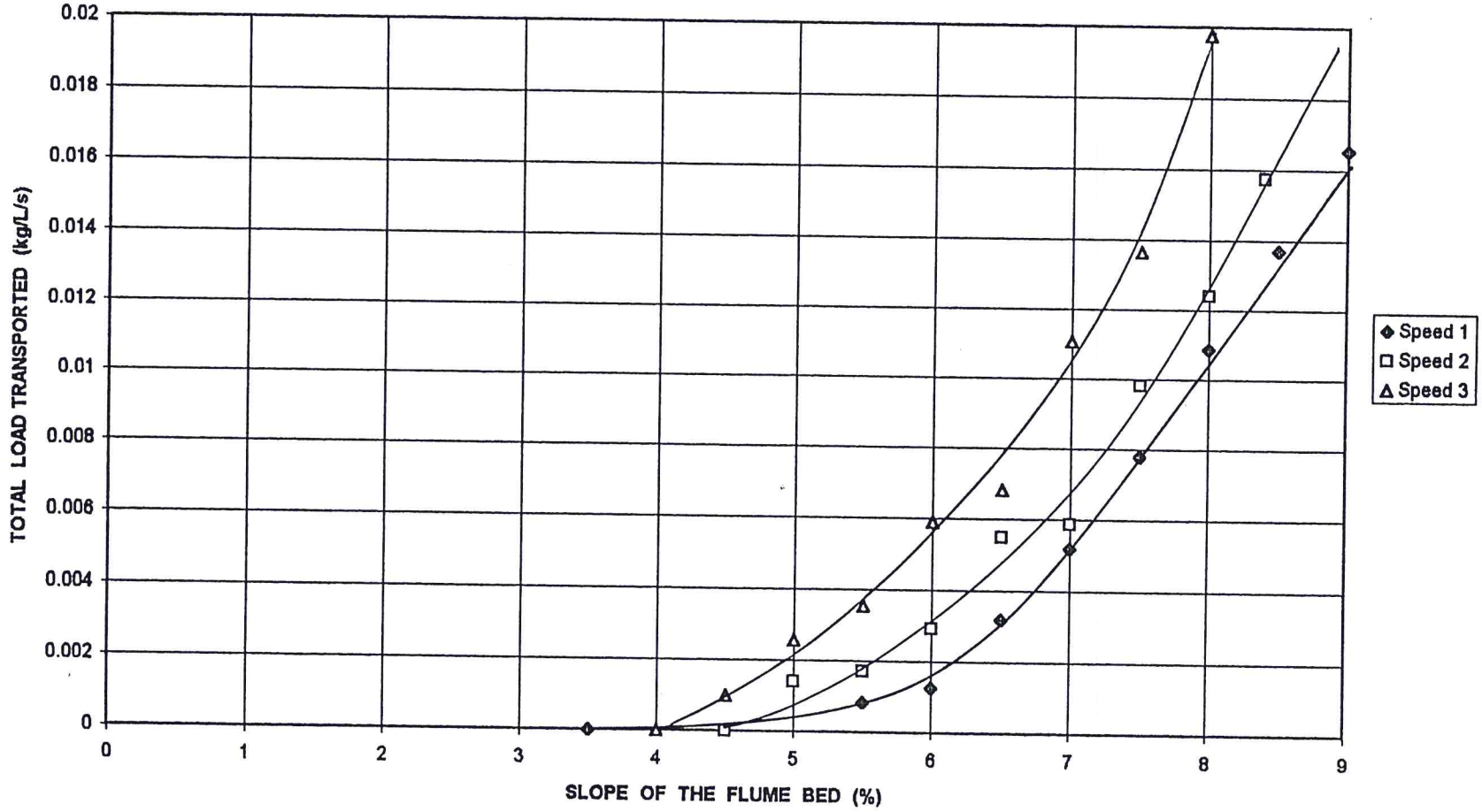
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST VELOCITY FOR PARTICLE SIZE OF 1.70 mm



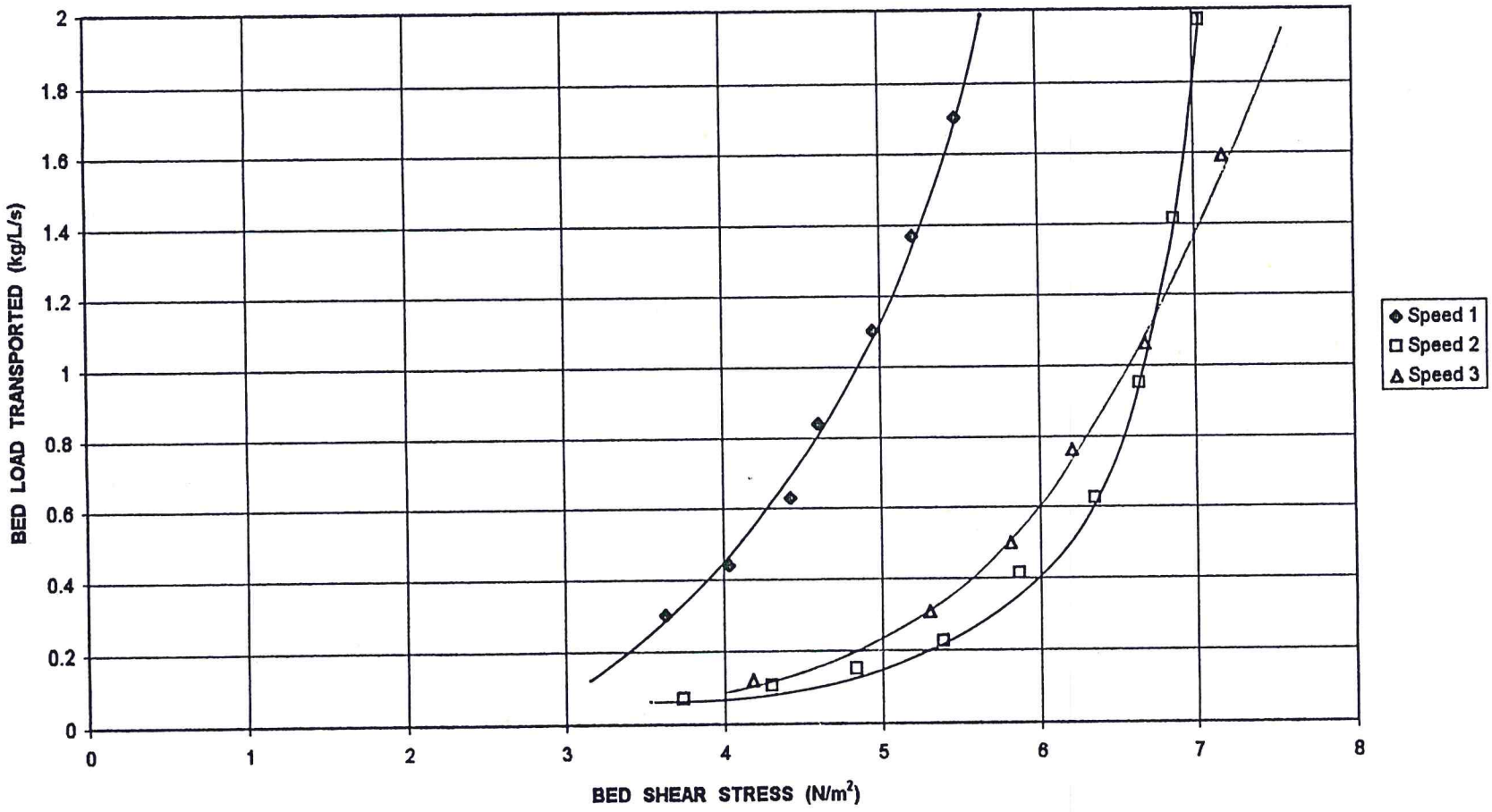
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED FOR PARTICLE SIZE OF 1.70 mm



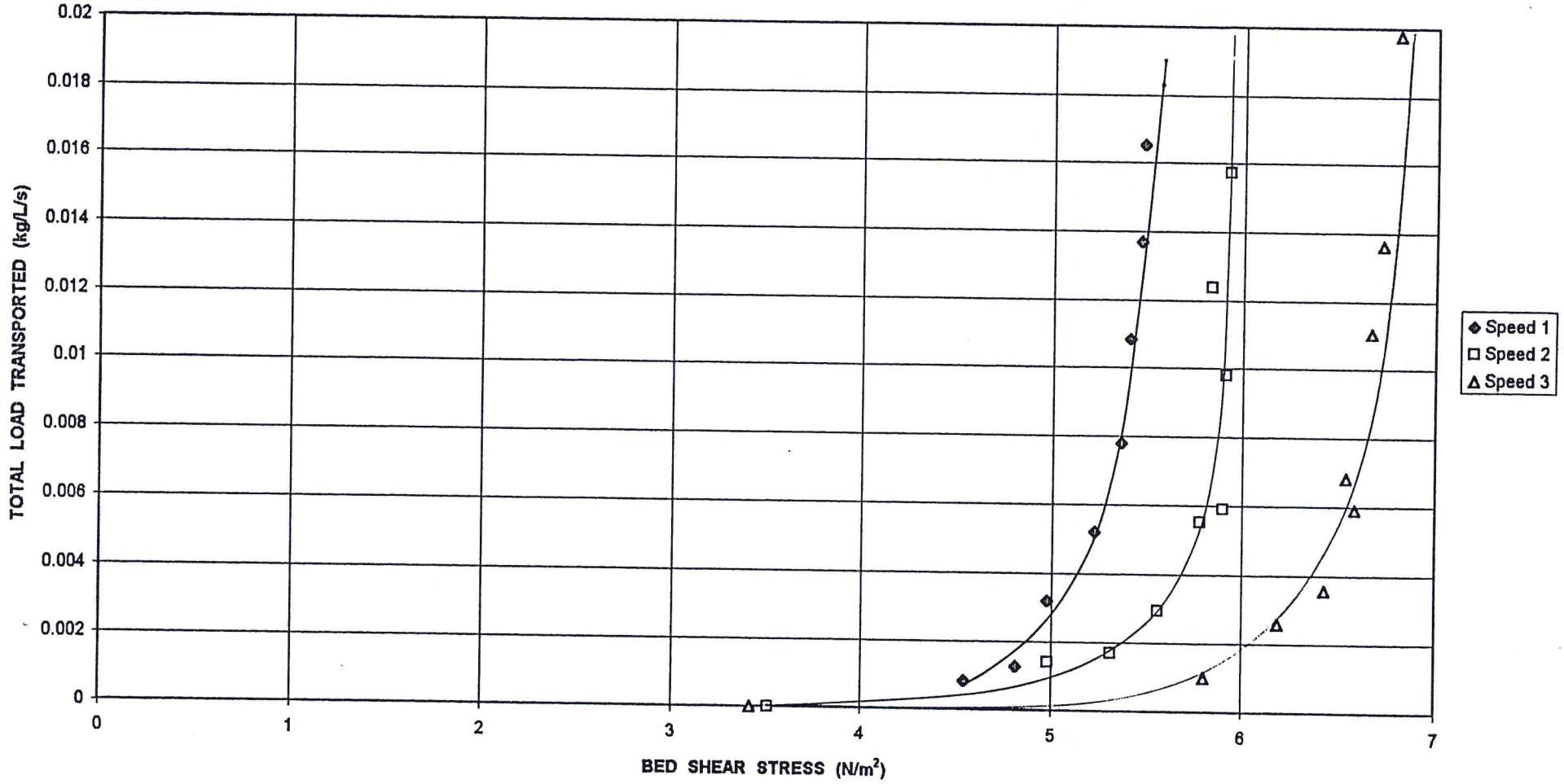
GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST SLOPE OF THE FLUME BED
FOR PARTICLE SIZE OF 1.70 mm



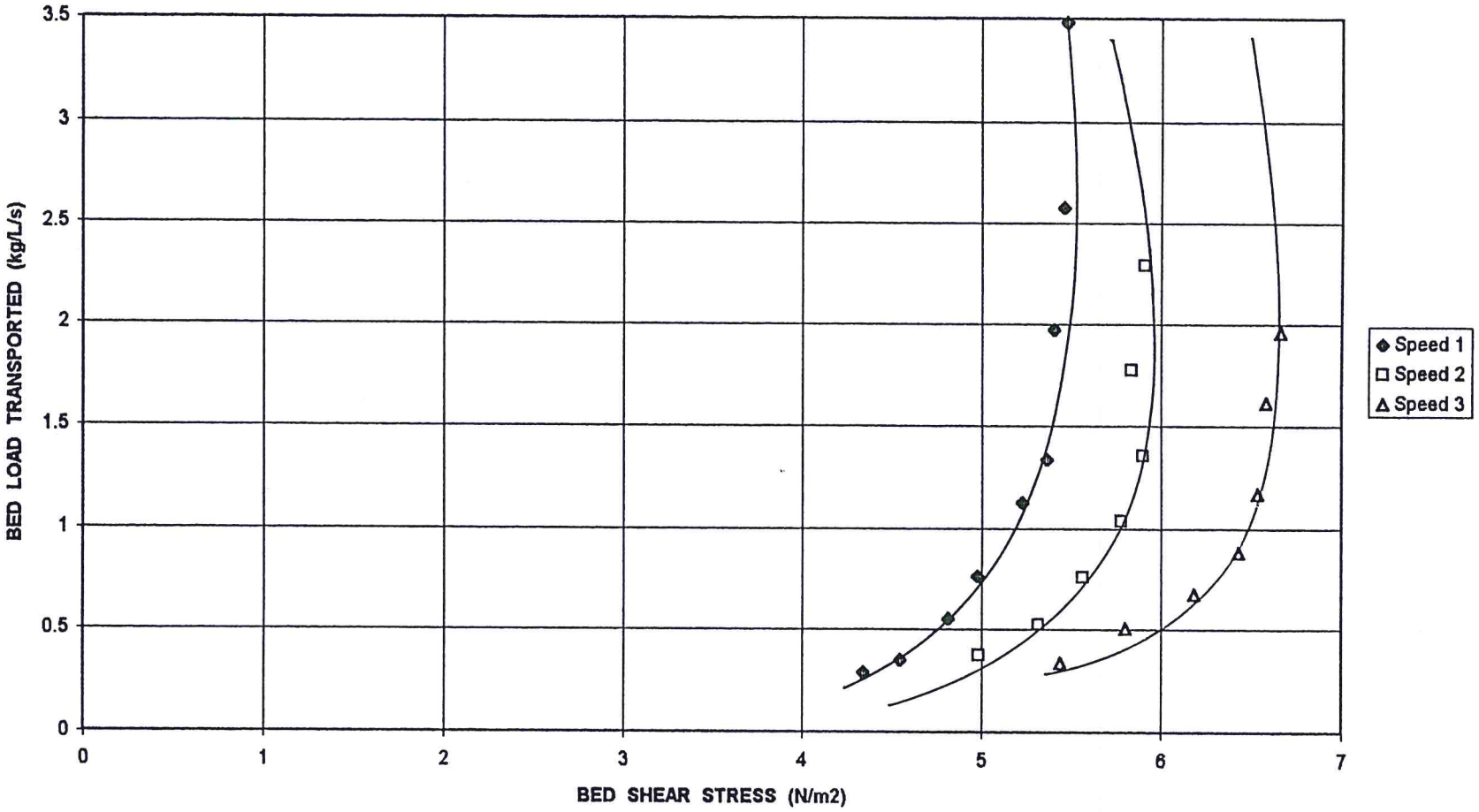
GRAPH SHOWS BED LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 1.18 mm



GRAPH SHOWS TOTAL LOAD TRANSPORTED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 1.70 mm



GRAPH SHOWS BED LOAD TRANSPORED PLOTTED AGAINST BED SHEAR STRESS FOR PARTICLE SIZE OF 1.70 mm



6.5 OBSERVATION AND DISCUSSIONS

[1] It can be seen from the graphs that the amount of sediment material transported (both bed load and total load) increases with an increase of any of the important variables, which are :-

[1] Velocity of flow.
[2] Slope/gradient of the bed.
[3] Bed shear stress.
[4] Discharge.

All these variables are initially related and a change in any one of them will bring about a compensation in another.

As we increase the slope of the flume bed the velocity of the water increases. The velocity of the water flowing in the channel is not uniform. It is usually greater near the center of the channel, away from the frictional drag of the wall and floor.

The velocity of the water was calculated from the equation below.

$$V = Q/wd$$

where V = mean velocity (m/s)

Q = volumetric discharge (m3/s)

w = flume width (m)

d = average depth (m)

Also with an increase in the slope of the flume bed there is also a simultaneous increase in bed shear stress.

The bed shear stress was calculated from the following equation.

$$t = rgRs$$

where t = average shear stress

r = density of water (1000 kg/ m^3)

g = acceleration due to gravity (9.81 m/s^2)

R = hydraulic radius

s = channel slope

and for a rectangular cross section of the flume, the hydraulic radius R is defined as follows.

$$R = wd/ (w + 2d)$$

where w = flume width

d = average depth (m)

With an increase in slope the friction between sediment forming the bed and water increases. Hence capacity of the flow to carry sediment increases.

[2] It can also be noted that, the velocity needed to cause the threshold of motion for the sediment at speed 1, speed 2, speed 3, differs lightly.

This shows that even with ones best effort, it is very difficult to define the threshold of sediment motion with certainty. This problem can be explained further by despite of all the effort of obtaining a flat uniform bed. There could still have some grains protruding slightly in the flow. Thus making it easier for the running water to lift them up from the bed. It could be also that some of the
sediment forming the bed could consist of some lighter minerals, such as mica. Which once more will move at an earlier stage than the rest of the bed materials.

[3] It is also noticed that the amount of sediment collected at the exit and which is considered as "Total Load" consist mainly of materials that are carried by as suspended load. And the bed load consist mainly of material that the stream carries by rolling, sliding and saltation. Therefore the amount of sediment which is considered as bed load has a greater mass.

The curves on the following pages shows the threshold of motion of the different sizes of materials used plotted against:-

[1] Velocity of flow.
[2] Bed shear stress.

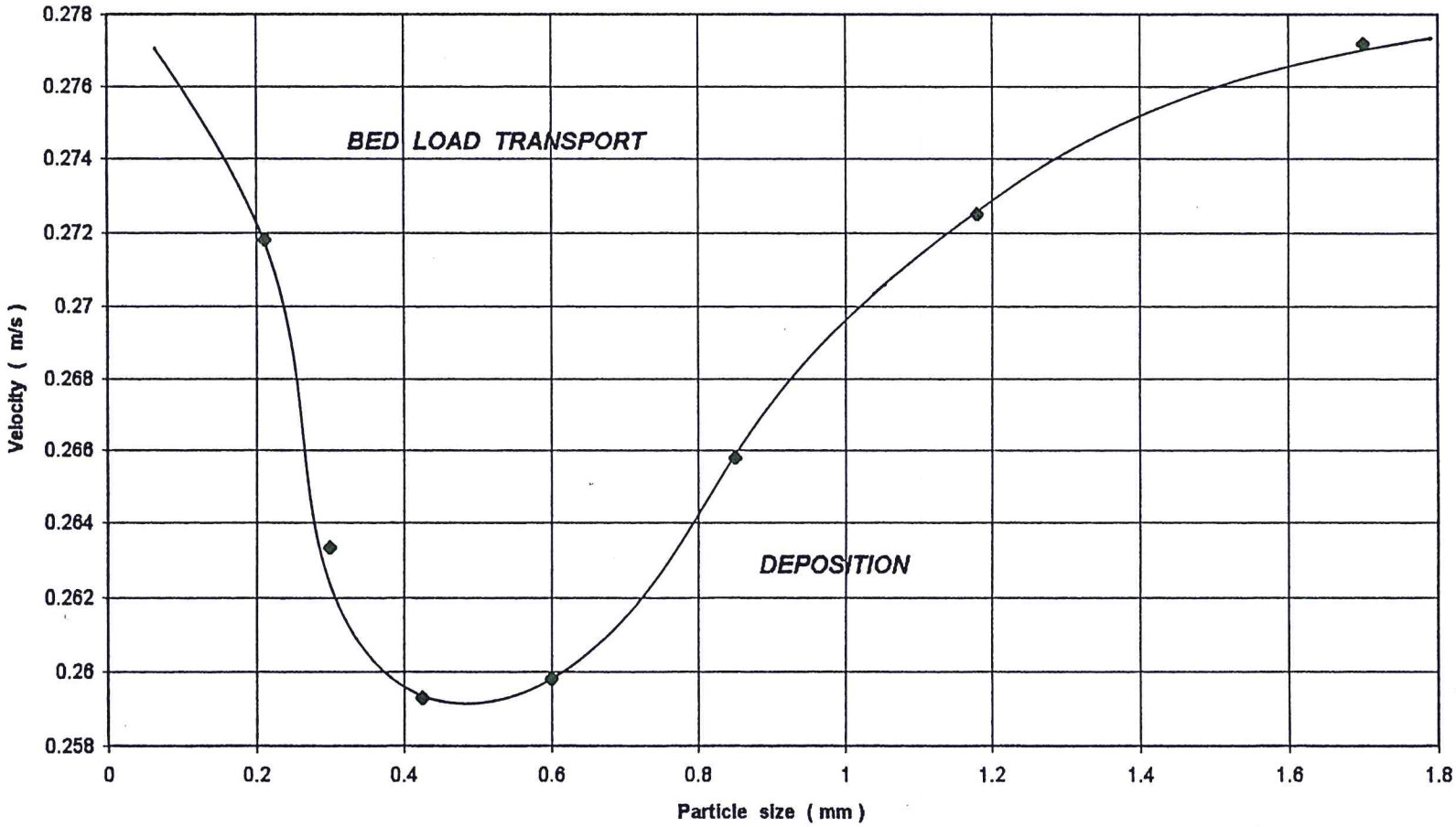
From the graph it is found that the velocity of the water required to move a particle of 0.212 mm diameter is greater than that of 0.300 mm and the latter needs a velocity greater than that of 0.425 mm diameter.

It seems unusually that a particle which is smaller and lighter than a particle of 0.300 mm or even 0.425 mm diameter needs a higher velocity or bed shear stress to be displaced.

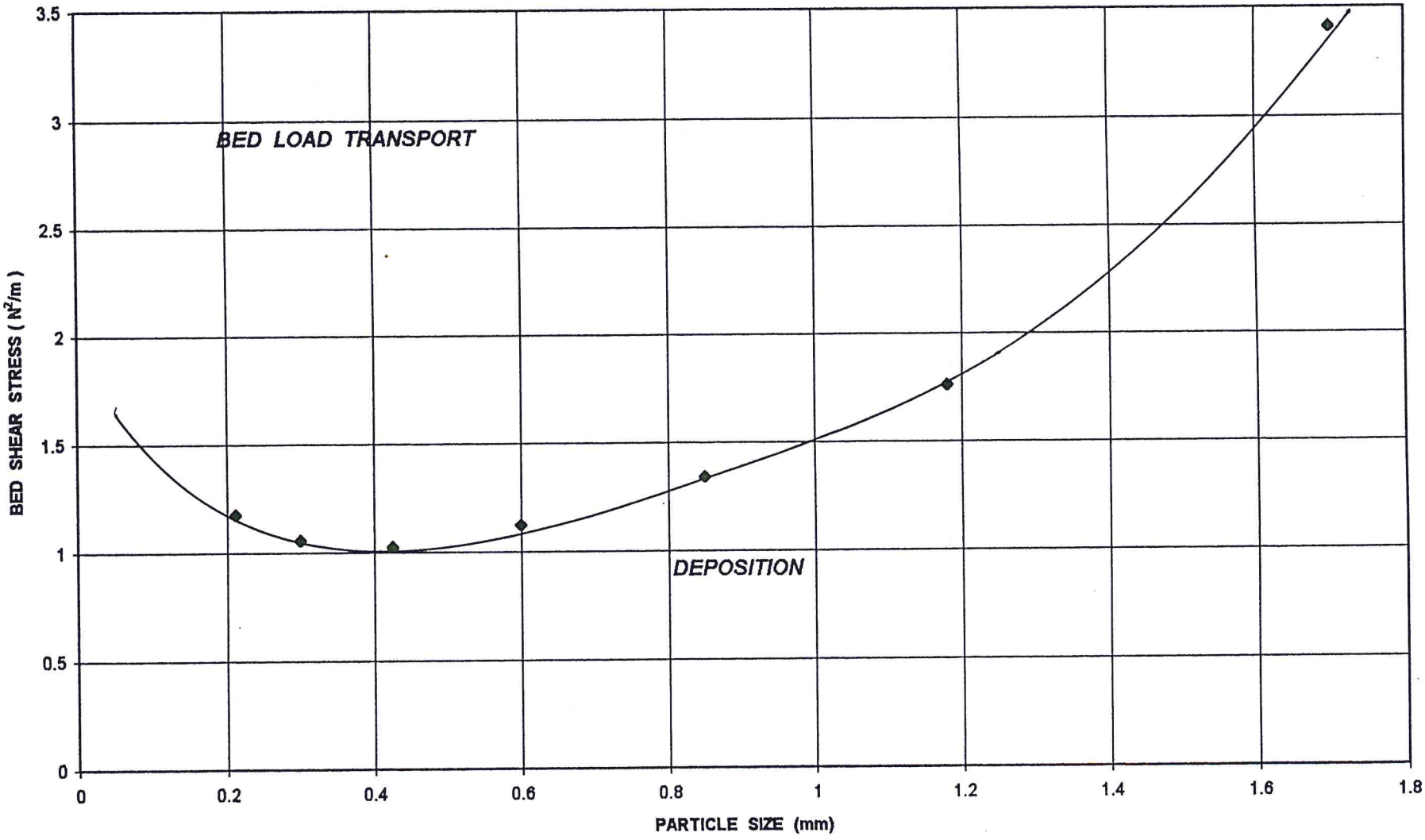
This can be explained as follows:-

The smaller the particle the cohesive force between them increases. Thus clay particles are much more cohesive than sand particles. Thus a greater force should be applied by the water to overcome the cohesive force to bring the bed to motion.

The curve shows the threshold of motion of the different sizes of materials used.

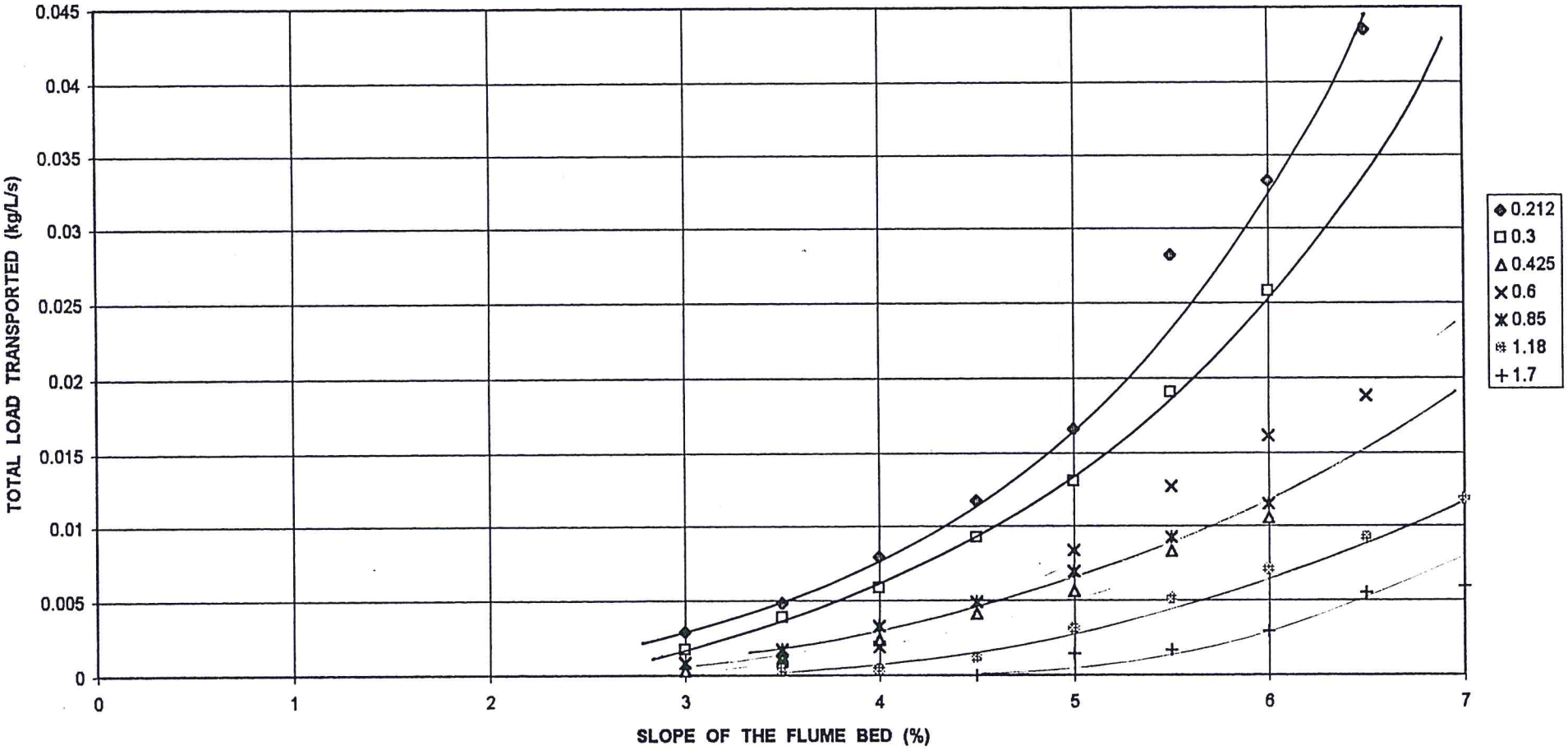


THE CURVE SHOWS THE THRESHOLD OF MOTION OF THE DIFFERENT SIZES OF MATERIALS USED

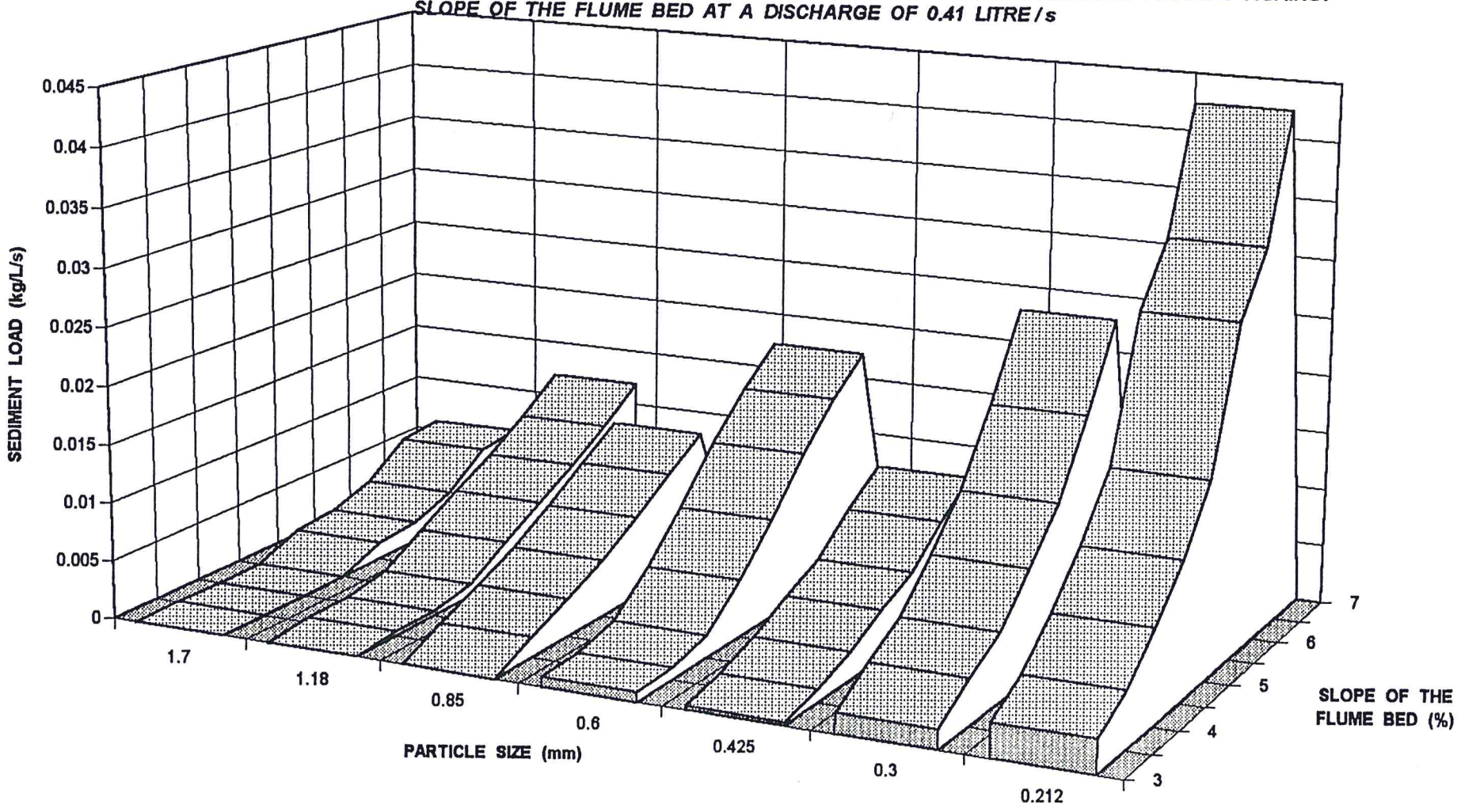


Another way of approaching the problem is that the smaller the particle size the friction due to grain roughness between the sediment and water decreases. Hence a greater velocity and bed shear stress than expected is required to bring the bed to a mobile condition.

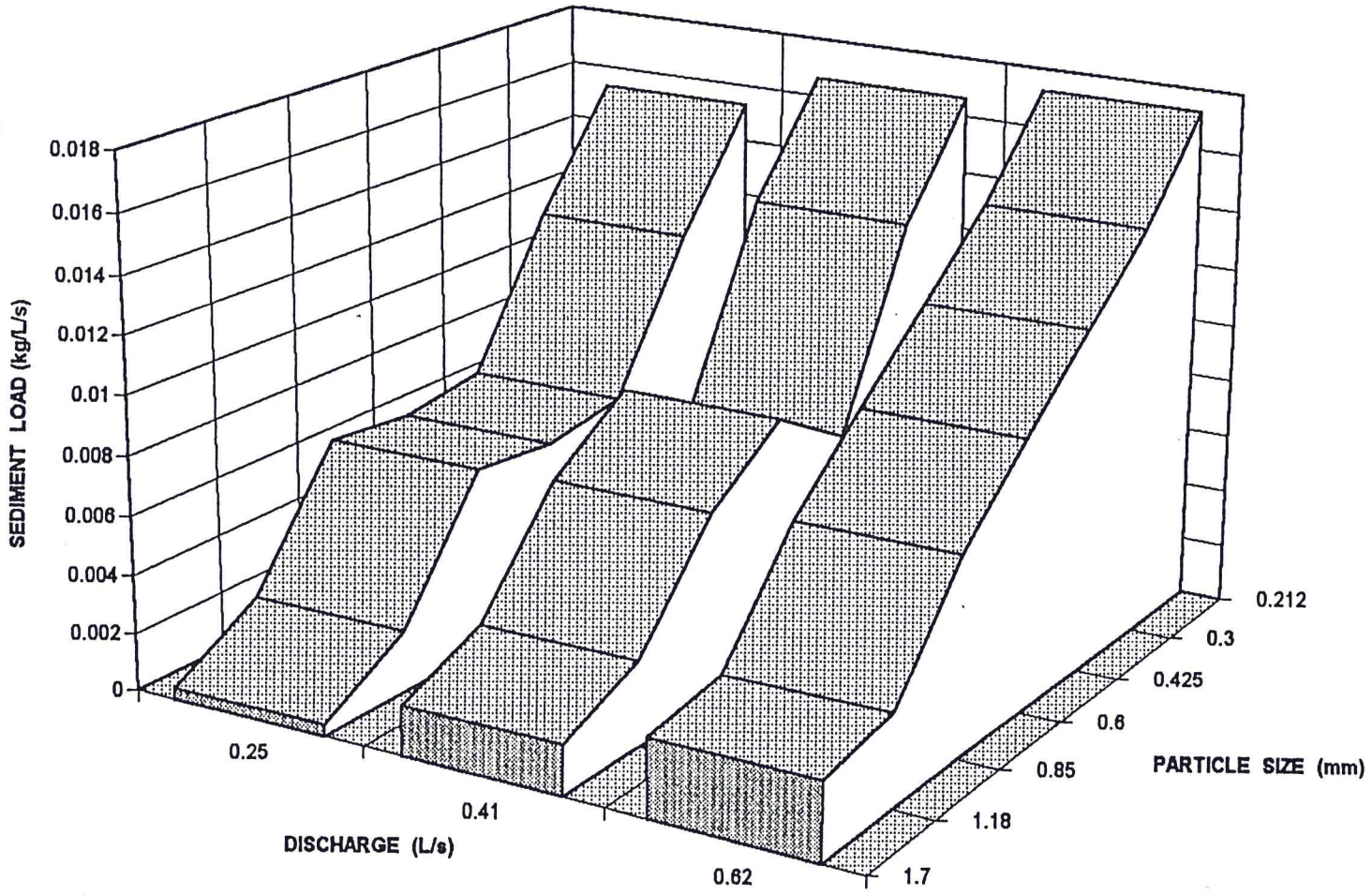
GRAPH SHOWS COMPARISON OF TOTAL LOAD TRANSPORTED OF DIFFERENT SIZES OF SEDIMENT PLOTTED AGAINST SLOPE OF THE FLUME BED AT A FIXED DISCHARGE OF 0.41 LITRES / s



GRAPH SHOWS COMPARISON OF TOTAL LOAD TRANSPORTED OF DIFFERENT SIZE OF PARTICLES PLOTTED AGAINST SLOPE OF THE FLUME BED AT A DISCHARGE OF 0.41 LITRE / s



GRAPH SHOWS COMPARISON OF SEDIMENT LOAD OF DIFFERENT PARTICLE SIZE FOR DIFFERENT DISCHARGES IN THE CHANNEL AT A FIXED SLOPE OF 5 %



CHAPTER 7

SEDIMENT DATA FROM RIVERS

7.1 DATA ANALYSIS

Data has been collected by the Central Water Authority during floods following heavy rainfalls or just after cyclones.

A rigorous analysis would require a direct correlation between rainfall affecting the river flow, the river flow and the sediment load collected. Unfortunately, it is not always easy to collect data in the way it is required to be analysed. In this particular case, it has been found more sensible to relate sediment load to river flow.

As has been mentioned previously, river flow suffers a time lag from the rainfall causing it. In this sense, when there is a heavy rainfall, it causes some soil erosion which is carried to the river. Initially even before the flow has reached its time of concentration, the river may be carrying a substantial sediment load. Later on, when the flow reaches its peak value, the sediment load being carried has subsided. This is, of course, one scenario among many.

The following graphs show, firstly the sediment load being carried by the tributaries of Grand River North West as a function of instantaneous flow. In view of the foregoing, it has been found easier to describe the relationship through a series of minimum and maximum lines, with a few freaks being neglected..

Table 7.1 gives the equation of the minimum and maximum lines.

Table 7.1: Minimum and Maximum Lines for Sediment Load

	Minimum	Maximum
W03	L = 0.408 Q	L = 3.469 Q
W04	L = 0.232 Q	L = 2.032 Q
W05	L = 0.471 Q	L =1.443 Q
W08	L = 1.000 Q	L = 3.600 Q
W10	L = 0.173 Q	L = 1.646 Q
L = sediment load in mg/L		
Q = flow in cfs		

The minimum line shows the minimum sediment load that may be expected in the river as a function of the flow.

The maximum line shows a higher bound value for the sediment load.

It must be emphasised that these sediment loads occur mainly after heavy rains or cyclones. Once the occurrence of heavy rain is over, after some time (a few hours to a few days), though the river flow is still high, there might be no appreciable sediment load in the river. After rain has stopped, river flow will take place through contribution from groundwater flow via the recession curve. This explains why the flow may still be high without any sediment being carried.

The above figures are therefore to be treated in this light.

During an actual flood, these lines will give an indication of what may be carried in the river. Integrating the values over time, will give an estimate of what load is being carried by the river.

Estimates made by the Central Water Authority give values of 20 tons/yr/km^2 for Grand River North West and 9-23 tons/yr/km^2 for River La Chaux.

7.2 SEDIMENT DEPOSITS AT CANAL DAYOT

The St. Louis River has a length of about 8 km. and runs through the village of Canal Dayot before exiting in the sea. Given the sea level with respect to the water level in the river, the sea acts as a huge sedimentation pond for this river. The St. Louis river has a catchment area of 13.7 km^2.

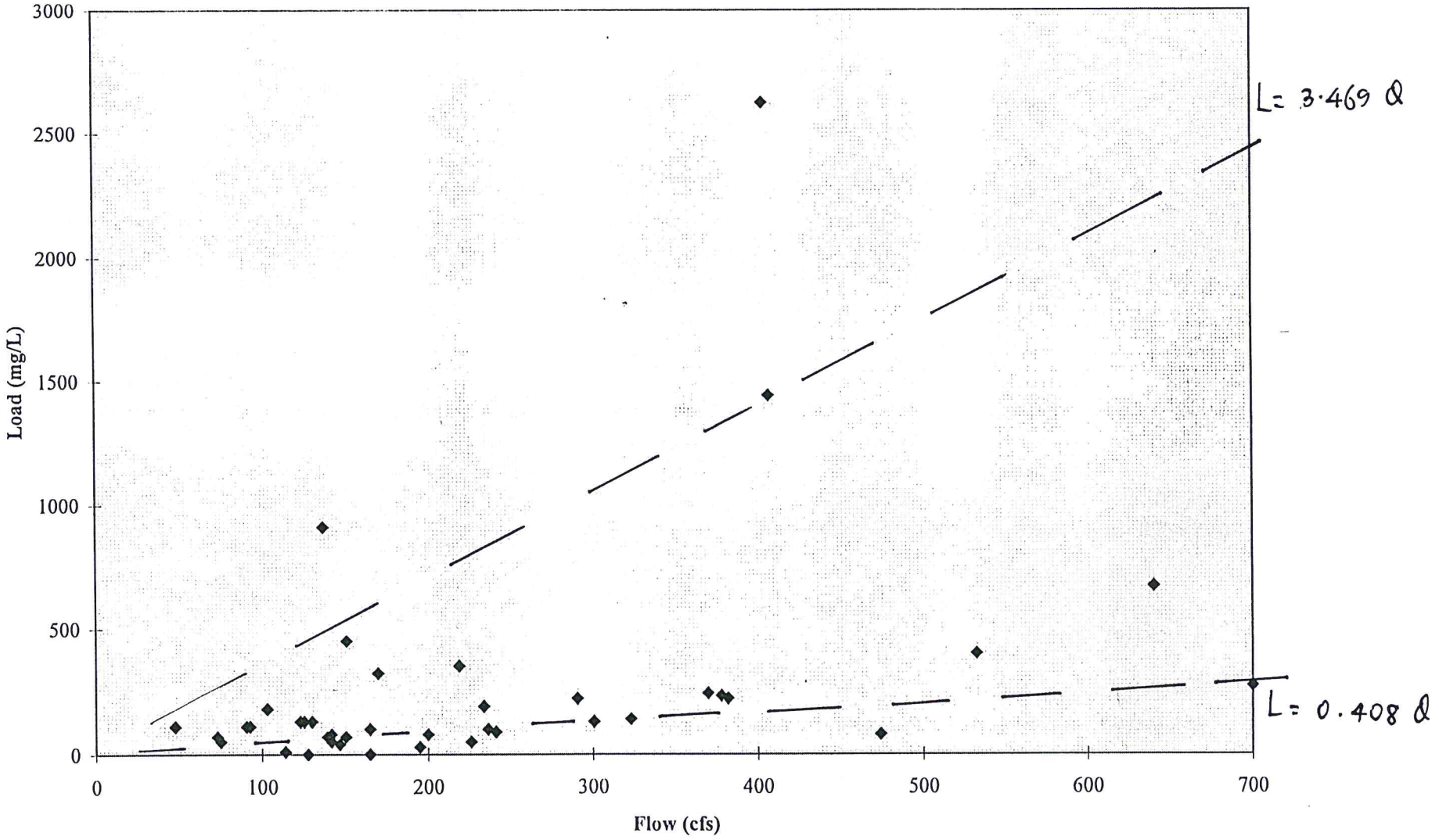
Recently, the confluence of the St. Louis river was dredged as a huge soil/mud deposit had been formed and was alleged to be blocking the flow in the river during heavy rains. Some 8000 tons of material have been dredged.

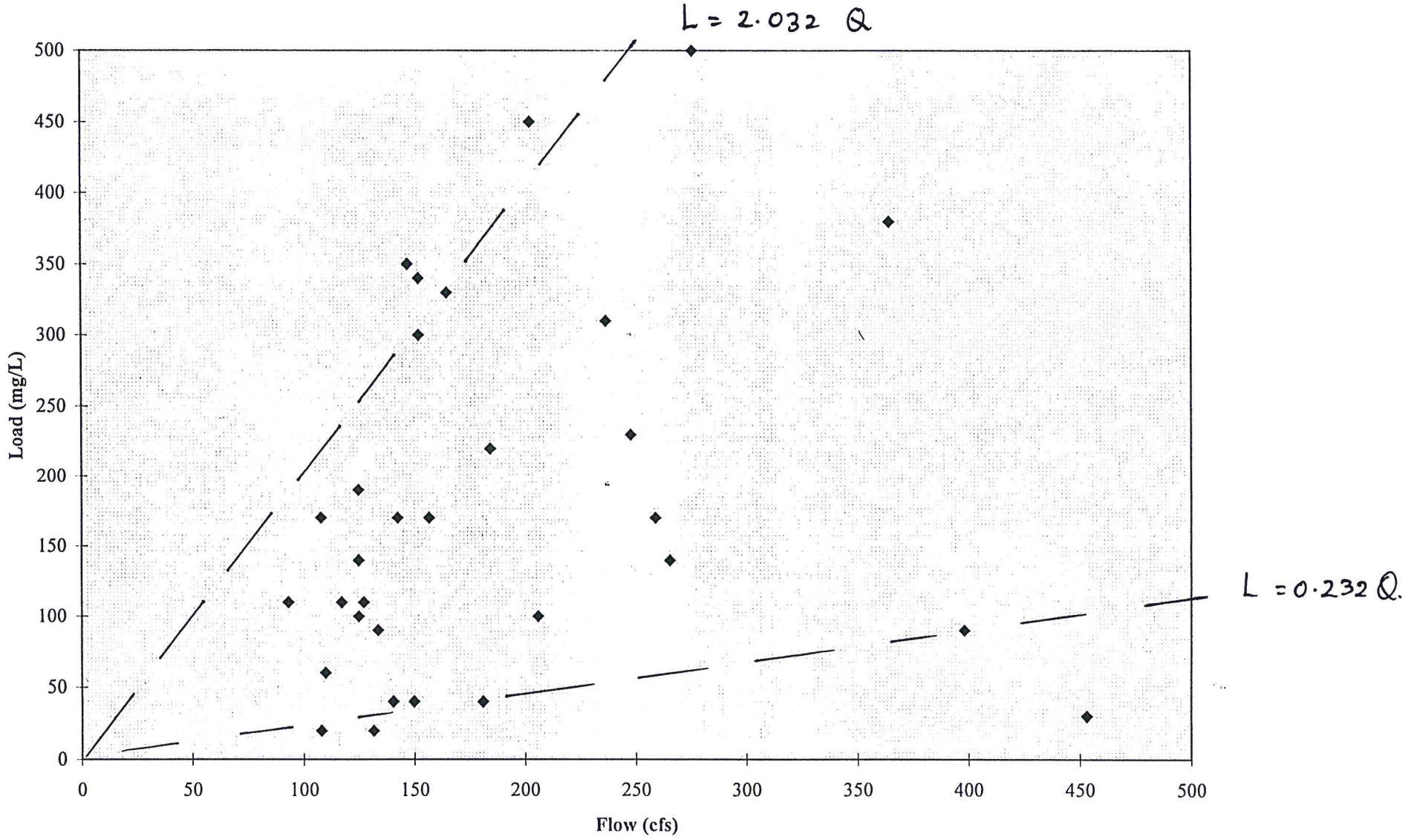
It is appropriate to note that the St. Louis bridge was built in the early 70's, just upstream of this soil/mud deposit. Assuming therefore that this soil deposit of 8000 tons took some 27 years to form (1970 - 1997), this works out to a figure of 21.6 tons/yr/km^2. This is a figure to be compared with the figures from the CWA. Of course, if it was being formed since a longer time, the sediment load would be a lower figure.

7.3 ANNUAL SEDIMENT LOAD

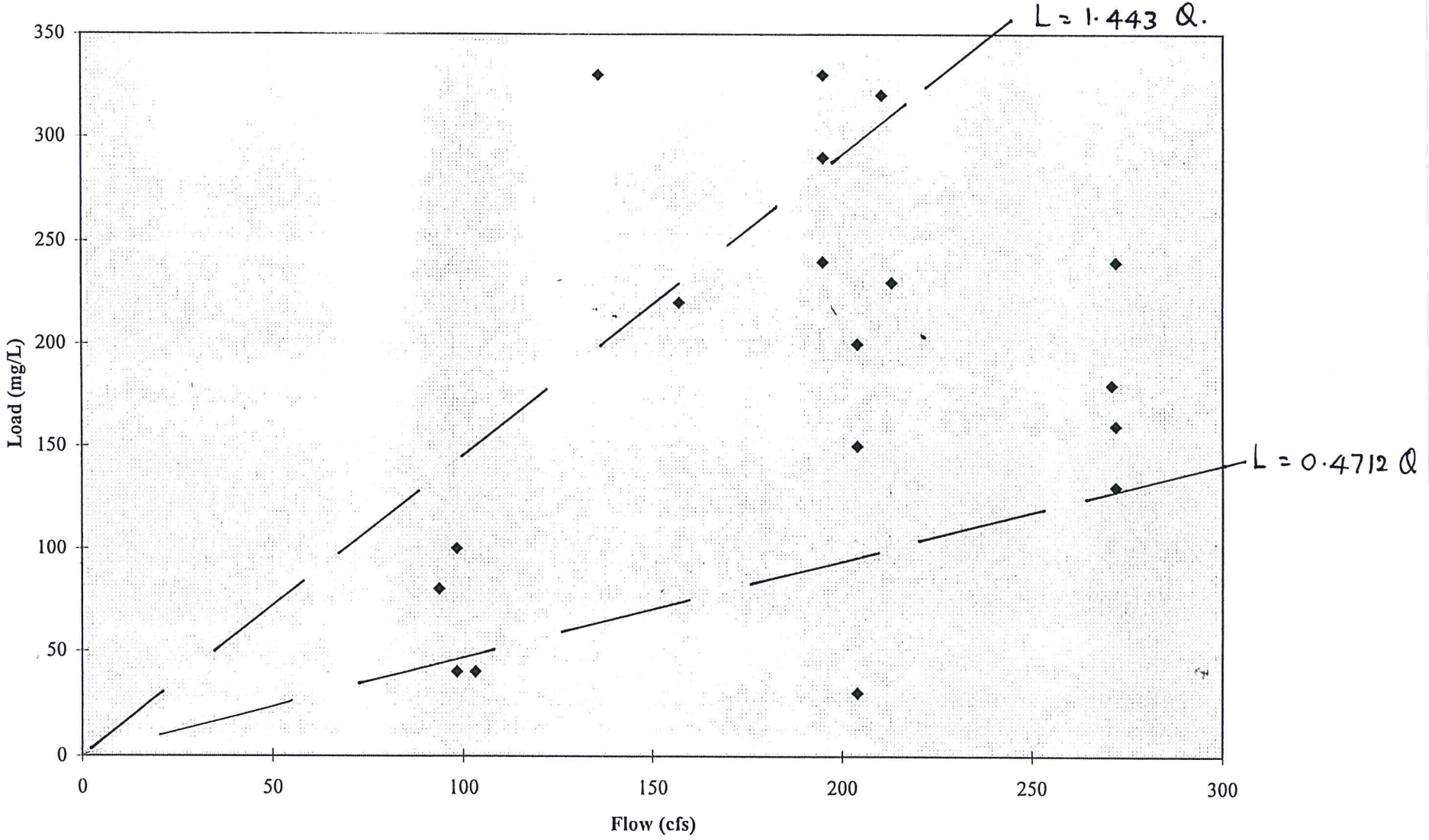
The above would there give an indication of a sediment load of the order of 20 tons/yr/km^2 of catchment.

Sediment load on River P. Wilhems W03

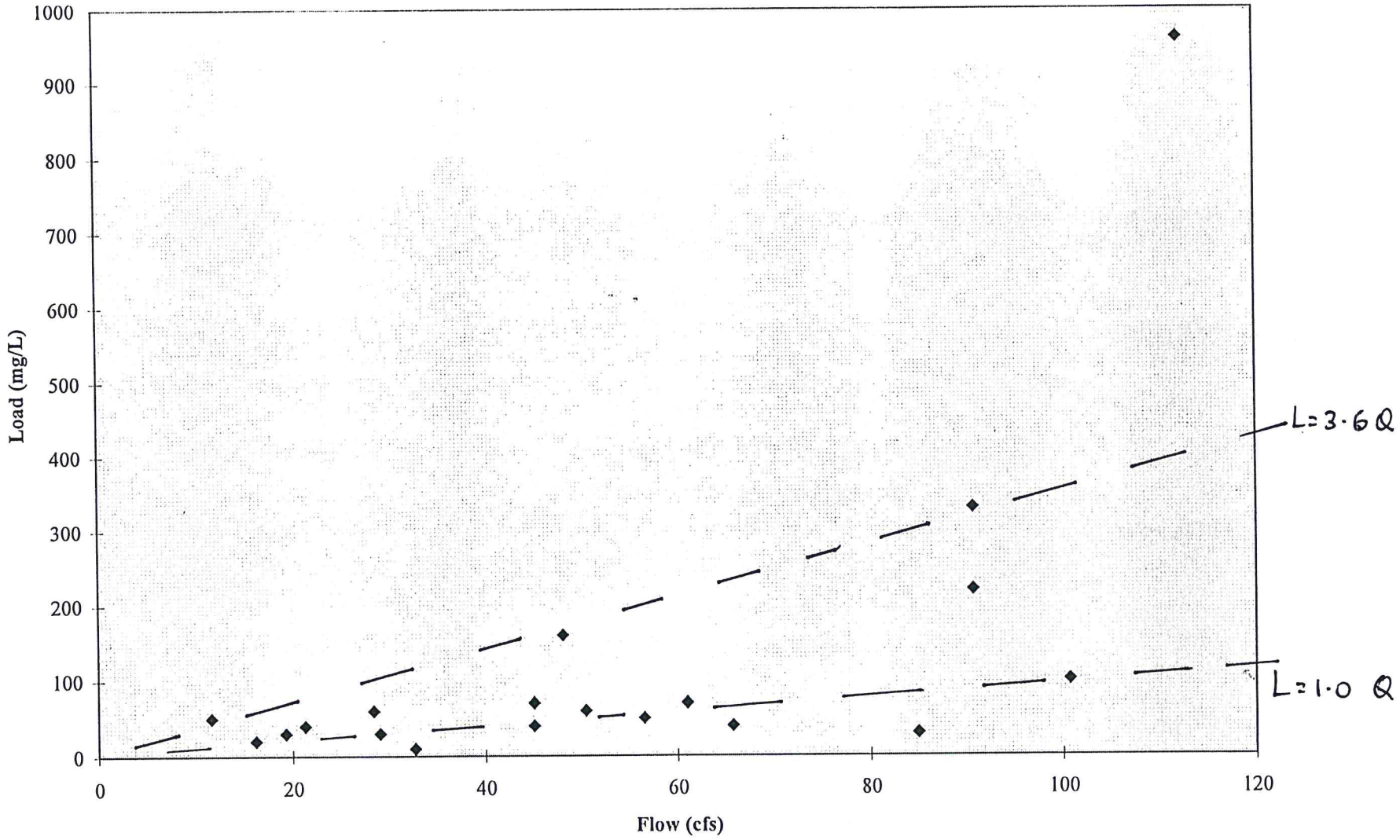


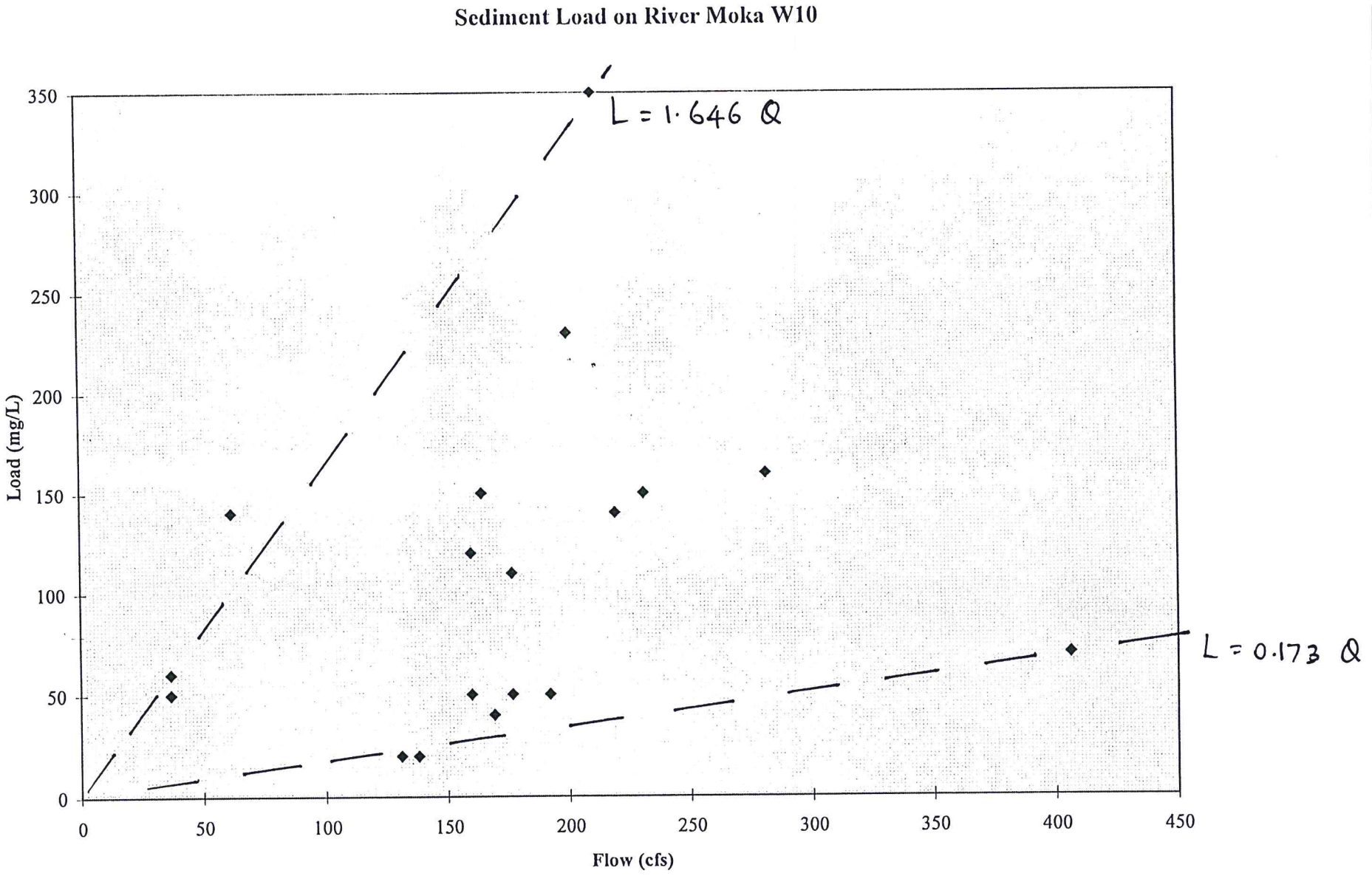

Sediment Load on River Terre Rouge W04
L = 2.032 Q
L = 0.232 Q.
Load (mg/L)
Flow (cfs)
0
50
100
150
200
250
300
350
400
450
500

Sediment Load on River Cascade W05

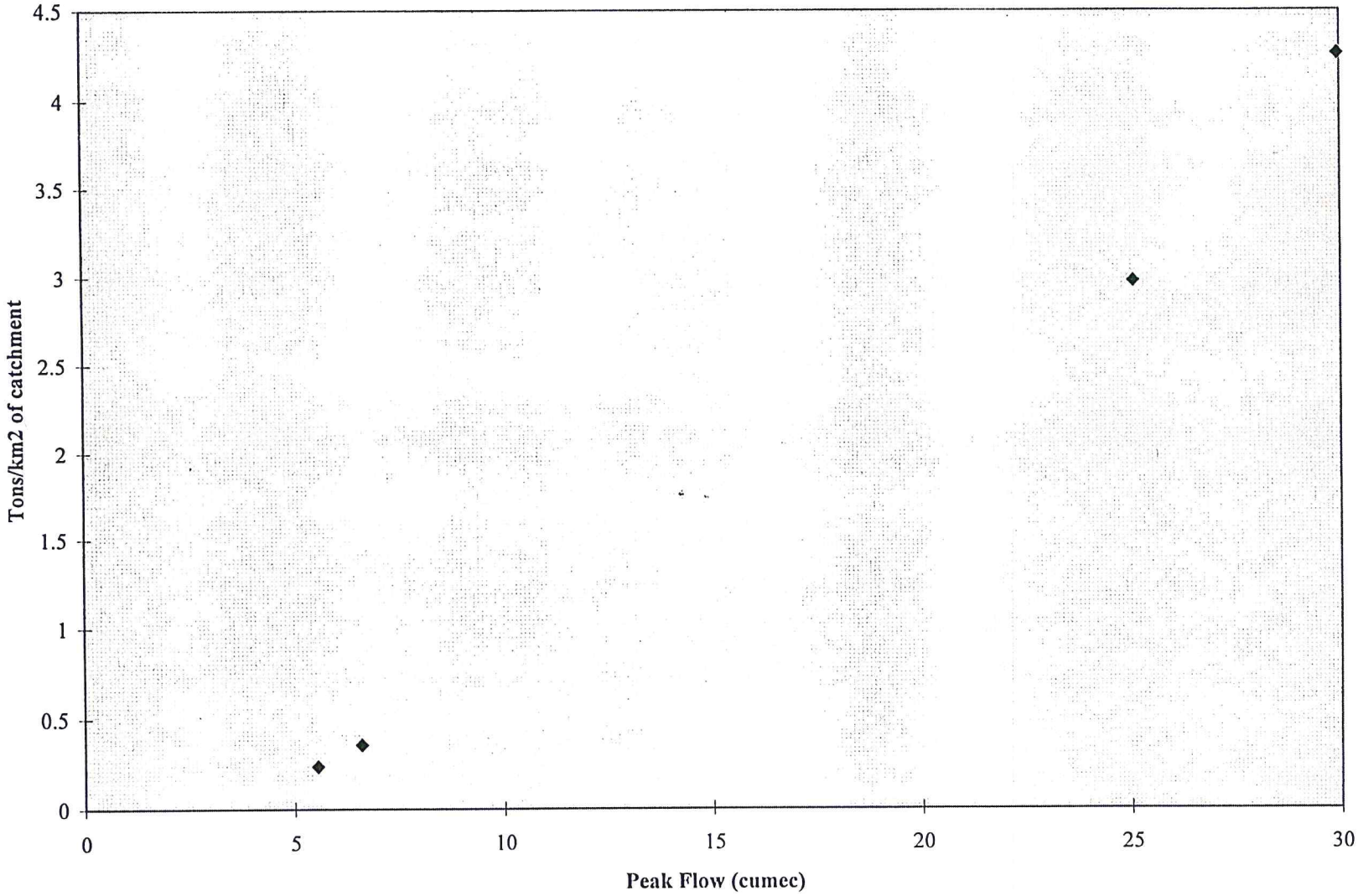


Sediment Load on River Profonde W08

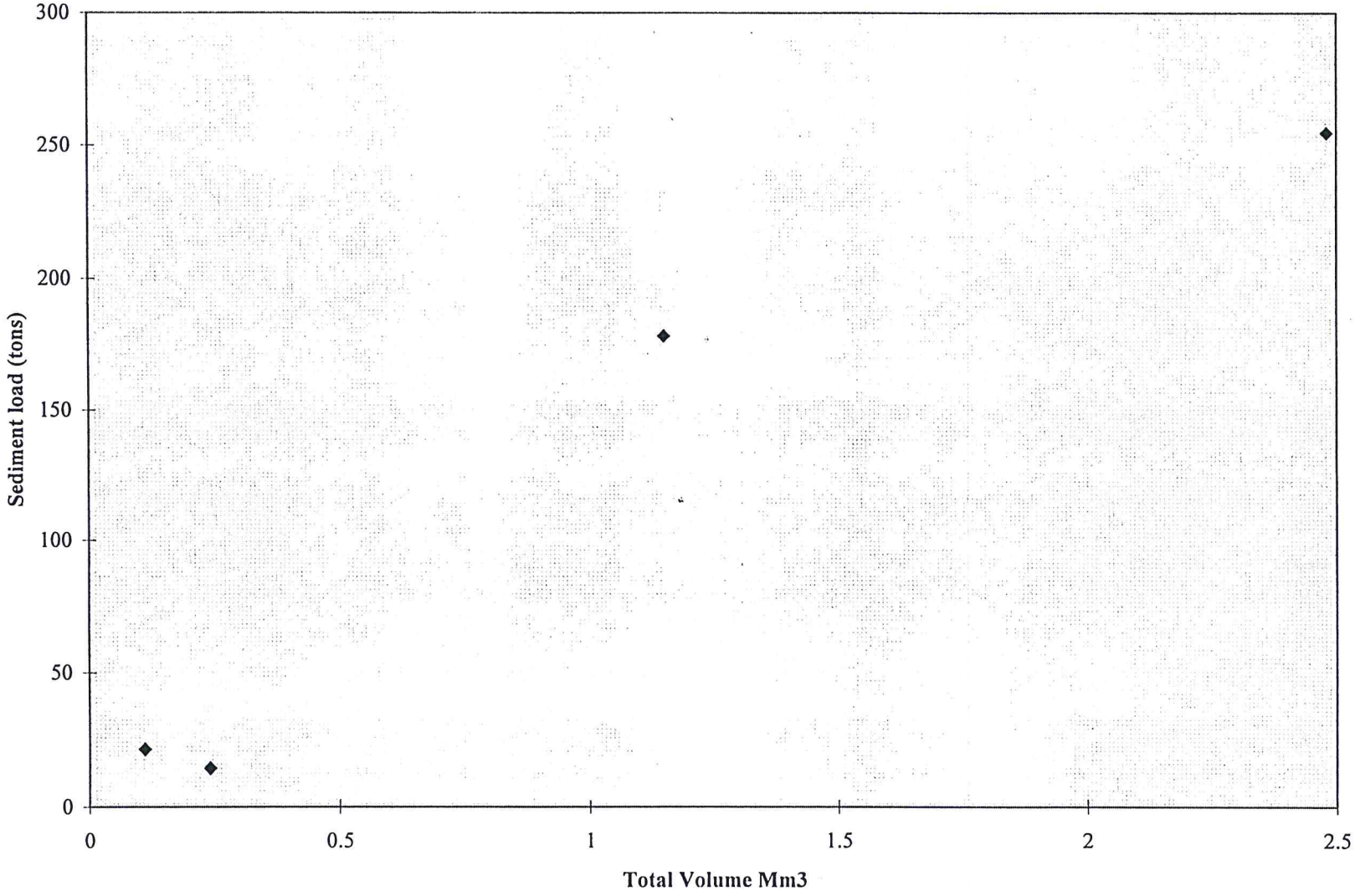



Sediment Load on River Moka W10
L = 1·646 Q
L = 0·173 Q
Load (mg/L)
Flow (cfs)
0
50
100
150
200
250
300
350
400
450

Sediment load on River La Chaux at Beau Vallon



Sediment Load on River La Chaux at Beau Vallon



CHAPTER 8

DISCUSSION

The experimental channel work carried out gives results which are comparable to those obtained by other people in other countries.

As regards actual evidence of sedimentation data, the situation is different. Reference to Fig. 3.11 (curve III, P > 600 mm) would indicate that for a ratio of $p^2/P = 40$, the sediment yield should exceed a figure of 1580 tons/yr/km^2. A high figure indeed.

Such a figure might not be unrealistic. Apparently in Java, figures of the order of 2600 tons/yr/km^2 have been recorded. This was brought to light during the investigation on Midlands dam.

It has been seen in the previous chapter that the Mauritian figure would tend to be of the order of 20 tons/yr/km^2.

Which figure to believe is a question which would of order.

During the repairs effected on Eau Bleue reservoir during the period 1991-1993, the reservoir was emptied and it was possible to go inside the reservoir bed and observe actual sedimentation. In many places, there was none, while at the deepest portions, the sediment consisting of very fine soil deposits was between 100-150 mm thick. Just upstream of the reservoir, where the river is gauged, the catchment area is 30.87 km^2. As the reservoir was constructed in 1962, this works out to a sediment load of around 60-120 tons/yr/km^2.

Both the estimates of 20 and 60-120 tons/yr/km^2 are lower than figures recorded elsewhere or in the literature. It must be agreed, however, that these are estimates made from actual measurements in Mauritius.

These low values of sedimentation, however, are borne out from deposits observed in other reservoirs, namely La Ferme, Mare Longue, Piton du Milieu and Mare aux Vacoas. These have not been quantified, but they are low, in fact much lower than would have been expected from world figures.

There may be very many varied explanations for this low sedimentation rate. Suffice it to retain that the sedimentation rate in Mauritius is of the order of 20-120 tons/yr/km^2.

This is a wide range, but clearly indicates lower bound and higher bound values.

BIBLIOGRAPHY

Basson M.S., Allen R.B., Pegram G.G.S., Van Rooyen J.A., 1994, *Probabilistic Management of Water Resource and Hydropower Systems*, Water Resources Publications, 424 p.

Morgan R.P.C., 1986. *Soil Erosion and Conservation*, Longman, 298 p.

Padya B.M., 1984. *The Climate of Mauritius*, Government Printing, 217 p.

Padya B.M., 1989. *Weather and Climate of Mauritius*, Mahatma Gandhi Institute, 283 p.

Pereira H.C., 1973. *Land use and Water Resources in Temperate and Tropical Climates*, Cambridge University Press, 246 p.

Schumm S.A., Harvey M.D., and Watson C.C. , 1988. *Incised Channels*, Water Resources Publications, 200 p.

Simpson F.S.W., 1951. *The Geology and Mineral Resources of Mauritius*, Colonial Geology and Mineral Resources, London Vol. 1, 1951, pp217-230.

Singh V. P., 1982. *Statistical Analysis of Rainfall and Runoff*, Water Resources Publications, 700 p.

Sok Appadu, 1988. *Torrential Water Rains*, Meteorological Services, 17 p.

Stelczer K., 1981. *Bed load Transport*, Water Resources Publications, 295 p.

White W.R., 1987. *Topics in Fluvial Hydraulics*, Water Resources Publications, 385 p.

Yen B.C., 1992. *Catchment Runoff and Rational Formula*, Water Resources Publications, 170 p.

Zavoianu I., 1985. *Morphometry of Drainage Basins*, Elsevier, 238p.