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# FLOODS IN EPHEMERAL STREAMS : EVALUATION BASED ON GEOMORPHOLOGY

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## FINAL SCIENTIFIC REPORT

*Principal Investigator:*
Asher P. Schick
Department of Physical Geography
Institute of Earth Science
The Hebrew University of Jerusalem
Jerusalem, Israel, 91904

*Co-Principal Investigator :*
Paul A. Shaw
Depatment of Environmental Science
University of Botswana
Gaborone
Bostwana

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# 1 - INTRODUCTION

The project work described and summarized in this report is based mainly on the combination of two approaches: conventional flood surveying and evaluation on the one hand, and the application of indirect techniques of process geomorphology on the other.

Originally the project was approved for a period of three years. The very first year happened to be one of the most devastating flood seasons ever recorded in Botswana. In the Metsemotlhaba River -- the main project site -- these floods completely destroyed the instrumental setup. Attempts made to reactivate the hydrometric monitoring systems at both ends of the study reach proved only partly successful, mainly because of logistical reasons.

As for the geomorphic part of the work, it was found, after an extensive effort of fieldwork, that a large proportion of the tracer sediment could be recovered, despite unexpectedly great longitudinal as well as vertical dispersion. Data from repeated benchmark-based river cross sections also proved revealing. To a lesser extent the chain sections were found useful, since a majority of them were totally uprooted and not found. The depth of scour simply exceeded all expectations which were based on the aggregate experience and accepted norms for the Botswana sand streams. Already at that early stage of the project, it became clear that the previously prevalent estimate that there is only little sand movement during flows in the sand rivers is untenable. The data proved that very large volumes of sand are transported, that depths of scour approach (and sometimes exceed), one meter, and that particles 2-4 phi units larger than the channel bed sand move hundreds of meters in large floods.

The occurrence of a high-magnitude low-frequency event at the very beginning of the project series of observed events posed a problem with regard to establishing a functional relationship between sediment tracer dispersion and water discharge characteristics. It was hoped, at the end of project season 1, that future events would elucidate the utility of this concept in reconstructing past flow attributes from tracer data. However, the following two seasons have produced only minor flows, and it was only towards the very end (March 1991) of the one-year no-funding extension granted to the project that another major flood occurred. This flood was, similarly to the 1987 flood event, a very high-magnitude event with great structural and economic repercussions in many parts of Botswana. In the Metsemotlhaba River some of its effects exceeded those of the 1987 event and produced a very valuable set of directly comparable geomorphic data.

The auxiliary research sites on the Bonwapitse and Taupye rivers were attended to, especially with regard to tracing -- though in much smaller doses -- during the first two years of the project. As work progressed and the complications of the sediment conveyance systems of the sand rivers became clear, the annual monitoring of these sites was discontinued.

The schedule of the main field operations at the Metsemotlhaba Research Site in relation to the main flow events which occurred during the four flood seasons studied is summarized in Tables 1 and 2. This report is presented in five parts. Part I includes an evaluation of the cooperation aspects (Chapter 2) and a description of the main research site (3). Part II describes and discusses several aspects of the 1987/88 flood season: Flow events (Chapter 4); Channel bed grainsize distribution (5); River cross-sectional changes (6); The longitudinal change pattern (7); Scour chains and

sediment volume moved (8); and sediment tracing (9). Part III evaluates the 1990/91 floods; its flow events and their hydraulic characteristics are presented in Chapter 10; Chapter 11 details the dispersion of the trace particles; and in Chapter 12 the phenomenon of overbank sand deposition and its relation to the sediment budget is discussed. Chapter 13 presents results from a low-flow sediment dispersion experiment. Finally, Parts IV and V address, respectively, results from the Nahal Shiqma (Israel) counterpart catchment and the conclusions emanating from the project, with recommendations for future research.

Fifty figures, which illustrate the main aspects of this report, follow the main text part. The two appendices, relating to the resource conservation aspect of the Botswana work (Appendix A) and to the sediment tracing in Nahal Shiqma (Appendix B), constitute the final pages.

Over the four year project period, about 45 man-weeks of field work were invested by Hebrew University scientists and technicians on the Botswana sites. This is in addition to considerable routine work and special tasks performed by the principal investigators and their assistants, each in his own country, on the project, both in the field and in the office. The work has generated a very large database, especially on the sediment tracing; the analysis of this information is far from complete, and will form the base for a number of papers to be published in the relevant scientific literature in the next few years. Appendix A, a paper entitled 'The Sand Rivers of Botswana - a Transient Resource?', submitted to the East African Agriculture and Forestry Journal (Nairobi), is a precursor of these.

Many persons in Botswana and Israel were helpful in the course of the work reported here: the USAID Mission in Gaborone, the Botswana Department of Water Affairs, the Department of Environmental Science of the University of Botswana, the Department of Physical Geography of the Hebrew University of Jerusalem, the Israel Hydrological Service, and others. Marwan A. Hassan, Tamir Grodek and Ekkehard Hahn have joined the field work in Botswana for various periods and have contributed to the data analysis. Shlomo Sharoni played a major role in the counterpart work in Nahal Shiqma. Sari Grossman was in charge of many aspects of the project administration. Judith Lekach and Eva Gerendas-Katrivas assisted in the production of this report.

Table 1: Schedule of Field Operations, Metsemotlhaba Research Site

| | |
|---|---|
| 1987 | Site selection<br>Instrumentation<br>Initial Survey |
| 1987/88 | Flood season*: major flood; structural damage |
| 1988 | Survey; partial reconstruction |
| 1988/89 | Flood season: minor flows only |
| 1989 | Survey |
| 1989/90 | Flood season: minor flows only |
| 1990 | Survey |
| 1990/91 | Flood season: major flood |
| 1991 | Survey |
| 1992 | Data analysis; summary |
| 1993 | Report preparation |

*A mid-season (Feb. 1988) resurvey of the sections was done during a hiatus between flows.

PART ONE - GENERAL

## 2 - COOPERATION ASPECTS

The collection of hydrological and rainfall data using automatic electronic equipment, such as installed by this project in the Metsemotlhaba River, has not been attempted in Botswana, and has aroused great deal of interest. In November 1987 the site was visited by a party of 32 delegates from a SADCC training conference on land management and utilization to discuss the application of the equipment to developing countries. The research site has also been visited several times by students from the University of Botswana taking hydrology as an optional course, and has developed into a semi-permanent learning aid and demonstration site.

The Department of Water Affairs (WAD) expressed considerable interest in some of our monitoring techniques, especially scour chains and associated cross sections. They are considering the use of these at gauging sites related to proposed large dams on Shashe, Motloutse, and Mahalapshwe Rivers. The sediment part of the feasibility studies for the Motloutse and Mahalapshwe project, performed by the Botswanese Co-PI (PS), relied heavily on data collected within the framework of this project.

The project employed a permanent watchman on-site, and provided employment for up to four laborers on a casual basis. The local population was informed by the PI's as to the nature and importance of the project, and were very cooperative. Only very few cases of vandalism with regard to prone field equipment and tracers were apparent.

The project has encountered great difficulties in attracting a suitable university graduate for work as a research assistant/ associate, preferably as part of an MSc/MA thesis within a graduate study program. We have found that appropriately trained university graduates are much keener to accept work which offers permanence. Even the Government of Botswana Water Affairs Department, with whom we have tried to share one of their young graduates, is losing personnel in favor of private companies, and is unable to accommodate our need for a research assistant, despite their obvious interest. We do not see an easy solution to this problem in future AID-sponsored research projects.

## 3 - THE SITE : GEOMORPHOLOGY OF THE METSEMOTLHABA BASIN

The Metsemotlhaba River is a left tributary of the Notwane River, itself a left bank tributary of the Limpopo. The Metsemotlhaba thus forms part of the network draining the continental divide eastwards across the African Planation Surface, with first order streams rising on the Kalahari Sand boundary in the west at 1,300 m a.s.l.

The experimental site lies between the villages of Thamaga and Moshupa in the upper Metsemotlhaba. The catchment of the site is a strongly asymmetric basin of 615 sq km area. In the east and south the basin drains 200 sq km of highly resistant Waterberg quartzites and sandstones along the interrupted escarpment of the Polokwe and Sesitijawe Hills, whilst the elongated western tributaries drain from the Kalahari Sand across a granite landscape formed from the Gaborone Granite Group, comprising the Thamaga Rapakavi Granite, Kgale medium grained granites, and the porphyry and micro-granites of the Ntlhantle Series. This landscape forms a typical etchplain surface of hill massifs, inselbergs and tors.

Drainage in the upper reaches comprises a series of rock-bed channels with a coarse sediment load, whilst the "sand river" section, a wide, flat sand bed of low gradient, appears at Moshupa and persists through Thamaga to the village of Kopong 20 km NW of Gaborone, where the river enter an area of wide floodplains and anastomosing channels termed the Kopong Swamps. This area coincides with an area of reduced relief and diminution of the sediment load. It is an unusual feature, now selected as a dam site for the auxiliary Gaborone water supply.

At the experimental site the river is 20-40 m wide, composed of a sand bed contained by granite outcrops and banks of loamy sands and clays. A narrow floodplain is confined within fairly steep pediments of coarse sandy soil containing large numbers of rounded quartzite pebbles derived from the Waterberg escarpments. The distance between the Sesitjawe Hills to the east, and the granite terrain of the Sephatlhaphatlha Hills to the west is about 4 km.

The existence of sand rivers has been attributed to climatic change the existence of humid periods in the past leaving to the deposition of large quantities of sand which represent non-equilibrium conditions, which must, therefore, be stable fossil landforms (Nord 1985, p.1). Attention has been drawn to both arid and humid fluvial landforms in the rivers of southeast Botswana by Wayland (unpublished paper, Museum of Botswana, 1951), who described raised terraces, gravel spreads and re-excavated on a large scale, often characterized by Early Stone Age implements. This line of research, however, has not been followed up.

An alternative proposal for the existence of the Metsemotlhaba sand river may be, quite simply, that it coincides with an area of relatively steep slopes, high runoff and steady sand supply from the erosion of adjacent granite terrain, conditions which are not satisfied either upstream or downstream of the sand river section. This would imply that the sand river is an equilibrium form in this case.

The maximum depth of the sand bed appears to be about 3 m, overlying a series of compartments in the underlying granite. The river has a relatively uniform bed at low gradient, giving correspondingly low velocities. Nord (1985) estimates that the maximum no-flow regime for the river extends to about 12 months, with average of 3-5 flows per year. Certainly since records commenced in 1976 there has been flow every year, varying from an annual peak of 110 cumecs in January 1978 to a low peak of 8 cumecs in 1981-82. The flood of 22nd December 1987 was measured at 97.4 cumecs at Thamaga before the gauge failed. The estimated flood was about 130 cumecs. Comparable floods have been identified in 1945, 1967, 1968 and 1974.

At present the gauging system in the catchment is inadequate. The Department of Water Affairs maintains the gauge at Thamaga, whilst the police in Thamaga collect rainfall data on behalf of the Meteorological Department. The proposal to construct the dam at Kopong has created a demand for data relating to the hydrology of the Metsemotlhaba.

Reference:

Nord, M., 1985, The Sand Rivers of Botswana. Phase II. Dept. Water Affairs, Gaborone, 2 vols.

Table 2 : Main hydrological data, 1987/88, Metsemotlhaba River @ Thamaga, WAD station 2421

| Event date (peak) | Maximum discharge m3/sec | Flow duration* Q>1m3/s/m hr | Q>2m3/s/m hr | Q>3m3/s/m hr | |
|---|---|---|---|---|---|
| 22 Dec 87 | 97(130?) | 25 | 19 | 14 | |
| 8 Jan 88 | 1.3 | 0 | 0 | 0 | |
| 11-18 Feb 88 | 40 | 68 | 0 | 0 | # |
| | | # Composed of 3 distinct and roughly equal sub-events | | | |
| 3-11 Mar 88 | 60 | 30 | 8 | 0 | ## |
| | | ## Composed of 2 distinct and nearly equal sub-events | | | |
| 11-15 Mar 88 | 33 | 13 | 0 | 0 | ditto |

* Based on a mean inter-bank width of 21.6 m for study reach (upstream section at bend excluded) and on the assumption that discharge at the WAD station is equal to the discharge in the study reach. In fact the discharge at the study reach may be 20% lower than the tabulated values, on the average.

PART TWO - THE FLOODS OF 1987/88

## 4 - FLOW EVENTS

The seven flow events which occurred on the Metsemotlhaba River (Table 2), as recorded at WAD Station 2421 near Thamaga, are shown in Figs. 2 and 3. The first event (22-24 December 1987) was the destructive one ; it put most of our gauging equipment out of operation, and was followed by a period of high water table until the three subsequent February flow events. these events were practically back to back and each peaked to 30 - 40 m3/sec at Thamaga. There is some uncertainty as to the peak discharge of the first event, depicted on Fig. 2 as peaking to nearly 100 m3/sec, but it may have reached 130 m3/sec.

The hiatus between the end of the fourth event and the onset of the fifth one (18 Feb - 3 Mar 1988) was used by the project field team for resurveying the cross-sections and making other observations. This work was repeated in a more comprehensive way, at the end of the season (Sep 1988), i.e. after the last three event of the season (Fig. 3). These events were similar in duration and peak flows to the three events prior to the hiatus, though the first two peaked to 50 - 60 m3/sec. The duration of all seven events was roughly 2-3 days each.

The WAD gauging station at Thamaga is located downstream of the junctions of the Kololwane and Mahatelo Rivers with the Metsemotlhaba. The project site on the Metsemotlhaba is upstream of these junctions, and therefore drains an area roughly two thirds of the area drained by the stream at the WAD gauge. Neglecting, of necessity, factors such as small-diameter rain cells in one of the sub-catchments, or massive infiltration into the sand bed between the project site and Thamaga, our general working assumption is that the peak flow values at the project site are approximated by 80% of the peak value at Thamaga.

Fig. 4 is an attempt to evaluate the frequency of annual peak flows on the Metsemotlhaba as based on the WAD record. The recording gauge was established only towards the end of the period analyzed. The squares on Fig. 4 show the magnitude-frequency behavior of the first twelve years. The circles indicate the change in the upper part of the curve caused by the addition to the record of the last three years (1988/89-1990/91), including the large flood of March 1991. This flood event was estimated by WAD to have peaked at Thamaga at 61.5 m3/sec, though from our observations upstream it may have been much higher (see Chapters 12-14).

Massive sand and tracer gravel transport, as indicated by our study, is probably limited to the 3-4 largest floods of this period. Since floods comparable in magnitude are known to have occurred at least four times in the recent pre-instrumental period (1945, 1967, 1968, 1974 - see Chapter 3), we have at least 7-8 events in 46 years in which very substantial amounts of sediment are transported by the Metsemotlhaba.

Hydrometric measurements undertaken during the recession of the fourth event (18 Feb 1988) yielded a mean flow velocity of 0.56 m/sec at a mean flow depth of 0.45 m. The discharge was 5.9 m3/s. By calculation, the Froude Number was 0.27 and the Manning roughness coefficient indicated by the data was 0.047. The channel bed was in dunes, length 1.5-2 m and height 0.20-0.25 m, with occasional scour holes up to 0.8 m deep. At a slope of 0.015 sand and even granules were moving, and the bed felt labile.

Three suspended sediment samples collected on 14 Feb 1988 at a discharge level of 6.6 m3/sec yielded a concentration of 1,000 mg/l for the two surface samples and of 3,000 mg/l for a depth of 0.30 m (2 cm above the channel bed).

## 5 - PARTICLE SIZE DISTRIBUTION

The sandy channel bed of the Metsemotlhaba River at the project site has a fairly consistent and symmetrical size distribution, both in surface and subsurface samples, with a median value of about 0.5 mm (Fig. 5-8). Changes related to depositional sequences do occur and are reflected in stratigraphic sections (Fig. 28).

The auxiliary sites on the Bonwapitse and Tautswe Rivers show a markedly coarser distribution, with median values around 1 or even approaching 2 mm (Figs. 9-11). These data are in agreement with the findings of the Swedish SIDA team (Nord, 1985, ibid.).

The figures shown represent only a small fraction of the data collected. The provenance of the sand and its depositional destination is a complex problem whose solution involves not only the information collected by us and by others, but also an evaluation of past geomorphic processes, perhaps operating under a different hydroclimate. This aspect deserves a separate research project.

## 6 - CROSS SECTIONS - METSEMOTLHABA RIVER

Figures 12 and 13 are examples of three recurrent benchmark based surveys done before (11.8.87), after (2.10.88) and in the middle (19.2.88) of the 1987-88 hydrologic year. The mid-season survey was done after the first four events of the season, termed in Chapter 4 (Fig. 2) the first observation period. The first of these four events was the high-magnitude event, estimated frequency between 1 in 7 and 1 in 20 years (Fig. 4). The last three events of the season (Fig. 3) occurred after the mid-season survey.

The sections covered a longitudinal distance of 1,400 m, starting at the downstream end of a sharp bend of the river. Section 1 (not shown in this report) reflects asymmetric activity of a large magnitude, with changes in bed level elevation reaching up to 0.6 m at certain points. The active width was 46 m during the first period and 39 m during the second. Nearly the entire large point bar, which had existed in the inner part of the loop before the season, was eroded by the events of the first observation period, most of it probably by the big December flood. At the same time, the deep inner channel, width 6 m, which had abutted on bedrock at its left bank, has been filled by 0.4-0.6 m of sand. However, the main trend was one of erosion. This trend continued during the second observation period : the bar continued to be lowered, though at a smaller rate, and some of the filled inner channel was scoured.

Section 1 is located at the main benchmark of the project site (L = 0 m). Over the first half of the surveyed river reach (L = 0 to L = 700 m) there is a section every 100 m (such as section 3 at L = 200 m; Fig. 12). The downstream half (L = 700 m to L = 1,400 m) represented by five sections (such as section 13 at L = 1,200 m; Fig. 13).

In all sections except the bend controlled section 1, the width of the active channel is fairly constant, and ranges from 16.9 to 29

m. Changes of bed level at a point rarely exceed 0.15 m ; however, values of up to 0.37 m for one period (section 3, Fig. 12) and of up to a cumulative 0.52 m for both periods (section 8) have been recorded.

While the upper four sections -- not counting section 1 -- seem to be at or near equilibrium, a consistent tendency of degradation is evident in most of the other sections. Sections 8 and 11 show consistent degradation for both observation periods. Other sections show degradation only for the first period, and equilibrium or even a small amount of aggradation for the second period.

These changes in themselves reflect the displacement of large amounts of sediment of the bed. These will be summarized in the following chapters from a longitudinally integrated viewpoint ; subsequently they will be juxtaposed with evidence of scour and fill deduced from tracer distributions and scour chains.

## 7 - THE LONGITUDINAL PATTERN OF BED LEVEL CHANGES

The flood events of the first observation period caused the degradation of all the 11 channel-bed reaches delimited by adjacent cross sections (Fig. 14). The same is true for each of the 12 sections, with the exception of sections 2 and 4, which aggraded 2.0 and 0.07 cm, respectively. These minimal aggradation values are more than offset by degradation values an order of magnitude larger, e.g. 34.9 cm for section 13 and more than 20 cm for four additional sections. The mean degradation for the entire study reach was 14.9 cm.

The second observation period caused moderate aggradation in all sections and inter-sectional reaches, with the exception of the upstream, bend-affected end and section 11. Values of aggradation ranged from 0.25 cm for the 300 m long reach between Sections 8 and 11 to 13.45 cm between Sections 3 and 4. Mean aggradation was 5.4 cm. Longitudinal variation was considerable with areas of considerable aggradation, such as L : 300-500, and L : 1,300-1,400, interrupted by areas of near equilibrium. This pattern is in contrast to the massive degradation, which was predominantly concentrated in the downstream half of the entire 1,400 m long reach.

As a very rough first approximation, these data suggest that the high magnitude flood of December 1987 (Fig. 2, Table 2) may have had a major degrading effect, while the subsequent six "normal" events of the season had an adjusting effect of aggradation, which, however, was far from restoring the pre-seasonal channel bed level.

## 8 - SEDIMENT VOLUMES

The sediment volumes involved in the degradation and aggradation processes as monitored are shown, for the first and second observation periods, in Figs. 15 and 17, respectively. The total degraded volume after the floods of the first observation period amounted to 5,130 m3. The second observation period, with its three moderate events, caused net accumulation of 1,590 m3. Hence, an additional net deposition of c. 3,500 m3 is required to restore the channel bed to its pre-December 1987 flood condition.

These volumes do not necessarily represent sediment exported from, or moving into, the study reach; theoretically, the origin, by erosion, of any individual sand particle which forms part of the

volume added to the study reach may be within the 1,400 m long study reach, or else its source could be further upstream. Likewise, the depositional destination of any individual sand particle which forms part of the volume missing in the study reach could be within the reach, or else further downstream.

However, other evidence points to a long-distance transport of the sand particles. This includes the sedimentological evaluation of seven trenches such as Fig. 18, which disclose a high level of sand transport activity. Nearly one thousand trace particles, at least an order of magnitude larger than the sand particles, moved hundreds of meters in a single large event (Chapters 9 and 11). It is, therefore, reasonable to assume that the sand grains move in such events, as a rule, thousands of meters.

If we accept the assumption that each of the three moderate events of the second observation period caused a net accumulation of c. 500 m3 of sand each, some 5-10 such events are needed to restore the pre-flood (December 1987) condition.

It is important to stress that we are dealing in this chapter with net values. As in similar geomorphological monitoring studies on rivers, here too the net degradation or aggradation represents only a residual of two much larger values of scour (usually developing during the rise of the flood) and fill (characteristic mainly of the falling limb of the flood). That the scour and fill values operating in a sand river like the Metsemotlhaba are indeed much larger than the residual values of net aggradation or degradation can be proved by evaluating scour chain data and redeposited tracer sediment. Both techniques were used in this study and they prove that this is indeed the case (Chapters 9 and 11).

## 9 - SEDIMENT TRACING AND SCOUR CHAIN RECORDS

Some 1,400 pebbles were injected into the channel beds of the Metsemotlhaba, Bonwapitse and Taupye Rivers. About 1,100 of them were small, synthetic, magnetized pebbles, weighing approx. 15 g each. Some were large, natural, magnetized pebbles, size 32-90 mm.

In the Metsemotlhaba main research site, 60 scour chains arranged in six cross section were also inserted. In this chapter some of the results obtained from the monitoring of tracers and chains will be described.

Bonwapitse River:

The tracer dose injected in September 1987 included 73 large particles (numbered 600 and over). The catastrophic flood which occurred on the Bonwapitse at the beginning of the rain season, immediately following the injection, was the main cause of the very large displacement of the particles.

Recovery rates were low: 10.6 per cent for the entire population. The 8 large particles recovered constitute 11.0%, and the 21 small particles recovered constitute 10.5%. Thus there is no effect of size on recovery rate.

The mean displacement of all the 29 particles recovered was 1,060 m. Displacement values for individual particles ranged from 386 to 1,408 m. The 8 large ones moved 1,002 m on the average, while the mean displacement of the 21 small ones was 1,082 m. Thus there is also no significant difference in horizontal displacement between the large and the small particles.

Table 3 : Schedule of operations associated with the tracing program, Metsemotlhaba River, 1987-91.

**TRACING HISTORY**

| | SMALL | LARGE | GREEN |
|---|---|---|---|
| INJECTION OF 1987 | 610 | 155 | |
| 1987/88 SEASON (BIG FLOOD) | | | |
| SURVEY | 178 | 33 | |
| 1988/89 SEASON (MINOR FLOWS) | | | |
| SURVEY | | | |
| INJECTION OF 1989 | | | 100 |
| 1989/90 SEASON (MINOR FLOWS) | | | |
| SURVEY | | | 66 |
| 1990/91 SEASON (BIG FLOOD) | | | |
| SURVEY | 150 | 28 | |
| TOTAL FOUND AT LEAST ONCE | 236 | 42 | |
| | 39% | 27% | |
| TOTAL FOUND AFTER BOTH BIG FLOODS | 25% | 21% | |

The mean burial depth of all 29 recovered particles was 27.4 cm. The deepest burial recovered was down to 60 cm. If the single particle found on the surface is excluded, the mean depth becomes 28.4 cm. For the large particles only, the mean depth is 25.5 cm and, if the single particle found on surface is excluded, 28.4 cm. If calculated for the 21 small particles, the mean depth of burial is 28.2 cm. Thus there is no
discernible effect of depth of burial.

Metsemotlhaba River:

The tracer dose injected in September 1987 included 155 large and 610 small particles. The high magnitude event of December 1987 was the first following the injection and entrained all 765 particles. The 165 recovered at the end of the season constitute 22%. Mean distance of movement was 924 m. Mean depth of burial was 44 cm. This result is the combined effect of the large event of December 1987 and of the six succeeding moderate events (Chapter 4). The same applies to the Bonwapitse River, though there the record of the succeeding events has not been evaluated. However, in both rivers, as well as in another auxiliary site on the Taupye River, the December 1987 was clearly of prime importance in moving sediment.

Three-dimensional distribution:

From previous tracer studies involving coarse sediment (Hassan, 1988; many others) it was concluded that the gamma distribution fits reasonably well the dispersion patterns of tracer particles, both vertically (burial) as well as longitudinally (downstream). Figs. 19 and 21 show the vertical displacement of the tracers at the end of the 1987/88 season in the Bonwapitse and Metsemotlhaba Rivers, respectively. The poor fit in the Bonwapitse may be explained, in part, by the small size of the sample. Probably both curves reflect selective redistribution by the small events which had followed the first big flood at the beginning of the season, resulting in an overconcentration in the range of 1-1.2 D/D.

In evaluating these distributions it must be remembered that the magnetic detector used has a sensitivity sufficient to recover a magnetized pebble up to a depth of about 1.1 m. While this limitation may have much effect on the Bonwapitse curve (D being 28 cm, i.e. roughly one quarter of the depth of maximum recovery), it is probably significant for evaluating the Metsemotlhaba curve. Other evidence, cited below, points to the possibility that a large number of the tracers not recovered in our survey are indeed buried in depths beyond the reach of the detector.

The downstream distribution patterns for the Bonwapitse and Metsemotlhaba, shown in Figs. 20 and 22, respectively, show similarly fair to poor fits with the expected gamma distributions. We assume, as working hypothesis, that large numbers of particles have indeed moved distances less than L, but being buried beyond the reach of the detector, they actually listed missing.

The model which may explain the distributions is one combining tracer transport with depth of scour. At the onset of the floodwave all tracers are entrained and they move downstream. Due to the steep rise of the flood, the scour depth becomes maximal at, or only a short while after, the entrainment. From then on deposition occurs simultaneously with a gradual fill which parallels the flood recession. Hence most of the tracers that move short distances are

buried deeply, while those that continue to move, settle in environments that have already been filled, and tend therefore -- at the end of the event -- to be in shallowly buried locations.

Fig. 23 shows the distance of movement versus the depth of burial for all recovered small tracers in the Metsemotlhaba River. It may be maintained that the depth of the deepest tracers indicate the maximum depth of the scour layer, provided that moving tracers are available for deposition. In actual fact, the very deepest tracers may settle in 'accidental' loci such as scour holes; hence it seems prudent to discard the 10 or 20% deepest tracers when reconstructing the depth of the general scour layer. The squares in Fig. 23 indicate the depth value, for successive 200 m long reaches, above which 80% of the particles were deposited. The line which is described by these squares indicates the generalized vertical position of the bed at the time of arrival of the fastest moving tracers. If we assume that the maximum general depth of scour was 90 cm (left end of line), and that it filled up to 55 cm at distances 1,200-1,800 m (Fig. 23) during 15-25 hrs of high flow (Table 2, event of 22 Dec 87), a mean velocity of 1,500 m per 20 hr, or 1.25 m/min is suggested.

The three dimensional distribution pattern of the large tracers (Fig. 34) suggests the same process and magnitudes, though the number of tracers is small. In contrast, the patterns for the Bonwapitse tracers suggest a bore-like flood translocation of the tracers, with a clear concentration around L = 800 to 1,200 m. Again, the numbers are small.

Scour chains:

The 60-odd scour chains were arranged in six cross sections located 80, 180, 280, 380, 580 and 880 m downstream of the origin point at the river band. With one or two exceptions, all chains in the first five sections were uprooted and not retrieved. Only section J (L = 880 m, see Figs. 5 & 7 for location) had most of the chains preserved, but they show scour and fill on the order of 50-70 cm. Presumably they were not uprooted because the flood power was distributed over the somewhat larger width of 28 m, in relation to the 17-23 m upstream.

Reference:

Hassan, M.A., 1988, The Movement of Bedload Particles in a Gravel Stream and its Relationship to the Transport Mechanism of the Scour Layer. Ph.D. thesis, Hebrew University, Jerusalem, 203+IX p.

## PART THREE - THE FLOODS OF 1990/91

### 10 - FLOW EVENTS; HYDRAULIC CHARACTERISTICS

On 18 March 1991 a major flood occurred on the Metsemotlhaba River. It has caused substantial damage and severe disruptions in transportation. Although the WAD gauging station at Thamaga indicated a peak discharge of only 61.5 m3/sec, the floodmark level at the project site was similar to that of the December 1987 event (peak discharge at Thamaga: 98.9 m3/sec) or even exceeded it. One striking effect of this flood -- the deposition of sand levees on the edge of the floodplain -- is described in Chapter 12.

The 1990/91 season was, in terms of this project, beyond the scheduled plan of operations which, which included three field seasons. Observations on individual flood events of medium and small magnitude were discontinued, since the seasons of 1988/89 and 1989/90 have shown that such events cause only insignificant translocations of the tracers. The major event of March 1991 has presented the long-awaited opportunity to resolve the question whether the extremely long transport distances covered by the tracers during the December 1987 event were due only to their initial shallow positions on the channel bed, or whether our model based on the simultaneous effect of scour, entrainment and transportation can indeed be confirmed. This topic will be presented in more detail in Chapter 12.

The HEC-2 program was run on the 15 cross sections spaced at 100 m intervals along the 1400 m long study reach. An example of the results
is shown as Fig. 27, which shows in a typical way the variation of the flow cross section with discharge (27a) and the downstream variation in mean flow velocity at a given discharge, in this case 100 m3/sec (27b).

In this section, the maximum depth at a flow level of 100 m3/sec is 2.3 m above the channel bed. An increase of 40% to 140 m3/sec entails an increase in depth of only 20 cm. The mean flow velocity at 100 m3/sec ranges from 1.08 to 1.79 m/sec, and is generally between 1.2 and 1.5 m/s. The mean velocity does not decrease substantially at lower flows: even at 20 m3/s only two out of the fourteen sections yield a mean velocity of less than 1.0 m/s, while at 140 m3/s a mean velocity of 1.9 m/s is exceeded in only one out of the fourteen sections.

The massive sediment transport and tracer dispersion monitored is, hence, associated with relatively moderate velocities and stream power values. These parameters are relatively insensitive to discharge levels, especially at high magnitude - low frequency flows, which become more effective laterally due to increased overbank flooding.

### 11 - DISPERSION OF TRACE PARTICLES

The application of tracer particles several phi-units coarser than the channel bed sand to the evaluation of sand transport is based on a model illustrated in Fig. 28. At stage I, before the flow, a given trace particle lies near the channel bed surface, barely covered by the sand. With the onset of a flow, the water level in the channel rises and, simultaneously, the channel bed surface lowers by scour. The particle is detached from the sand medium and is propelled downstream by the flow (stage II). As the flow wanes,

Table 4 : Annual summation of downstream dispersal of tracer pebbles, Metsemotlhaba River, Botswana.

| A | B | C | D | E |
|---|---|---|---|---|
| YEAR | # PBLS IDENTFD | PBLS MOVED (%) | MEAN DIST. OF PBLS WHICH MOVED (M) | CUM. DIST. BASED ON ALL PBLS FOUND (M) |
| 1987 | | | | |
| | 164 | 99% | 842 | |
| 1988 | | | | 837 |
| | 122 | 23 | 82 | |
| 1989 | | | | 856 |
| | 214 | 32 | 13 | |
| 1990 | | | | 860 |
| | 92 | 85 | 310 | |
| 1991 | | | | 1,123 |

some of the sand in transit is deposited on the channel bed and progressively raises the channel bed level. At some stage within this process the moving particle is deposited as well, and soon thereafter it is covered by the continuous process of fill up to the cessation of sand movement and the end of the flow.

For reasons explained in Chapter 12 below, we do not introduce the dunes as part of the system involved. Dunes in the Metsemotlhaba may develop, if at all, only towards the very end of the flow.

In the model described above, the transport distance of a trace particle can be established, if located both before and after the flow. If we have a number of trace particles, the deepest values of burial indicate the maximum scour depth of the previous event which moved them. As the particles are replaced, following retrieval, in the same positions in which they were found, the re-entrainment of a buried particle by a subsequent flood indicates the depth of scour during that flood.

The operations schedule associated with the Metsemotlhaba tracing program is summarized in Table 2 above. The salient features of the program are (i) the very large three-dimensional dispersion of the tracer population by the first flood to follow the installation - the December 1987 event; and (ii) another very large flood which has caused similar dispersion, but to a widely distributed population -- longitudinally and vertically -- which occurred 40 months later. The period intervening between these two major events had a series of only minor flows which have barely affected any of the embedded tracer particles. Thus, for the entire season of 1988/89, only 23% of the identified particles moved, and for the 1989/90 season the number increases only slightly to 32% (Table 4).

In Table 4, which lists the mean distance which the tracer pebbles moved, a distinction is made between two ways of computing the mean distance of movement. Column E shows the mean value of the cumulative distance of movement as established at the end of each season, based on data for all the particles located and identified in the end-of-season survey. The trace particles of any one of these populations is not necessarily identical with the population of the preceding or following end-of-season survey. That substantial differences in the composition of these populations do exist is also clear from the different rates of retrieval, which range around 20-40% of the original population.

In contrast, Column D (Table 4) lists the actual mean distance of movement, based only on those individual particles identified both at the beginning and at the end of the season-long trajectory. The figures so derived are much more realistic than those arrived at by the first method; they show, for the first major flood, a mean translocation of 842 m and, for the second major flood, of only 310 m. The discrepancy is due to (i) the ready entrainment of particles placed in surface position before the first flood, in contrast to vertically distributed particles, often buried deeper than 1.0 m (the sensitivity limit of the detector), before the second flood; and (ii) differences in hydrograph characteristics of both events as well as the occurrence of additional, medium size flows during the 1987/88 season.

Table 5 is a tentative and crude attempt to approximate the annual sediment discharge of the Metsemotlhaba, based on two assumptions as listed. Based on a unit channel width value of 22 m at the research site, the seasonal sand discharge for 1987/88 should be 3 times higher than for 1990/91, 40 times higher than for 1988/89,

and 200 times higher than for 1989/90. The effect of high magnitude - low frequency flood events on the sediment discharge of the sand streams is highlighted by these data.

## 12 - OVERBANK SAND DEPOSITION

The flood of March 1991 caused overbank deposition along the study reach of the Metsemotlhaba River to a substantial extent. Along roughly 20-30% of the channel of the 1400 m long study reach, discernible natural levees were formed. Preferred depositional loci were at the outer curves of bends and at local depressions in the floodplain level.

A survey along the study reach identified 13 levee patches, totalling 745 sq m in area. The data for the three largest levee patches are listed in Table 6. Most of the other patches show, likewise, a maximum depth of deposition of 40 cm and a mean depth around 20 cm. Most of the patches are located 1.8 - 2.1 m above the channel bed, and thus indicate a minimum peak discharge for the event of over 100 m3/sec (Fig. 27a). As no levees were discerned after the December 1987 flood, and, in contrast, the levees after the March 1991 were very conspicuous, we must conclude that, at least at the project site, the peak flow in 1991 exceeded that of 1987.

Following event 12, particle size analyses of soil/sand samples were carried out on and near the levee sites, as follows: 7 samples of levee sand from the floodplain, 2 samples of channel bed sediment, and 3 samples of bank material (Fig. 29). With one exception, the median grain size of the levee material ranges from 0.27 and 0.35 mm (the exception sample has a value of 1.3 mm). In contrast, the channel sediment has a median particle size of 0.8 mm, a value slightly coarser than shown in Fig. 5 and significantly coarser than the levee material. The bank material has a mean particle size of 0.035-0.090 mm and includes 3.8-7.8% of organic material. In the channel and levee sand only some of the samples show traces of organic material.

The difference in median particle size of the channel sand and the levee sand (0.8 mm versus 0.3 mm) is instructive and rather expected. It confirms that, even at high levels of discharge, and probably due to the relatively moderate velocity at these discharges (Fig. 27b), much of the coarser sand is transported close to the bed. However, it was rather surprising to find six tracer pebbles (five small ones and one large) embedded in the levee deposits. The significance of this result is substantial with regard to the understanding of the process involved in the behavior of pebbles in a sandy fluvial environment in general, and in the applicability of the tracer method to the reconstruction of a hydroclimatological record of sand streams in particular.

## 13 - TRACING LOW FLOW PARTICLE MOVEMENT

The 'green' generation of 100 tracer particles was placed along a bank to bank transect of the Metsemotlhaba River within the study reach during the relatively dry 3 year long period which intervened between the two major floods reported here. A minor flow, peak flow depth -- by estimate -- no more than 50 cm, duration no more than a few hours, distributed these particles downstream.

**Table 5 : Estimated unit width annual sand discharge, Metsemotlhaba River, and assumptions involved in its approximation.**

Estimated unit width annual sediment discharge, Metsemotlhaba River, Botswana, based on Assumptions A & B above

| | | | |
|---|---|---|---|
| 1987/88 | 18,300 | cu.m. | big flood, protracted flow |
| 1988/89 | 420 | | small flows |
| 1989/90 | 90 | | ditto |
| 1990/91 | 5,800 | | big flood, levees, short? |
| 1991/92 | 0 | | no flow |

Assumption A:

The depth of the scour layer can be approximated by using the observed parameter "percentage moved" as an indicator, relative to the sensitivity depth of the search instrument (in our case +/- 1.0 m).

If correct, then column C indicates the depth of the scour layer, in cm.

Assumption B:

The mean distance of the pebbles which moved approximates the mean translation distance of the channel-bed sand (overpassing balanced by temporal stationarity/burial).

If correct, then the annual sediment discharge of the river can be approximated.

Table 6 : Estimate of area, depth and volume of levee patches deposited on the floodplain edge of the study reach, Metsemotlhaba River, by the March 1991 flood.

| Distance (m) | 0+900 | 0+1000 | 0+1030 |
|---|---|---|---|
| Location (max. extent) | 900-1000m right bank | 1000-1030m right bank 30m from edge of channel | 1030-1155m right bank 30m from edge of channel |
| Extent of deposition (m) | 105x18 | 30x30 | 125x8 |
| Max. depth of deposits (cm) | 35 | 40 | 40 |
| Mean depth of deposits (cm) | 15 | 20 | 20 |
| Elevation above channel (m) | 1.80 | 2.00 | 2.05 |
| Volume ($m^3$) | 283 | 180 | 200 |

Fig. 31 shows the initial and terminal locations of the 66 particles retrieved after the flow. Their three dimensional distribution bears the imprint of the flow which dispersed them. A tendency is evident for the flow to concentrate into two thalwegs (Fig. 32). This tendency is remarkable because, superficially, the reach seems to be decidedly in the plane bed category. The flows indicated by the trajectories are far from parallel; angular deviation ranges over more than 50 degrees.

An intense meandering-braiding process is probably responsible for the pattern of trajectories (Fig. 31) -- a pattern not visible on the channel bed surface after the flow. This pattern may be explained by active lateral shifting during the short period of the shallow flow; it is evident that any point in the channel was subject to at least two different flow directions. These directions can be differentially selected to show zones of influence during certain stages of the flow period (Fig. 34).

The data prove that the model of Simons and Senturk (1992), based on the entrainment of pebbles in interdunal depressions in sand streams, is not applicable here. This conclusion is also supported by the finding of tracer pebbles in the sand levees deposited high above the channel bed (Chapter 12).

The data in this experiment were subjected to a large number of comparative analyses. Two of these were shown in Figs. 35 & 36. Fig. 35 is an attempt to characterize all particles with a trajectory showing a very high lateral deviation (>20°) to the right. The result is that four out of five particles in this category underwent very deep burial (40-50 cm) -- comparable in size to the entire depth of flow. A selection of all such very deeply buried pebbles, irrespective of trajectory direction, is shown in Fig. 36. Four out of the five pebbles in this category are the same ones as in Fig. 35. The fifth is a long traveller which got deeply buried after covering a distance of 24 m during this minor flow.

The association between "sinking" nearly in place and deep burial is probably due to the process identified in the laboratory by Fahnestock & Haushild (1962); this research is the first field proof of its validity. However, less than 10% of the pebbles were found to behave in that way; hence we conclude that it is not the dominant process governing the behavior of individual large clasts within a sandy fluvial environment. Clearly, the intense three-dimensional dynamics of pebble movement evident even in such a small and short flow is quite surprising and it offers an opportunity to describe and understand these processes, which are usually hidden under a transient blanket of turbid water, and are disclosed neither by the pre- or post-flood channel morphology nor by sedimentological-stratigraphic analysis.

References:

Fahnestock, RF, Haushild, WL, 1962, Geol. Soc. Am. Bull. 73:1431-1436

Simons, DB, Senturk, F, 1992, Sediment Transport Technology, WRP, Littleton, CO.

PART FOUR - NAHAL SHIQMA

## 14 - THE NAHAL SHIQMA COUNTERPART STUDY

Nahal Shiqma is an ephemeral stream network covering a total area of 740 km2. Its upper tributaries start in the southern part of the Judaean Mountains in the vicinity of Hebron (Fig. 37). The elevation there is around 800 m a.s.l. and the lithology is predominantly limestone and dolomite of Turonian-Cenomanian age. The central part of the catchment is a foothill zone composed mainly of Eocene and Neogene rocks of lower resistivity to erosion, considerable soil cover, and lower infiltration capacity than the mountainous, semi-karstic zone. The western part of the catchment is entirely within the coastal plain with Pleistocene and recent sand, sandstone and various soils, combining with loess in the southern part, to form a terrain of variable infiltration capacity.

The rainfall, as represented by the Dorot station, is similar to that at the main study site in the southeastern part of Botswana: 300-400 mm per year (Fig. 38). However, the rainfall at Shiqma occurs exclusively in winter, and may therefore be more effective hydrologically than that in SE Botswana.

Several characteristric rainfall intensities typical of the Nahal Shiqma area are shown in Table 7.

Table 7: Typical values of duration and probability of rainfall intensities, Nahal Shiqma area.

| Probability | 80% | 50% | 20% |
|---|---|---|---|
| Duration, min. | | | |
| 15 | 25.6 | 32 | 48 |
| 30 | 17 | 21 | 33 |
| 60 | 11.5 | 14 | 21.5 |

Flows in Nahal Shiqma are discrete floods which usually last from less than one day to a few days. Several typical flow events, ranging in peak discharge from 10 to more than 100 m3/sec, are shown in Figs. 38-43. All records refer to Israel Hydrological Service Station No. 21130 at Beror Hayil (Fig. 37). As evident from a frequency-duration analysis (Fig. 44), flows at discharge levels capable of moving sand (assume a threshold of 5-10 m3/sec) are infrequent and do not exceed, in total, 100 days over a period of 27 years. Flows capable of moving coarse particles (assume a threshold >20 m3/sec) occur for an aggregate duration of about 10 days, and represent less than 0.1% of total time.

These characteristics seem to be rather similar to those prevalent at some of the Botswana sand streams like the Metsemotlhaba. This similarity seems to apply also to the characteristics of peak discharges (Fig. 45), though the short duration of record in the Metsemotlhaba precludes a firmer statement. At Nahal Shiqma, the recurrence interval of an event which causes substantial movement of coarse bed material (estimated at >40 m3/sec) is 2.3 years. If the annual series, on which Fig. 45 is based, is transformed into a partial duration series, the conclusion is that such an event occurs, on the average, once a year or at least twice in 3 years.

Prior to the onset of the rain season 1987/88, a typical 1 km long channel reach in the western part of the catchment was selected. The selected reach has not been canalized or otherwise substantially disturbed by engineering works. The catchment area to the study reach is 510 sq km and the channel slope was found to be 0.184% . These values, especially the slope, are quite similar to the Metsemotlhaba at the investigated reach.

Nine cross sections were surveyed along the Shiqma study reach and four chain sections, totalling fourteen 1 m long scour chains, were installed. Two categories of magnetized tracer bed particles were inserted: 400 small artificial particles and 140 large natural pebbles. The sizes and characteristics were identical to those used in Botswana.

During the flow season of 1987/88 the project gauging station was not yet in operation. The events recorded during that season at the IHS station at Beror Hayil, 3.5 km upstream of the study reach, are listed in Table 8.

Table 8: Flows, Beror Hayil Station, Nahal Shiqma, 1987/88; Courtesy Israel Hydrological Service

| Event | Date | Peak discharge, m3/sec |
|---|---|---|
| 1 | 2- 5 Feb 88 | 3 |
| 2 | 17-21 Feb 88 | 8 |
| 3 | 23-28 Feb 88 | 23 |

During event 2 velocity measurements enabled the backward computation of the Manning friction coefficient, which was found to be 0.030.

Event 2 entrained practically all tracers and caused their burial to varying depths. A comprehensive survey following event 3 yielded a 50% recovery rate for the large particles and a 32% recovery rate for the small ones. Longitudinal displacement ranged from 20 to 850 m. Vertical displacement (nearly in all cases by burial) ranged from 0 to 15 cm for the small particles and from 0 to 45 cm for the large ones.

The experience of the 1987/88 season suggested that even moderate flows have the capacity to entrain, transport, and bury particles which are several phi units larger than the median size of the channel bed material. This material is nearly exclusively sand, and it is probable that the coarser material is drastically supply limited. In anticipation of the 1988/89 season an ENMOS water level recorder has been installed on site. Regular post-event tracer surveys have been initiated. In addition, 25 boulders, weight 4-5 kg each, have been placed in the study reach. Correlations between vertical and horizontal displacements of the tracers and the event characteristics have been studied as part of the MSc thesis of Shlomo Sharoni (Appendix B).

## PART FIVE - CONCLUSION

### 15 - SUMMARY

Three main conclusions emerge from the research work performed in the framework of this project :

On the general science level, coarse sediment tracing in sandy matrix proved to be a powerful and versatile research tool, and has the potential to correlate, together with other geomorphic and sedimentologic criteria, with the magnitude and frequency of the flows which cause them to move. The scour-fill controlled model of coarse particle translocation by floods has been qualitatively substantiated and may serve as a promising basis for a long-term and more detailed determination of the tracer-flow history relationship in sand rivers. A massive database of tracer dispersion has been constructed. This database, though overshadowed by the effects of two high magnitude - low frequency events which had occurred during the four year research period, is of a pioneering value and is certain to be of use in future research. Such research depends on the one hand, on further monitoring, at reasonable multi-annual intervals, of the three- dimensional dispersion of the Metsemotlhaba traced particle population and on the construction of a numerical model of this dispersion, taking into account the relevant hydrologic and sedimentologic parameters.

On a more local level, it became clear that the transport of sand by the floods of the Botswana sand rivers exceeds by far whatever values were assumed before (e.g. from the Nuane Report). The Botswana sand rivers are dynamic systems in which the available sand volumes are eroded and transported at appreciable rates. Further, this research strongly suggests that, in general, the sand rivers may not be in dynamic equilibrium in the sense that, over time, the available sand volumes in the channel beds are replaced by flood deposition at a slower rate than the rate of removal by flood erosion. The sand may, therefore, constitute a non-renewable resource inherited from a set of hydroclimatic conditions operating in the (geologically) recent past and different from those today. If the current global warming will express itself in an increased incidence of major floods in Botswana, and in a parallel diminution of medium and small rainstorms, the above trend may be expected to become more prominent. Thus the river channel sand deposits, which do not exceed in most rivers a few meters in depth, are -- over the next few decades -- in a danger of serious degradation. The prime importance of this resource as a shallow aquifer for much of the Botswana livestock calls for urgent further research on this problem.

On the LDC cooperation level, the project has experienced substantial difficulties in running a process-based field study in Botswana. Despite the efficient cooperation between the visiting PI and the resident PI, the proximity of a science base at the University of Botswana, and the sustained help from Government organizations such as WAD, the caliber of the local observing staff and the lack of intermediate research-oriented personnel posed severe limitations. Our effort to bridge this gap, based partly on a larger than usual field presence of the senior staff and on high-tech instrumentation, has been only partially successful.

## 16 - RECOMMENDATIONS FOR FURTHER RESEARCH

(1) In order to maximize the considerable investment made in this project, a resurvey of the Metsemotlhaba tracers should be undertaken at reasonable time intervals (e.g. in 1-2 and in 4-6 years).

(2) A concentrated research effort should be made to construct a process- based numerical model describing the three-dimensional fluvial dispersion of pebble-sized tracers in sand streams.

(3) A geomorphological study of the potential upstream source areas of the fluvial sand in the Metsemotlhaba and in other Botswana rivers should be undertaken. The loci, extent and characteristics of the downstream depositional areas of the fluvial sand (in non-dammed rivers) should be determined. A morphoclimatic historical interpretation of the fluvial sand deposits should be attempted and combined with the above.

(4) Sediment studies on several selected sand rivers in Botswana should be undertaken and maintained on a routine basis. Sediment studies in reservoirs should be performed at appropriate time intervals.

APPENDIX A

Paper submitted to the East African Agricultural and Forestry Journal

# THE SAND RIVERS OF BOTSWANA - A TRANSIENT RESOURCE ?

Paul A. Shaw * and Asher P. Schick **

* University of Botswana, Gaborone, Botswana
** Hebrew University, Jerusalem, Israel

ABSTRACT

The sand beds of the seasonal rivers of Eastern Botswana, which drain the terrain east of the African continental divide towards the Limpopo River, serve as a shallow aquifer replenished by percolating summer flows. Holes dug in the bed in the dry winter months provide water for cattle and domestic use.

At present it is not known whether the sand deposits, which can be several metres deep and extend tens of kilometres length ways, are a relict from a different (more humid ?) climate or represent the normal sediment stores in transit from headwaters to mouth. Recent studies on the Metsemotlhaba River show that major flood events activate the sand bed to depths of many decimetres, moving much larger quantities of sand than previously anticipated.

Detailed observations along a selected river reach, aided by repeated surveys, scour chains and magnetic tracers, suggest that large events degrade the bed while small events aggrade it. The patterns of sediment movement have implications for water impoundment schemes of all scales. Furthermore a depletion of the sand aquifer may follow a shift in the earlier balance between the frequencies of large and small floods, with possible consequences for rural water supplies.

## INTRODUCTION

Sand rivers can be defined as broad, low gradient ephemeral rivers with beds composed predominantly of medium to coarse sand. They are a common feature of arid and semi-arid tropical environments. In southern Africa they were described by early European travellers in Botswana/South Africa (e.g. Cornwallis Harris, 1852), Namibia (Andersson, 1857) and Zimbabwe (Selous, 1893). Some were unlucky enough to encounter a sand river in full spate, as did Richard Frewen in eastern Botswana in 1878 (Tabler, 1960).

In countries where water resources are scarce, sand rivers assume enormous importance. In Botswana some 30% of the rural population extract their water supplies from wells dug into the beds of sand rivers, whilst in Namibia a pumping station at Rooibank on the Swakop River has extracted water for the nearby town of Swakopmund for over a century. Although surface flows are sporadic, and dam sites poor, a series of massive dams has been planned for Eastern Botswana on the Shashe, Motloutse, Lotsane and Mahalapye Rivers, to be connected by a pipeline in the next decade. The construction of small dams, using earth bunds, has been widespread for the past 100 years, and has already been extended to most small tributaries. The rivers are also an important source of sand, both for building materials, and for smelting flux, as at the Selebi Phikwe mine.

Despite their importance as a resource, the history, hydrology and sediment transport of sand rivers is poorly understood. This is due to a number of factors, which include

their relative inaccessibility, lack of suitable techniques for monitoring, and from a scientific viewpoint, the practical difficulties of studying a hydrological system which tends to be both erratic and extreme in its behaviour. In the past most estimates of sediment movement have come from small plot studies, which provide a very limited view, or from the measurement of sediment in dams, which tends to reflect conditions in the immediate upstream reach only. Catchment studies (e.g. Sutherland and Bryan (1991) in Kenya), and the study of specific hydrological events (e.g. Frostick and Reid (1979) in Kenya) have become prominent only in the past fifteen years. This paper describes the sand rivers of Botswana, and the setting up of a monitoring programme to study sediment transport in them. The significance of some preliminary results to the sand river resource are discussed.

## THE DISTRIBUTION AND MORPHOLOGY OF SAND RIVERS

Sand rivers in Botswana are mostly restricted to the eastern part of the country, known as the Hardveld; an ancient erosion surface on which bedrock lies close to the surface. Here a series of rivers drain eastward from the Kalahari watershed, known as the Kalahari-Zimbabwe divide, to form the left bank tributaries of the Limpopo River (Figure 1). The evolution of these rivers has been strongly influenced by Tertiary uplift along the Kalahari-Zimbabwe divide (Shaw, 1989). Some streams, such as the Nata and Mosetse, drain hardveld west towards Sua Pan, but are only sand rivers in part.

The morphology and sediment characteristics of the major sand rivers have been studied in detail by Wikner (1980) and Nord (1985) as part of hydrological resource surveys. In northeast Botswana rivers such as the Shashe, Tati and Motloutse have very low gradients (0.15-0.20%) and have sand beds throughout their lengths, with sand and gravel thicknesses of up to 15 metres over Precambrian bedrock. In southeastern Botswana rivers such as the Metsemotlhaba have sand beds only in their upper catchments (average depth 3-6 metres), with lower segments composed of rock beds or alluvial infill.

The sand deposits usually occur as a continuous layer over a series of basins in the channel substrate, leading to a discontinuous aquifer controlled by buried rock barriers. The sand bed aquifer is recharged by direct rainfall onto the river bed, and by surface run-off in the channel. It can have great potential, for example, the Shashe has an estimated resource of 28,000 $m^3$/km in its upper reaches, and the Motloutse above Mmadinare some 37,000 $m^3$/km (Wikner, 1980). In some areas there are substrates of finer material of low permeability which affect both aquifer recharge (Sir Alexander Gibb and Partners, 1970), and sediment transport patterns (Crerar et al, 1988). Botswana's sand rivers are of lower gradient, and contain fewer clay strata, than those of Namibia (Wipplinger, 1958).

## THE PALAEOENVIRONMENTAL HISTORY OF SAND RIVERS

The juxtaposition of sand, alluvial and rock bed rivers raises questions about long term evolution which have not yet

been answered. The presence of extensive terrace sequences, often containing large pebbles and cobbles, on the Notwane River led Wayland (1950) to suggest that re-excavation of earlier infill under a different climatic regime had occurred, but the terraces have never been mapped, and the hypothesis remains to be tested. However, there is a general belief that sand rivers originate by valley erosion during humid geological periods, with subsequent sand deposition during more arid phases when rivers are unable to cope with sediment loads (e.g. Nord, 1985). By extension of this argument the sand beds must therefore be fossil forms with restricted movement under present climatic conditions, particularly as high permeability would lead to rapid absorption of flow into the underlying aquifer.

An alternative hypothesis is that the sand rivers represent equilibrium forms in which sand beds accumulate wherever there is sufficient sediment and water input. This may be applicable to rivers which have sand beds in their upper catchments, such as the Metsemotlhaba (Figure 2). In this stream the sand bed persists between the confluence of rock bed low-order tributaries near Moshupa, and Kopong 60 km downstream, where reduced gradients and diminished flow lead to anastomosing channels cut in alluvium. This hypothesis is supported by empirical studies of the Motloutse River (Sir Malcolm McDonald and Partners, 1989) which show that sediment input into sand rivers is by no means uniform, and is dependent on minor variations in topography, rock type and land use. The long term evolution of sand rivers is a fundamental question which has bearing on their future as a resource, which can be partially answered by experimental work.

THE HYDROLOGY OF SAND RIVERS

Sand rivers are ephemeral by nature, flowing in response to precipitation events within their catchments. In southern Africa most precipitation falls within the summer months, so such flows tend to be restricted to that season. The flows, like the precipitation, exhibit high intra-annual and inter-annual variability. Gauging of the Mahalapye River, for example, has indicated that the river has only failed to flow on two years out of the past 100, with an extreme dry period averaging 10 months (VIAK, 1984). Some fluvial activity can thus be expected every year, with several flood events during good rain seasons.

The hydrograph of a flow event (Figure 3) has the characteristic steep rising limb of a flash flood, with initial flow sometimes occurring as a bore. Flows in response to individual precipitation events are short, usually returning to base flow within three days, although longer flows may occur in response to prolonged, widespread rain. As would be expected, there is high transmission loss by recharge of the sand bed.

The main characteristics of sediment transport in arid and semi-arid rivers have been summarised elsewhere (e.g Reid and Frostick, 1989).The movement of sediment through bedload and suspended load is, of course, restricted to the duration of flow events, although there may be transmission of solutes through the aquifer. The dominant process appears to be the scouring of the upper layer of bed sediments during the rising flow, and deposition by fill as the flow recedes. The depth of scour, volume and distance of sediment movement are dependent on a

number of factors, including channel morphology, flood magnitude and duration. All experimental data on sediment transport, particularly bedload transport, has limitations (Gomez, 1991). Most has come from gravel bed rivers where available techniques are easier to employ; sand rivers are poorly represented in the scientific corpus.

## THE METSEMOTLHABA PROJECT

In 1986 a collaborative research programme was set up between the Department of Physical Geography, Hebrew University, and the Department of Environmental Science, University of Botswana, to study floods in sand rivers in both countries. It is referred to as the Metsemotlhaba Project after the principal investigation site in Botswana, although a total of three sites were used in Botswana, and one in Israel. The results discussed here were drawn mostly from the Metsemotlhaba River site.

The overall long-term aim of the project was to establish a method for using the three-dimensional dispersion of traceable sediment particles by floods to evaluate flow attributes and stream regime. Such a method would be of importance in planning development projects involving ungauged streams, particularly in developing countries where hydrological monitoring networks are poorly developed, and financial resources are not always available.

Data collection focused on both hydrological and sediment monitoring. At Metsemotlhaba a 1400 metre reach of the river was surveyed longitudinally, and as a series of cross sections 100

m apart. The periodic resurvey of established sections provided the information on bulk changes over time. Scour and fill of the largest annual flood were measured from six sections containing a total of 60 scour chains, whilst magnetic tracers were used to simulate the movement of individual particles. Initially 744 particles were injected in six lines, of which 595 were synthetic tracer some 15 gm mass, the remaining 149 were larger (32-90 mm) tagged pebbles of Judean limestone. A subsequent generation of 200 synthetic tracers was injected in June 1990. In the first year data on suspended sediment load was collected using two Hayim 7 multiple stage automatic suspended samplers.

Flows were measured using two transducer based automatic stage recorders at 100 m and 1100 m on the profile, collecting information at two minute intervals on ENMOS recorders, whilst two automatic rainfall gauges used similar recording devices. This data could be compared with conventional readings from manual rainfall gauges at Thamaga and Moshupa, and a mechanical water stage recorder operated at Thamaga by the Department of Water Affairs. Other surveys included flow velocity measurements and sediment sampling.

## PRELIMINARY RESULTS

The original intention was to collect precipitation and flow data continuously, whilst assessing the changes to bed morphology and tracer distribution on a flow by flow basis. This turned out to be impractical as raised water tables in the sand bed after each flow precluded the relocation of tracers and chains.

Resurvey of chains, sections and tracers was then carried out in the dry season and linked to the previous wet season flows.

Some difficulties were encountered with equipment, particularly the Hayim sediment samplers, which proved to be unanchorable in a sand bed, and the ENMOS data collection system, which suffered from a number of different problems. Of more importance was the incidence of a high magnitude flood event in December 1977, shortly after the equipment was commissioned, which damaged much of the instrumentation, but ultimately provided some unique data.

Monitoring to date has covered the wet seasons 1987-8, 88-89, 89-90 and 90-91, with resurvey of the site in February and September 1988, October 1989, June 1990 and August 1991. In these seasons the river experienced low flows in 88-89, moderate flows in 89-90, and three of the largest flow events on record; December 1987, February 1988 and March 1991. The analysis of the data is not yet sufficiently advanced to comment on its applicability to the original aims of the project, but the main results can be summarised as follows:

1: The sampling programme covered a wide range of flow conditions, from minor events (<1 $m^3$/sec) upto floods of an approximate discharge of 130 $m^3$/sec, with a return period of about 20 years. Tracer movement occurred with flows of less than 10 $m^3$/sec peak discharge, and proved useful in demonstrating patterns of bedform movement at this magnitude.

2: Transport of sediment in larger floods far exceeded previously assumed values. The December 1987 flood entrained all of the tracer, and 165 particles (22.3%) were recovered at the

end of the season. The mean distance of movement was 924 m and the mean depth of burial 44 cm. Some of the particles moved beyond the measured reach to 2 km downstream. Subsequent evaluations of major floods in the Metsemotlhaba, and the other Botswana sites of Taupye and Bonwapitse indicate that this is the normal behaviour of the particles. Recovery rate of tracer in the Metsemotlhaba averages 25 % per annum.

3: Cross sections indicate that scour is the predominant activity in large floods, with subsequent aggradation during lesser events (e.g. Figure 4). The December 1987 flood led to net degradation of 5,130 $m^3$ in the measured reach, with net accumulation of 1,590 $m^3$ in the following three moderate events (Figure 5). The loss of all of the upstream scour chains in the December 1987 event suggests depths of scour exceeding 1 m during the rising limb. The only surviving chain line, at 880 m, indicated scour and fill of the order 50-70 cm.

4: The three dimensional distribution of particles (horizontal = downstream, vertical = burial) (Figure 6) can be explained by a model in which movement of all tracer is initiated by the floodwave, with maximal scouring at, or shortly after the time of entrainment. Deposition occurs simultaneously with sediment fill, thus the tracers which move short distances are buried most deeply, whilst those continuing to move into the later stages of the flood recession have shallow locations.

## CONCLUSION : LONGTERM PROSPECTS AND APPLICATIONS

The mobility of sediment associated with high magnitude

flood events has implications for the interpretation of the origins of sand rivers, and for their usage. Pre-instrumental records of the Metsemotlhaba River indicate that large floods occurred in 1945, 1967, 1968 and 1974, and it is probable that floods capable of moving substantial amounts of sediment have occurred at least 8 times during the past fifty years. This does not accord with the hypothesis that sand rivers are stable "fossil" forms. A more likely scenario is that the sand beds are an equilibrium storage form receiving sediment influx at specific points in the catchment (small tributaries, lateral over-bank recharge) where relief, soils and land use favour sediment mobilisation. Transport through the main sand storage is then as a series of increments corresponding to large flood events. A sampling programme to examine the bed sediment characteristics throughout the catchment is now required to test this hypothesis further.

Dam construction on both large and small scales is likely to be affected by sedimentation. Empirical studies of major dam studies on the Mahalapye and Motloutse Rivers suggests that the proposed dam sites are located at points of sediment influx (Sir Malcolm MacDonald and Partners, 1989; Aquatech, 1989), and that dam sedimentation rates are likely to be higher than suggested by present studies on reservoirs, particularly if a large flood occurs shortly after dam closure. The impact of sand transport on small dams is now being assessed.

The present study has shown that integrated tracer/mass budget studies are a valuable aid to hydrometry. Some of the techniques employed in this study, such as cross-section surveys,

are now being incorporated into Department of Water Affairs monitoring programmes in Botswana.

ACKNOWLEDGEMENTS

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Figure 6: Longitudinal and vertical displacement of small magnetic particles in the Metsemotlhaba River, between September 1987 and September 1988. The curve, based on squares computed for 200 m long reaches, indicates the depth limit of 80% of the particles.



38

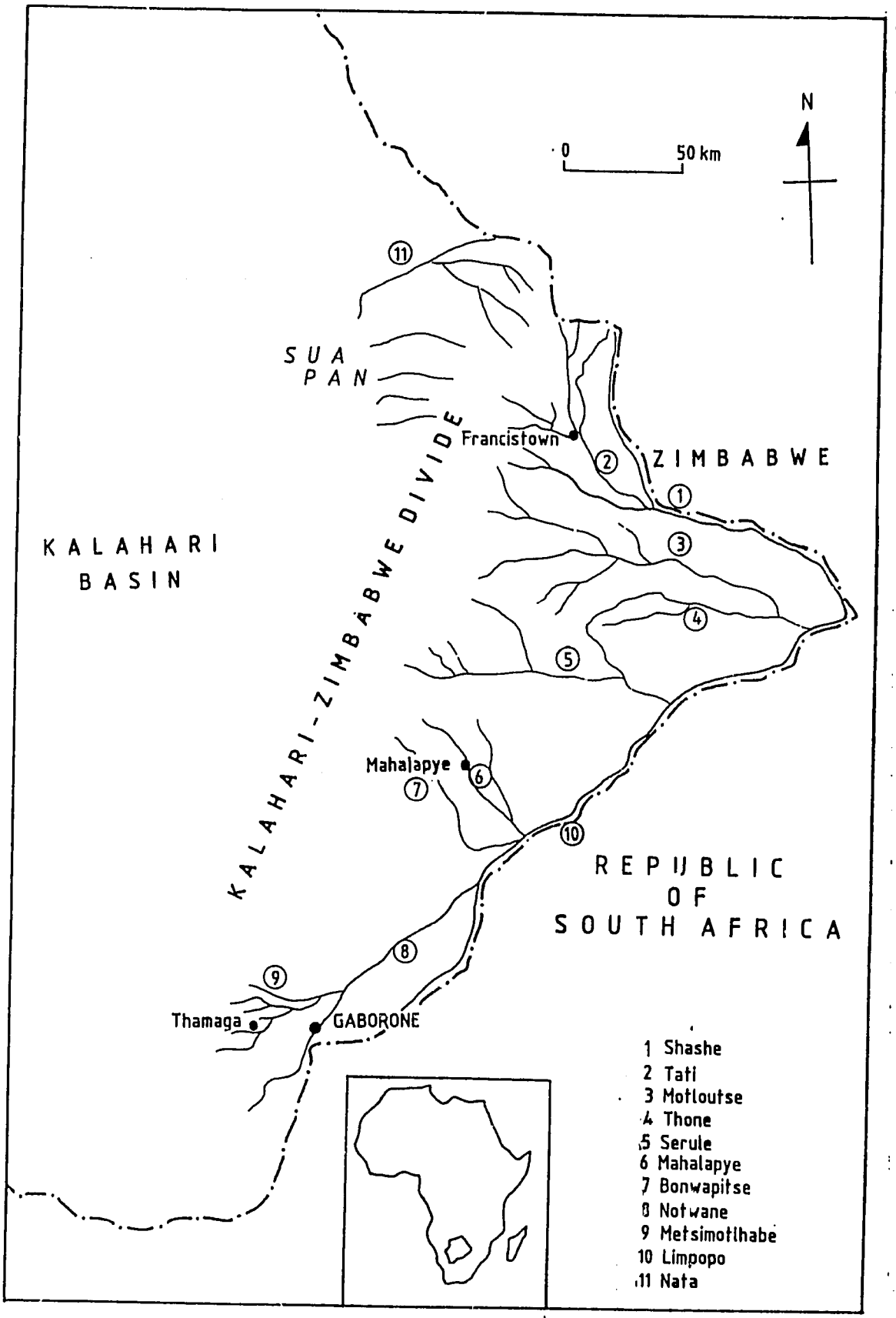

N
0
50 km
SUA PAN
Francistown
ZIMBABWE
KALAHARI BASIN
KALAHARI-ZIMBABWE DIVIDE
Mahalapye
REPUBLIC OF SOUTH AFRICA
Thamaga
GABORONE
1 Shashe
2 Tati
3 Motloutse
4 Thone
5 Serule
6 Mahalapye
7 Bonwapitse
8 Notwane
9 Metsimotlhabe
10 Limpopo
11 Nata

Fig. 1

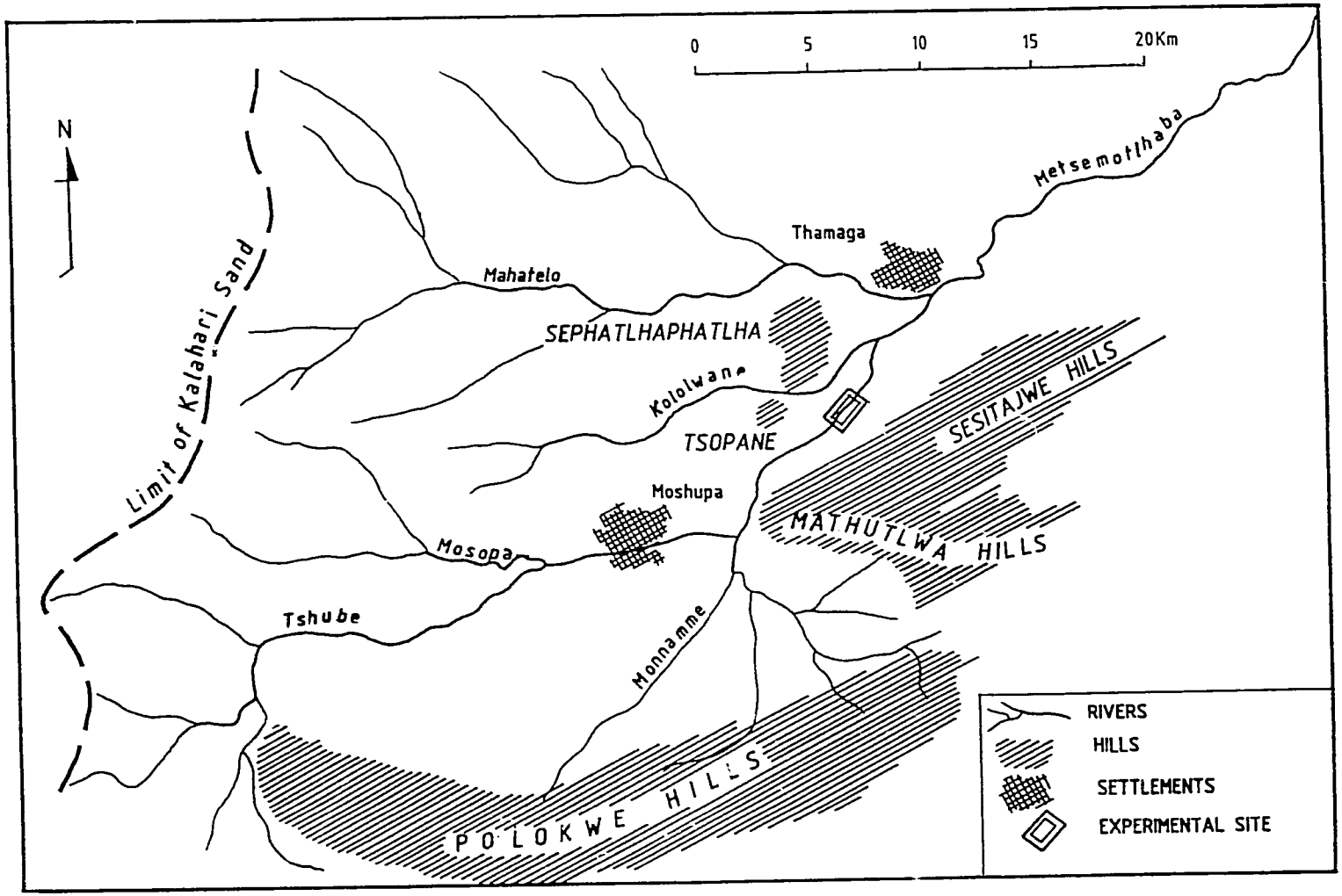
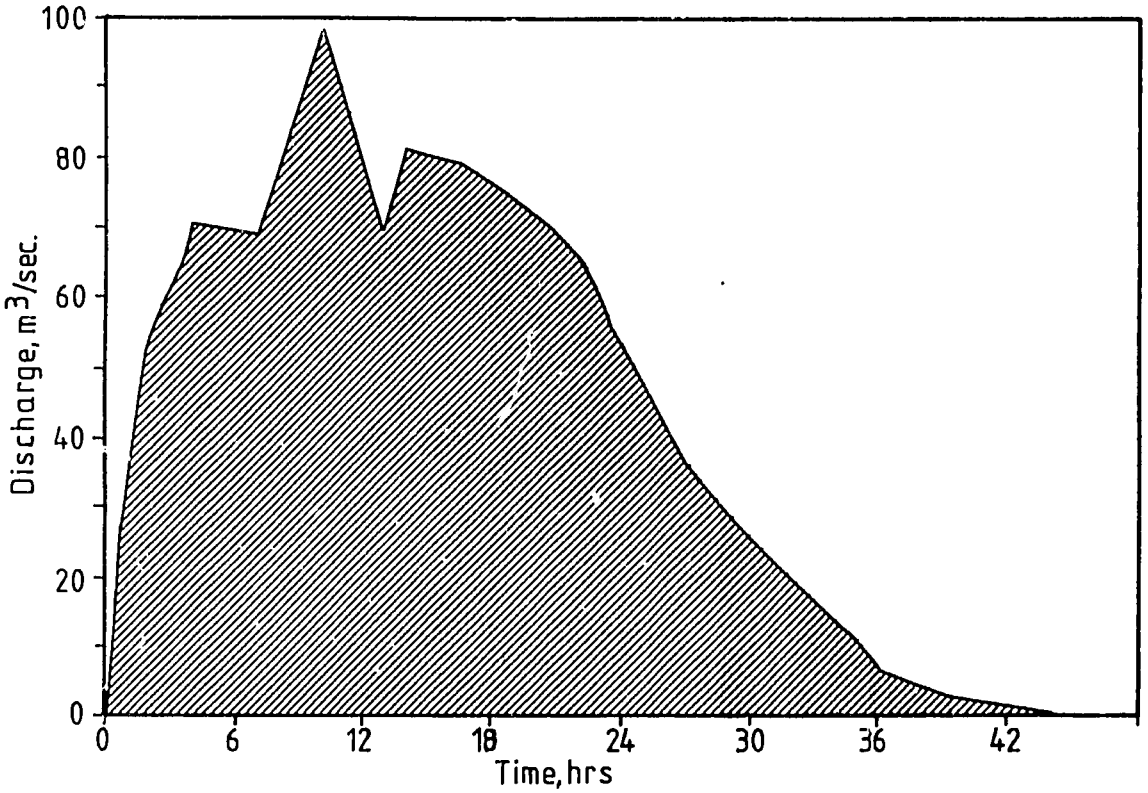

0
5
10
15
20Km
N
Limit of Kalahari Sand
Metsemotlhaba
Thamaga
Mahatelo
SEPHATLHAPHATLHA
Kololwane
TSOPANE
SESITAJWE HILLS
Moshupa
MATHUTLWA HILLS
Mosopa
Tshube
Monnamme
POLOKWE HILLS
RIVERS
HILLS
SETTLEMENTS
EXPERIMENTAL SITE

Fig. 2

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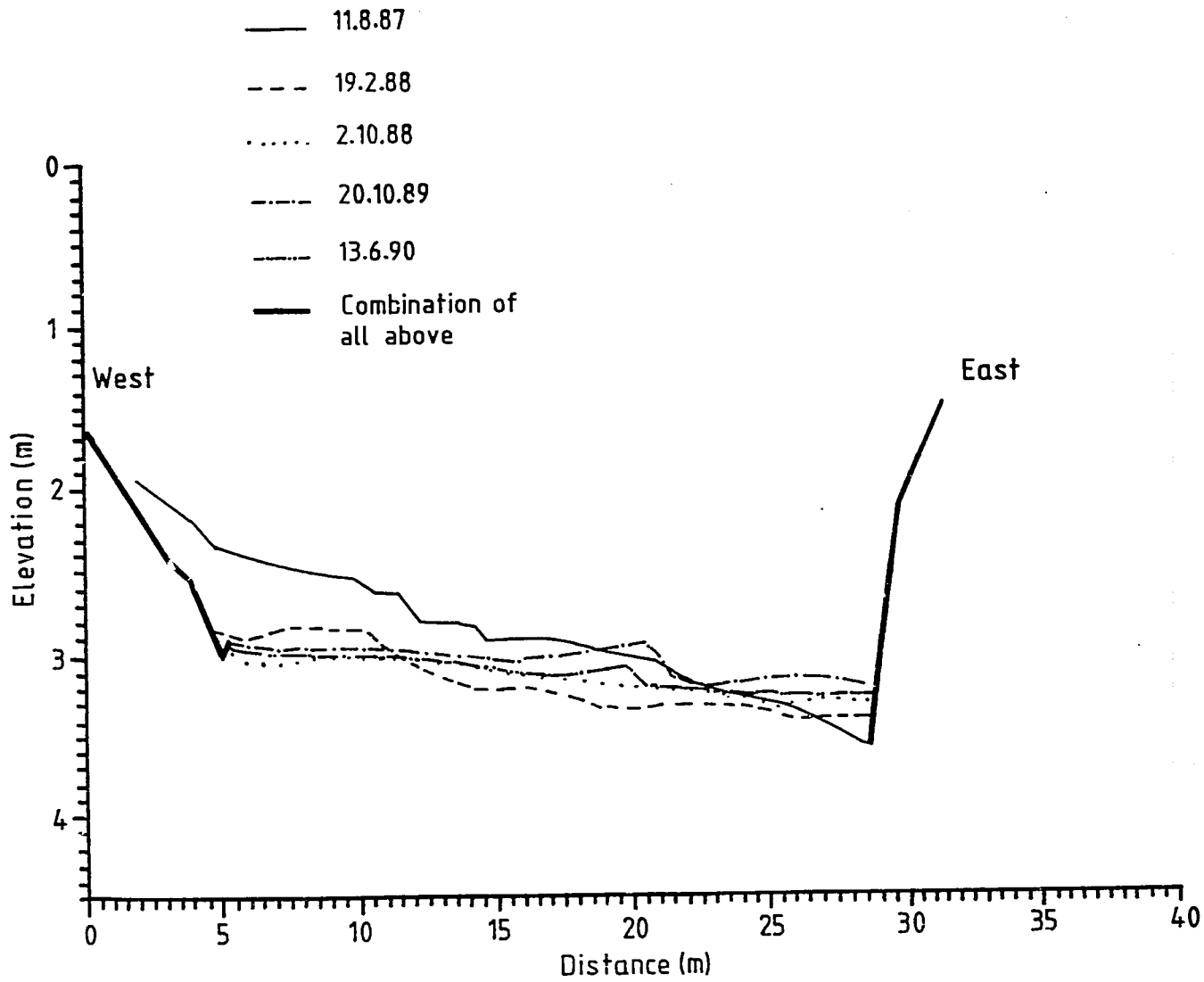
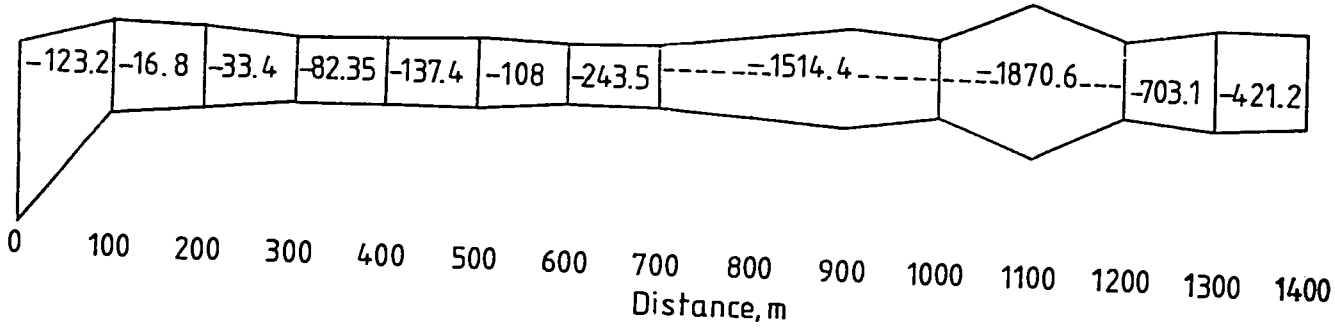

11.8.87
19.2.88
2.10.88
20.10.89
13.6.90
Combination of all above
West
East
Elevation (m)
0
1
2
3
4
0
5
10
15
20
25
30
35
40
Distance (m)

Fig. 4

A)


-123.2
-16.8
-33.4
-82.35
-137.4
-108
-243.5
-1514.4
-1870.6
-703.1
-421.2
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Distance, m

B)

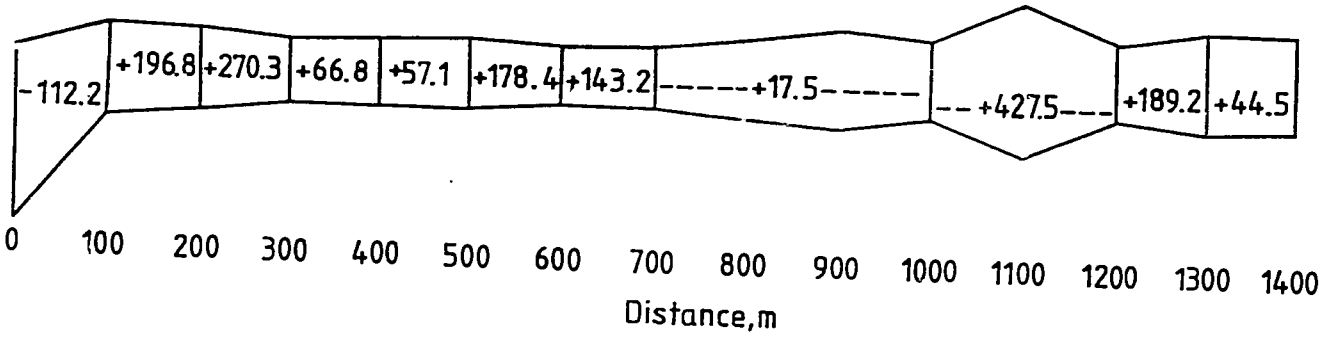

-112.2
+196.8
+270.3
+66.8
+57.1
+178.4
+143.2
+17.5
+427.5
+189.2
+44.5
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Distance,m

Fig. 5

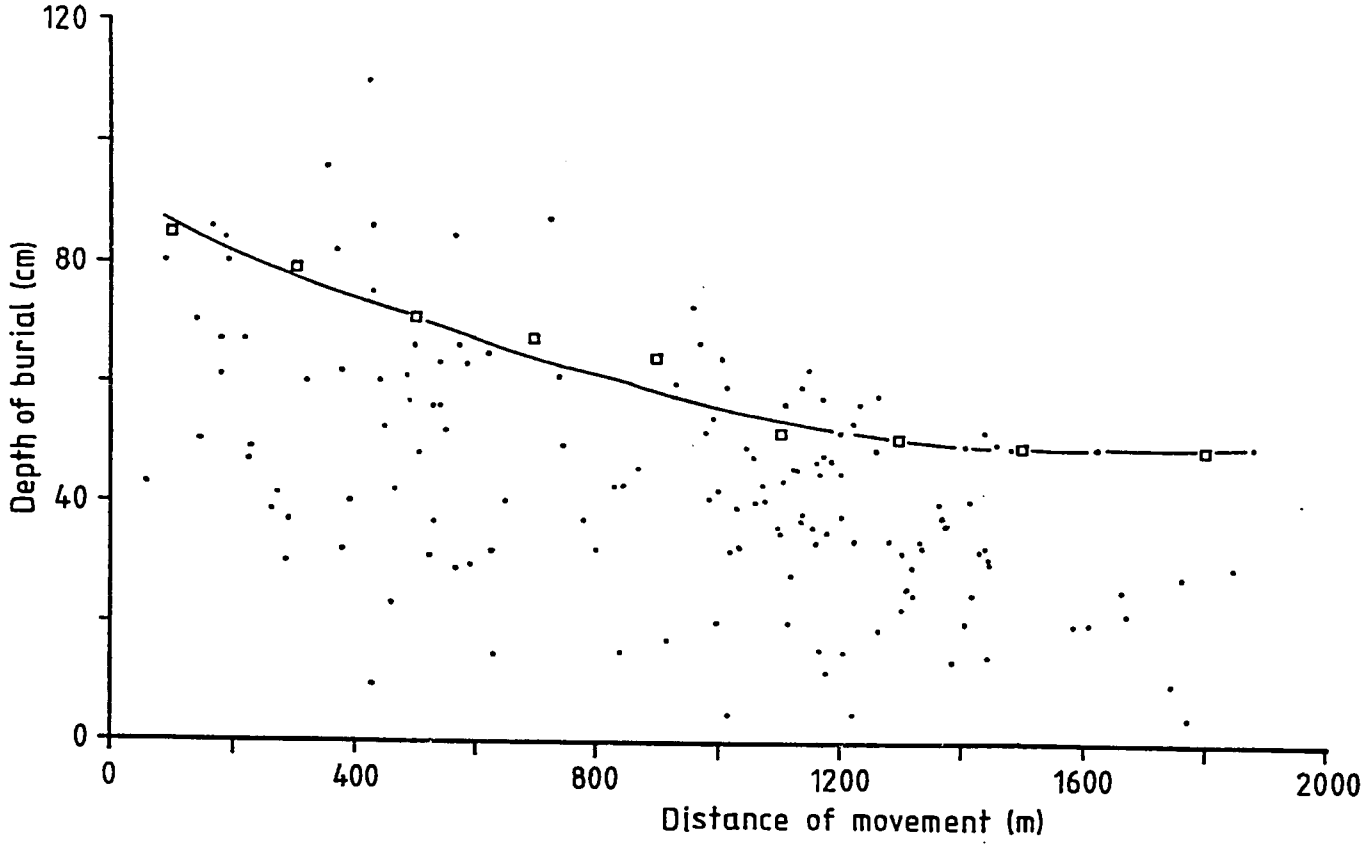

120
80
40
0
Depth of burial (cm)
0
400
800
1200
1600
2000
Distance of movement (m)

Fig. 6

Appendix B – SEDIMENT TRACING IN NAHAL SHIQMA, ISRAEL; THE MOVEMENT OF COARSE MAGNETIC PEBBLES IN A LOW GRADIENT SAND BED

Abstract of MSc thesis by Shlomo Sharoni

## INTRODUCTION

In sandy bed rivers, bed forms are related to stream power and particle diameter (Simons&Richardson 1966). The geometry of the bed form is dependent upon the bed material properties and the sediment transport rate. The dune dimensions are related to the depth of flow.

When dealing with flow regime sandy bed rivers are usually classified as flowing in lower or upper regime. The flow regime controls the bed form (Simons&Richardson 1966; and others). In the lower flow regime, the common bed forms are dunes and ripples, while in the upper flow regime the common bed forms are plane bed and anti-dunes. Those two types of flow are connected by a transition zone, and are strongly related to Froude number.

In general, the literature refers to the flow as being in the upper regime when the Froude number exceeds unity, and in the lower regime when Froude number is less than one. But, as mentioned by Simons& Simons (1987), the Froude number alone is not sufficient to distinguish between the two types of flow regime.

Often a stream which, in its upstream parts, has a bed which consists of larger particles (e.g. cobbles or gravel), changes as the flow increases downstream, to a bed with a small particle size, e.g. sand.

A large number of publications deals with the reasons for this downstream diminution. As mentioned by Ikeda&Iseya (1988), there are two alternative, or complementary explanations: abrasion and sorting due to gradient decrease downstream.

## RESEARCH OBJECTIVES

1. To trace the movement and dispersion of coarse pebbles in a sandy bed, ephemeral river.

2. To substantiate the causal linkage between certain diagnostic geomorphic attributes of a sandy bed ephemeral stream and its flooding characteristics.

In attempting to achieve these objectives, a contribution to the solution of the question why gravel bed rivers change into sandy bed rivers, under certain lithological condition, was being sought.

## THE STUDY LOCATION

The Nahal Shiqma watershed is located in the Northern Negev, alias the Southern Lakhish region, in central-south Israel. The watershed lies between meridians 34°28'-35°01' and parallels 31°23'-31°40' (Fig. 37). The general orientation of the watershed is ESE-WNW. Its elevation ranges from sea level to 900m in the eastern mountainous part. The catchment is 50 km long, with the longest tributary being 70 km. Watershed width varies between 10 and 27 km. Three physiographic zones are distinguished, from east to west: a mountain and foothill region (300-900m), a region of undulating hills (150-300m), and a coastal plain (0-150m).

The eastern zone of the catchment consists of an ancient peneplain of Turonian and Cenomonian limestone and dolomite, which is dissected by a secondary erosion cycle. The central zone results from a more recent fluvial erosive network, that cut into a more recent level of peneplanation of soft Neogene sediment. Headwaters of the erosive network are located in the Hebron anticline. A recent post Pliocene uplift contributed to the active erosive capacities of the wadis. The western zone is a flat area with small very recent deposits of aeolian sand dunes (kurkar).

Average rainfall over the entire watershed varies greatly from year to year, the driest year on record being 130mm, and the wettest year with 530mm (Fig. 38). Rainfall occurs any time between October and April. Some aspects of the flow characteristics are described in Chapter 14 (Figs. 39-44). The largest flow on record, which occurred after the project period, is shown in Fig. 46.

## RESEARCH METHODS

In order to enable the tracing of coarse pebbles, the method of magnetic tracing (Hassan et al. 1984), was chosen. Since the threshold for particle movement was unknown, small synthetic magnetic pebbles were applied alongside large natural magnetized pebbles.

During the second season of the research, when the movement of coarse material in the sandy bed was already well established, large cobbles were added to the system in order to find the upper limit for transportation.

Before the season of 1987/88, 300 artificial magnetic pebbles and 140 natural magnetic pebbles were placed on cross section 0 of the study reach. Further downstream along the study reach, nine cross sections were measured and their morphological characteristics were observed and recorded. In four of these sections scour chains (Leopold et al. 1964) were installed

.

## RESULTS

During the season of 1987/88, three flood events occurred. Their peak discharges were, respectively, 3, 7.5, and 23 $m^3$/sec.

Transport Distance (Fig. 47): In the artificial (smallest) pebbles population, all the pebbles moved to distances ranging from 10 to 1,140 m. Among the natural (bigger) pebbles 22%, did not move. The distance of movement among this group was between 10 and 600 m.

Depth of burial (Fig. 48): Only 6% of the pebbles were found on the surface. The depth of burial of the small pebbles was between 0.02 and 0.70 m. The larger pebbles were buried between 0.02 and 0.80 m. All of the large pebbles found on the surface (9% of this class) were around areas with morphological distortions (bars, micro-canyons).
Scour chains: The use of scour chain enables to monitor the depth of scour in sandy bed rivers. According to some researchers, this depth represents the maximum depth of the inter-dune depression (Colby 1964). The aggregate comparison of scour & fill volumes indicated that the stream is in an equilibrium state, and that the depth of the inter-dune depression agrees with the depth of burial.

During the season of 1988/89, six floods occurred: 7.9, 0.6, 7.5, 0.7, 4.7, and 1.9 $m^3$/sec were the maximum discharges. Prior to the onset of this rain season, 23 additional large cobbles were placed at the site, along with a simple automatic suspended sediment sampler.

Entrainment Rate and Transport Distance (Fig. 49): Small pebbles - 56%, to between 2 and 750m; large pebbles - 78.5%, to between 2 and 750 m. Standard deviations are high; hence mean transport distances are barely representative.

Depth of burial (Fig. 50): Small pebbles - 37% were found buried near the surface; additionlal 54% were buried between 0.03 and 0.25 cm. Large pebbles - only 10% were found on the surface (on bars). Large cobbles - none of them moved in the downstream direction but all of them, except those placed either on bars or at loci that contain a large proportion of clay, changed position only in the vertical sense, i.e. they underwent a process of "sinking" in place.

DISCUSSION

1. In a low gradient sandy channel bed, large pebbles move even during flood events of a short recurrence intervals. But, after being buried at a certain depth, an event of at least the same magnitude is necessary to continue the downstream movement.

2. Cobbles change their stationary placement also by sinking into the saturated sandy bed.

3. Comparing the two populations of the small and the large pebbles, a small longitudinal sorting was observed.

4. The distribution of the depth of burial at certain lengths along the study reach suggests that there may be a tendency for a preferred depth of burial

5. In some cases, large bedforms are being preserved after an event, depending on the characteristics of the hydrograph (rapid or protracted decline).

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Based on 12 resurveyed benchmark-based cross sections. Small numbers are aggradation(+) / degradation(-) values for reach between two sections. Section numbers are encircled.
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Upstream section 0 - 100 is excluded.

Fig. 15 : Change in volume of alluvial sediment, Aug 1987 to Feb 1988, Metsemotlhaba R.
Based as in Fig. 24. Small numbers are interbank section lengths in meters. Large numbers are volume changes, for each reach between two cross sections, in cubic meters. The total minimum volume exported from study reach (section 100 to section 1400) was 5,130 m3. Reach 0 - 100 was excluded from computation because of bend effects.

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Based on 12 resurveyed benchmark-based cross sections. Small numbers are aggradation(+) / degradation(-) values for reach between two sections.
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Upstream section 0 - 100 is excluded.

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Based as in Fig. 26. Small numbers are interbank section lengths in meters. Large numbers are volume changes, for each reach between two cross sections, in cubic meters. The total volume moved into study reach (section 100 to section 1400) was 1,590 m3. Reach 0 - 100 was excluded from computation because of bend effects.

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C - Longitudinal section

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Fig. 41 : Flow of 31 Jan 1974, Nahal Shiqma at Beror Hayil.

Fig. 42 : Flow of 3 Jan 1978, Nahal Shiqma at Beror Hayil.

Fig. 43 : Flow of 8 Nov 1986, Nahal Shiqma at Beror Hayil.

Fig. 44 : Flow frequency, Nahal Shiqma at Beror Hayil, 1960-1987.

Fig. 45 : Magnitude and frequency of annual flows, Nahal Shiqma at Beror Hayil, 1960-1987.

Fig. 46 : Flow of 23-25 Jan. 1991, Nahal Shiqma at Beror Hayil.

Fig. 47 : Distance moved by trace particles (N=218), Nahal Shiqma, 1987/88.

Fig. 48 : Depth of burial v. transport distance, all tracer particles (N=218), Nahal Shiqma, 1987/88.

Fig. 49 : Distance moved by trace particles, Nahal Shiqma, 1988/89.

Fig. 50 : Depth of burial v. tranport distance, Nahal Shiqma, 1988/89.

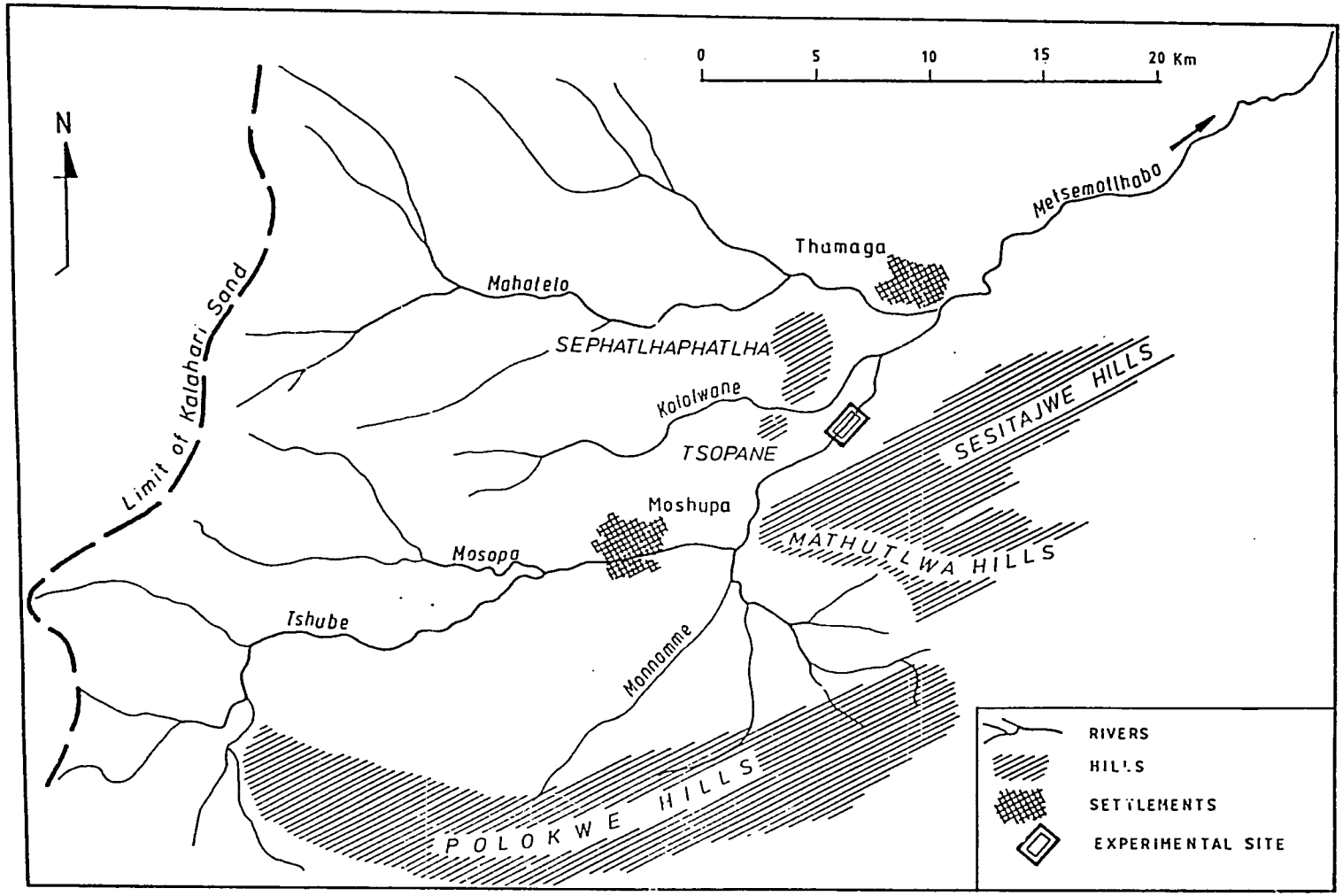



Fig. 1 : Location map : the Upper Metsemotlhaba catchment

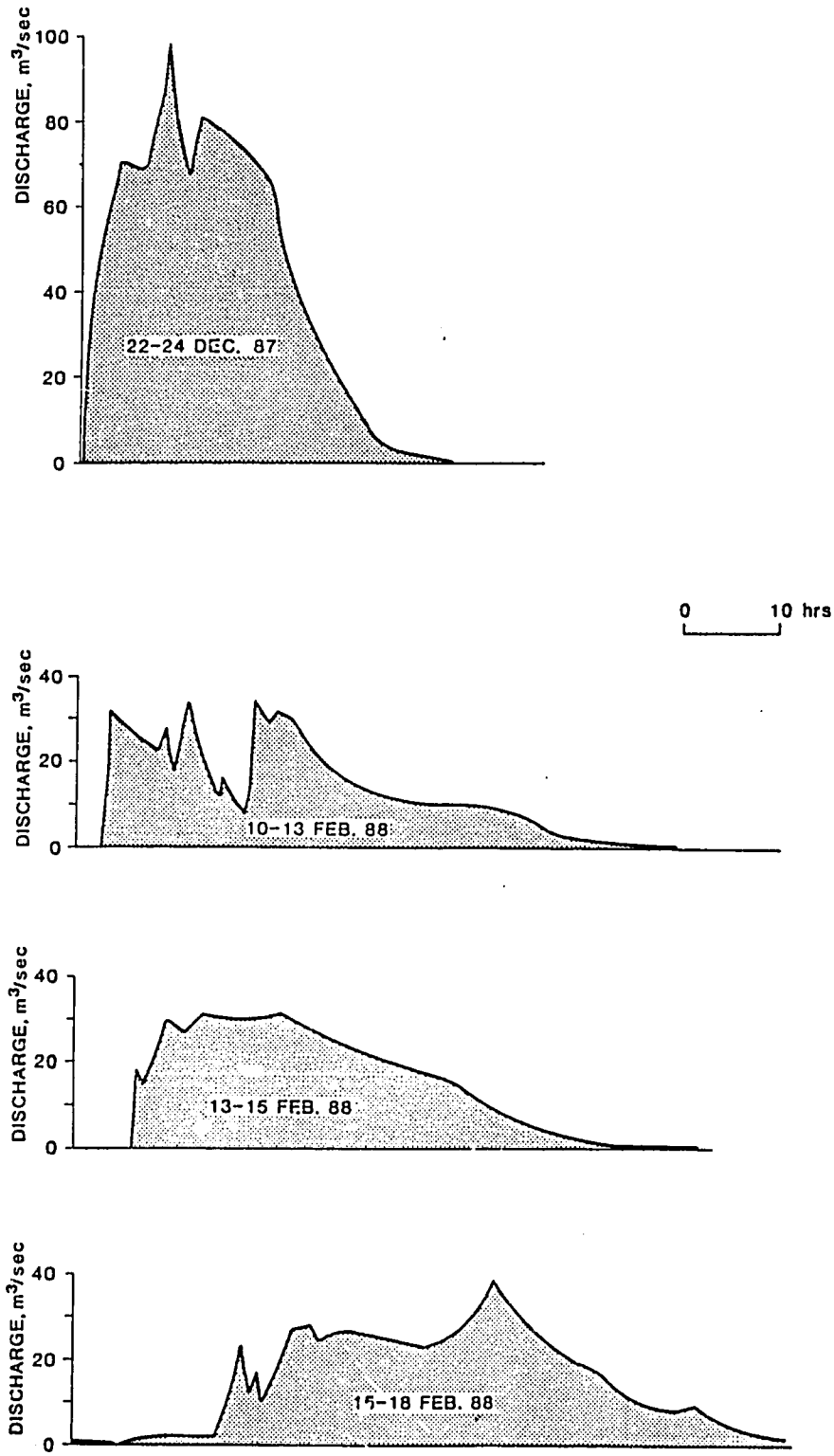



Fig. 2 : Generalized flow record, first observation period, Sep 1987 - Feb 1988
Metsemotlhaba R. at Thamaga, WAD Station 2421

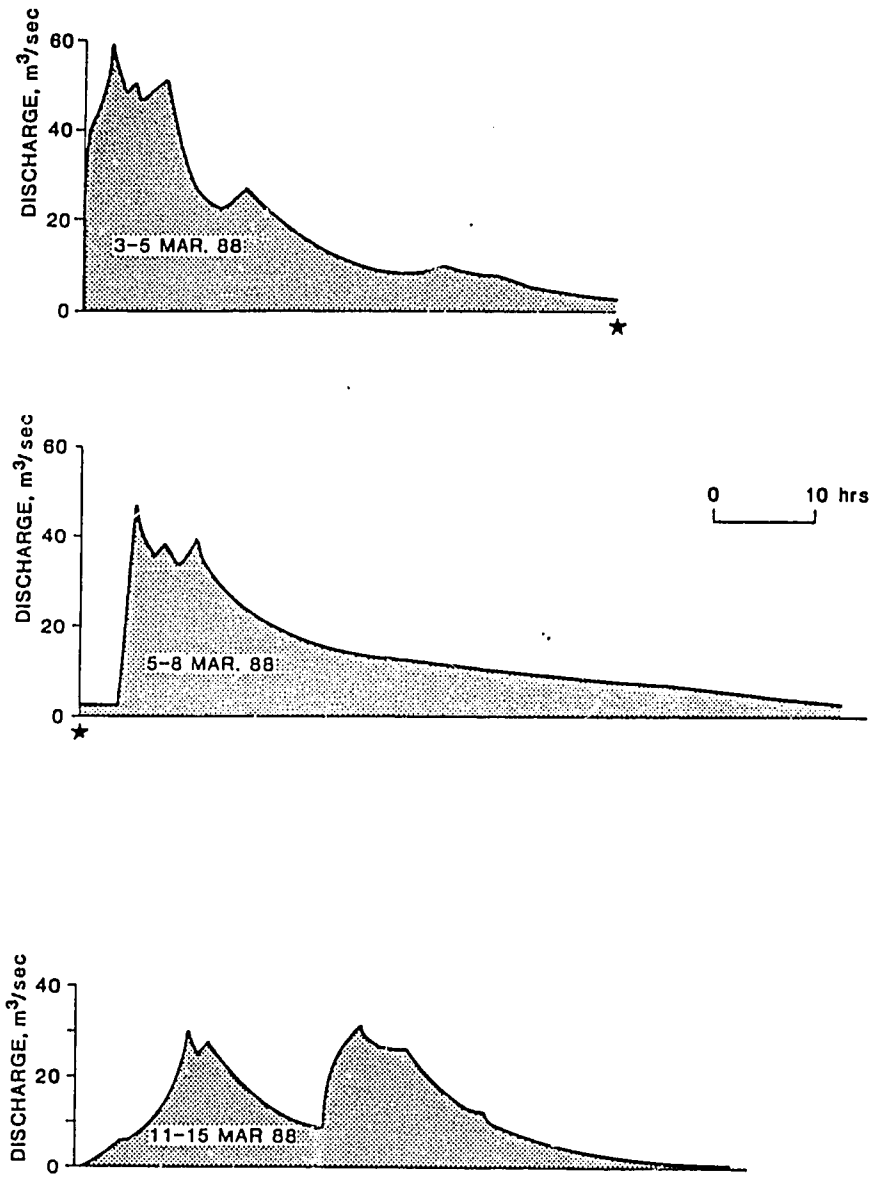



Fig. 3 : Generalized flow record, second observation period, Feb - Sep 1988
Metsemothlaba R. at Thamaga, WAD Station 2421

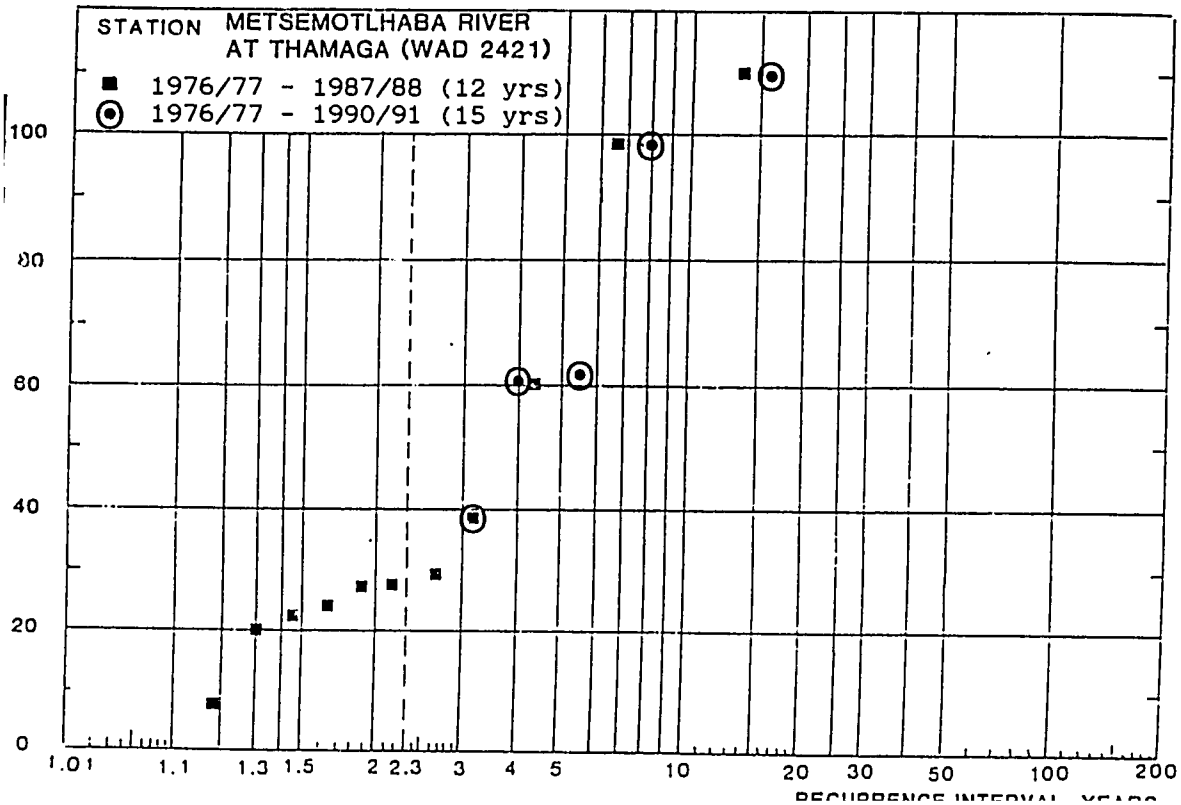
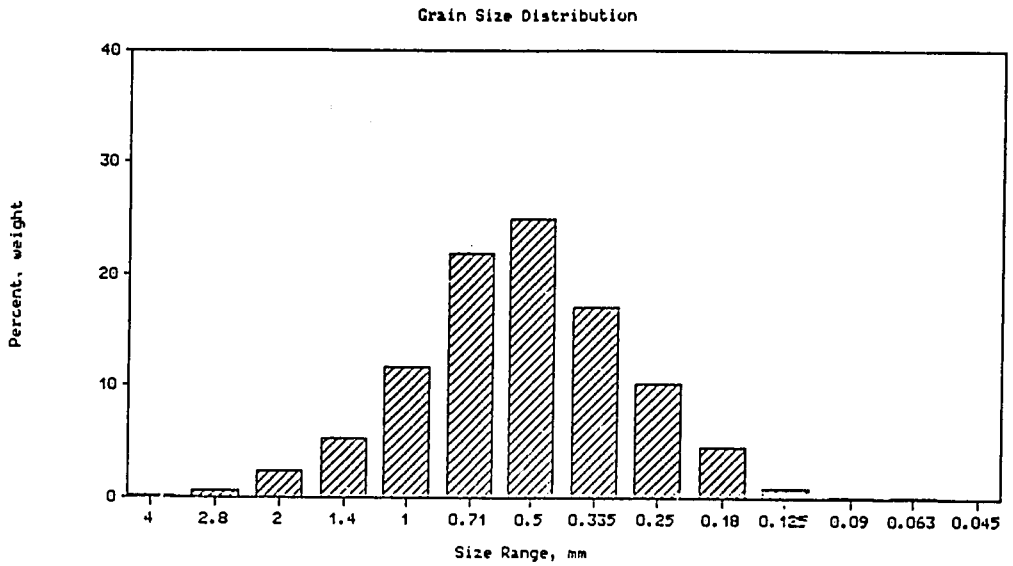



Fig. 4 : Annual peak flows, Metsemotlhaba R. at Thamaga, WAD Station 2421

Note: For the extended period only the five highest points are plotted



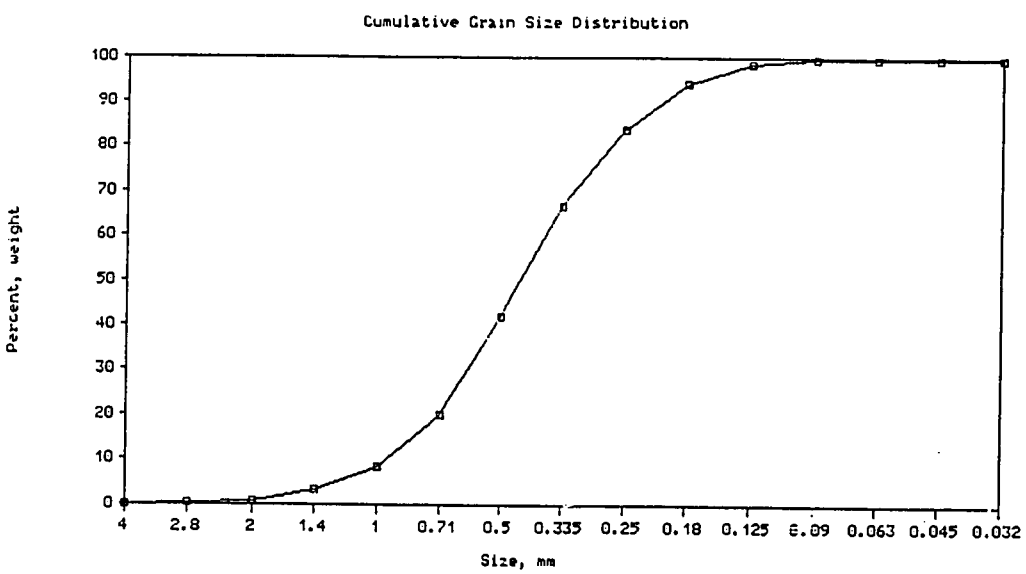
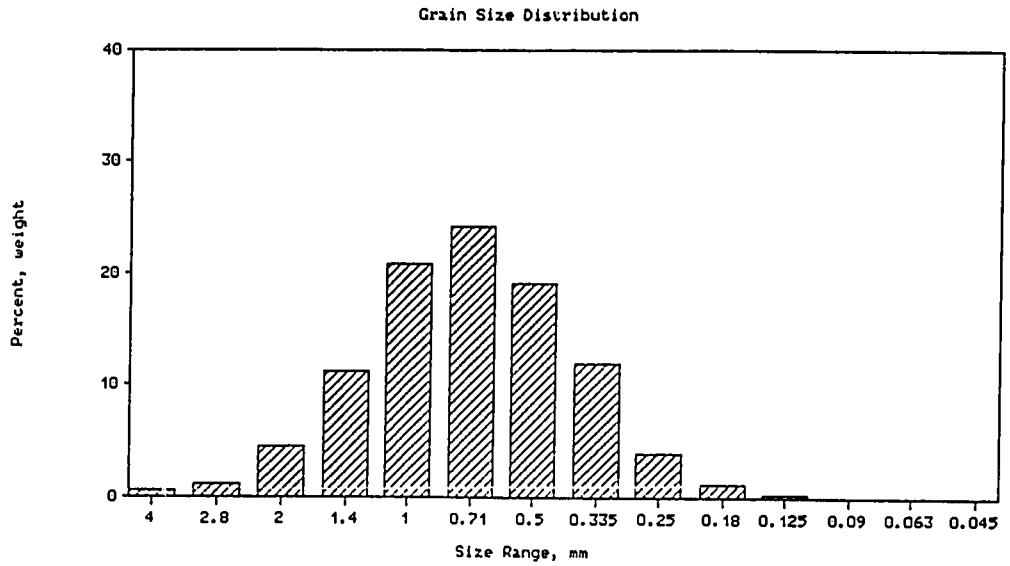




Fig. 5 : Size distribution of channel alluvium, surface sample No. 3W6 (Lab. No. 15), Metsemotlhaba R.



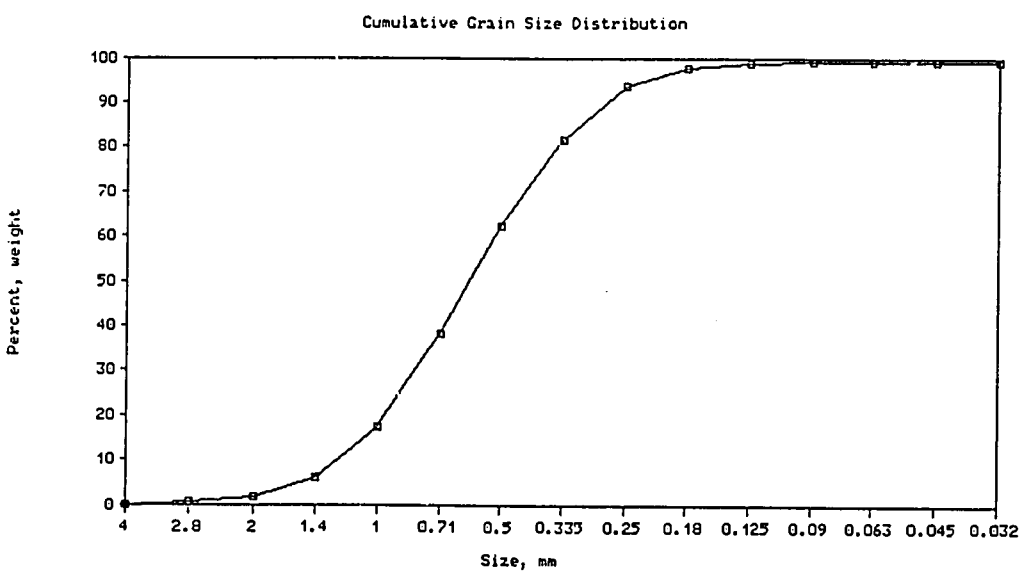
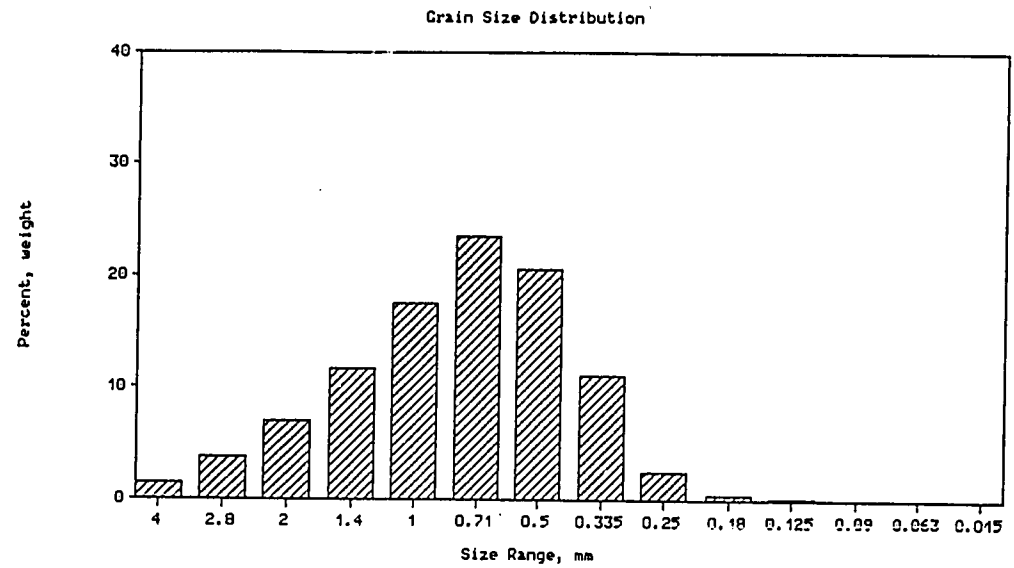




Fig. 6 : Size distribution of channel alluvium, sub-surface sample No. 3W5a (Lab. No. 11), Metsemotlhaba R.



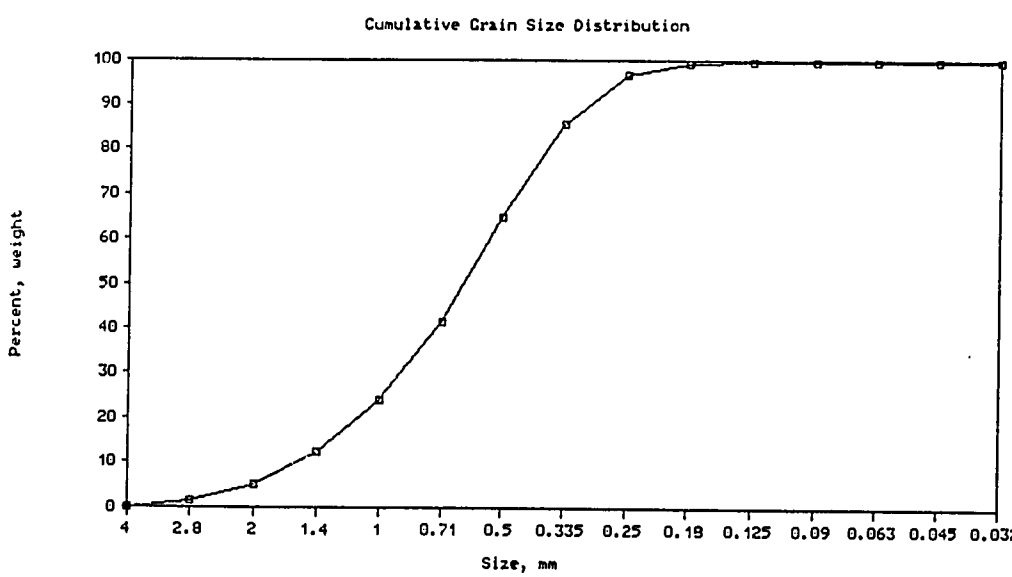
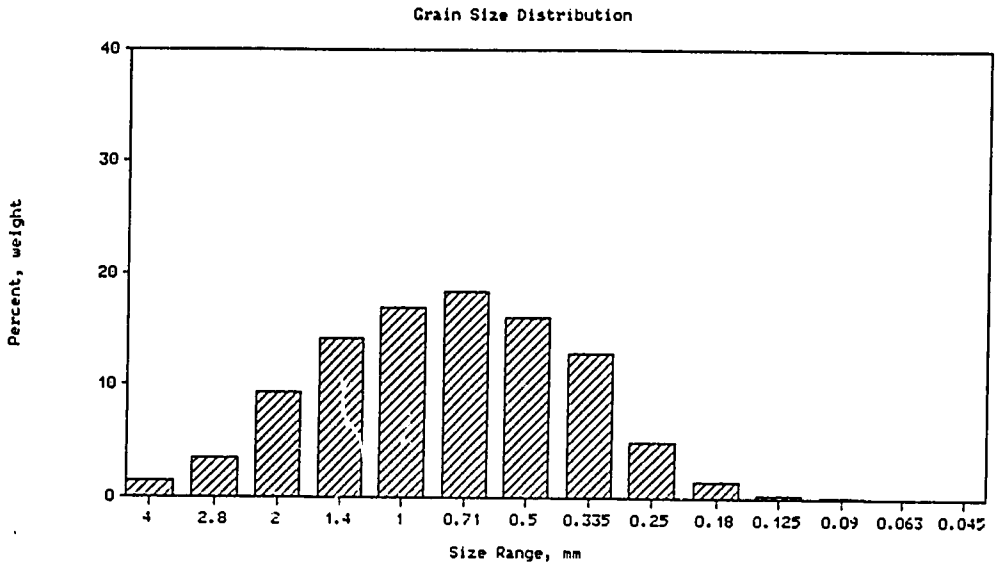




Fig. 7 : Size distribution of channel alluvium, sub-surface sample No. 3W7 (Lab. No. 23), Metsemotlhaba R.



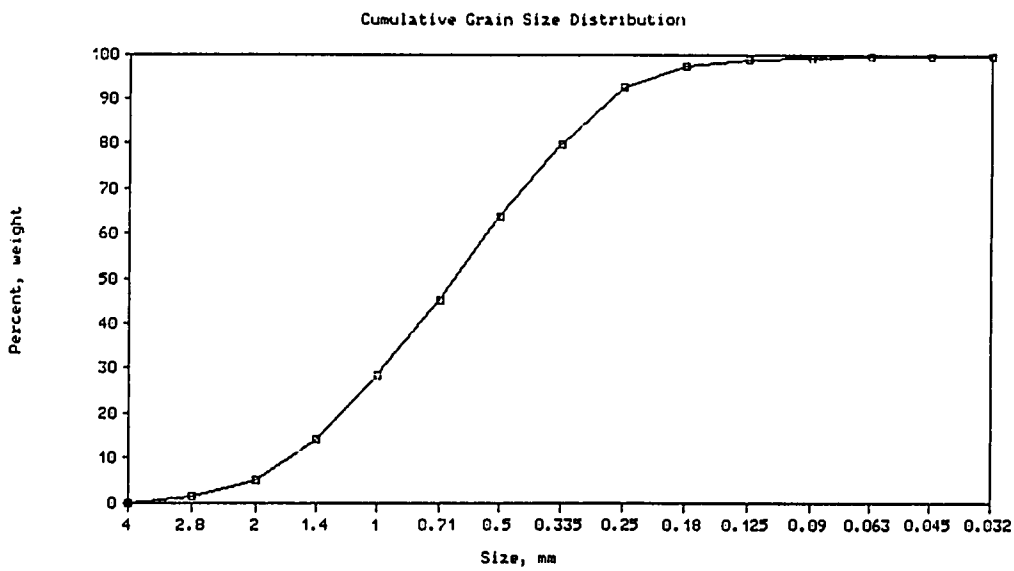
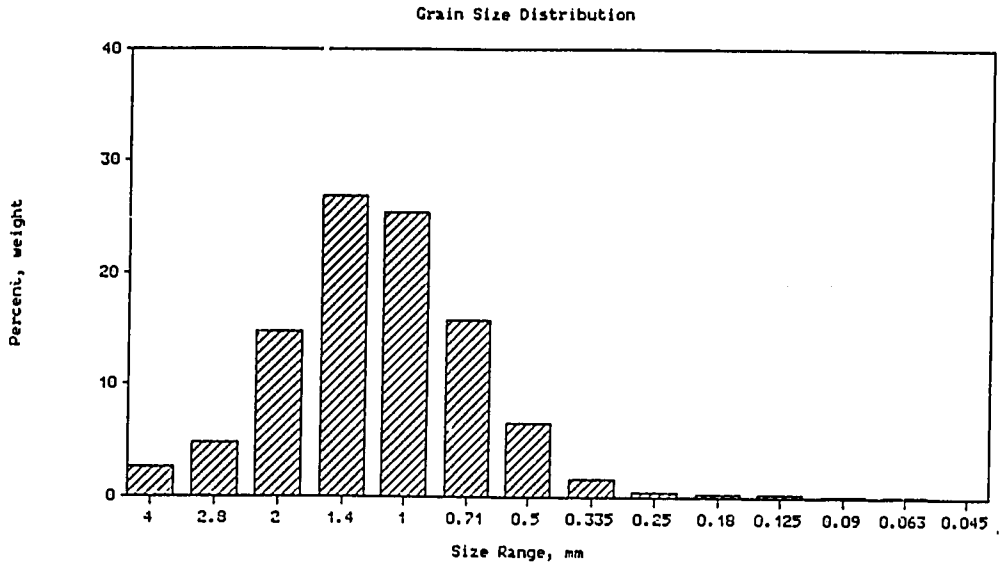




Fig. 8 : Size distribution of channel alluvium, sub-surface sample No. 3W4 (Lab. No. 51), Metsemotlhaba R.



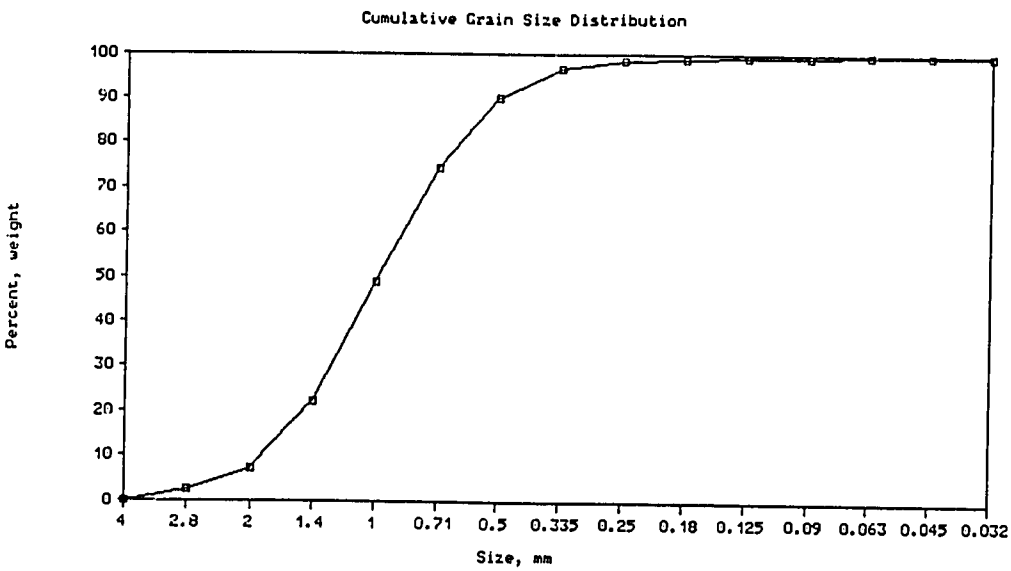
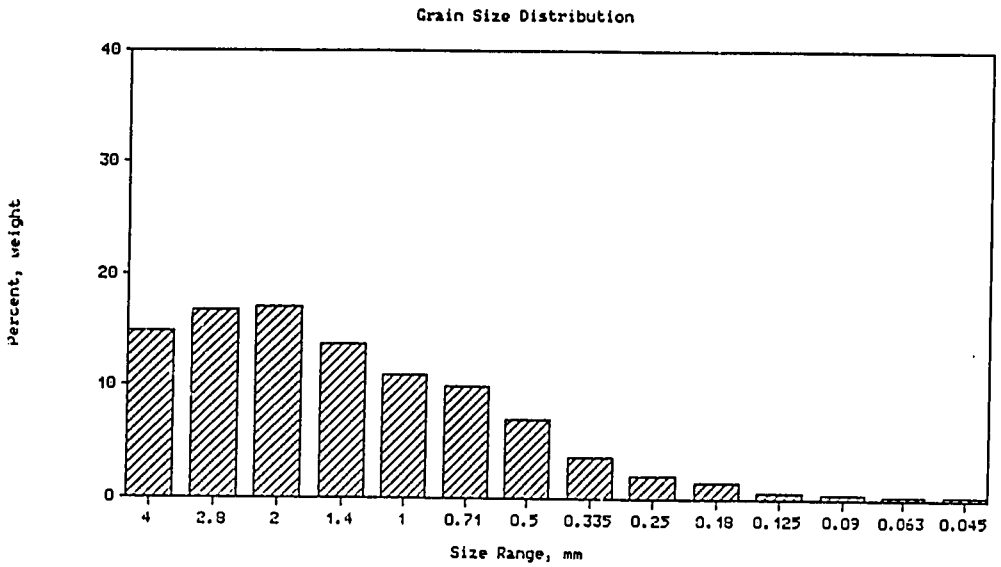




Fig. 9 : Size distribution of channel alluvium, surface sample No. 2Sec1 (Lab. No. 31), Bonwapitse R.



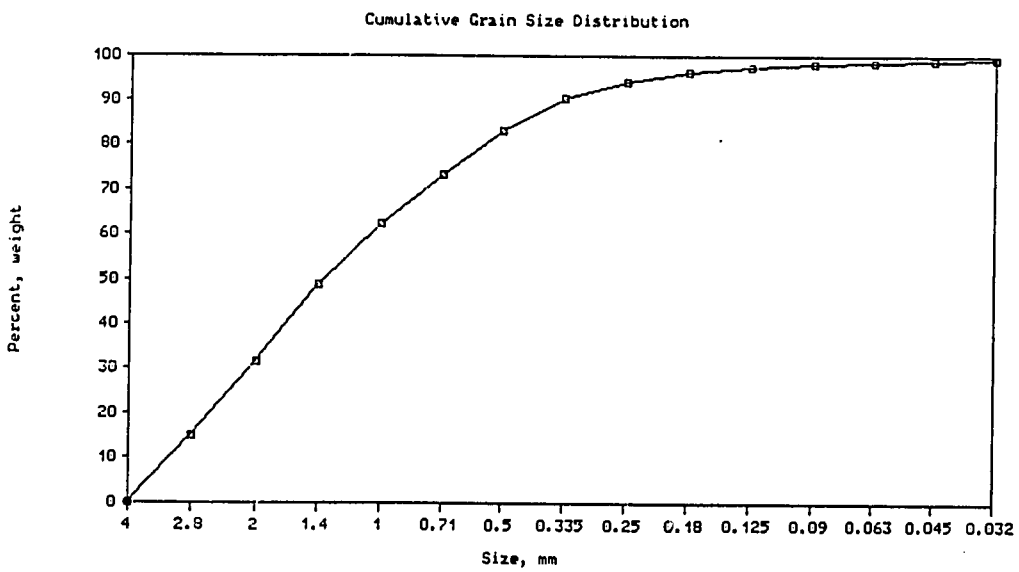
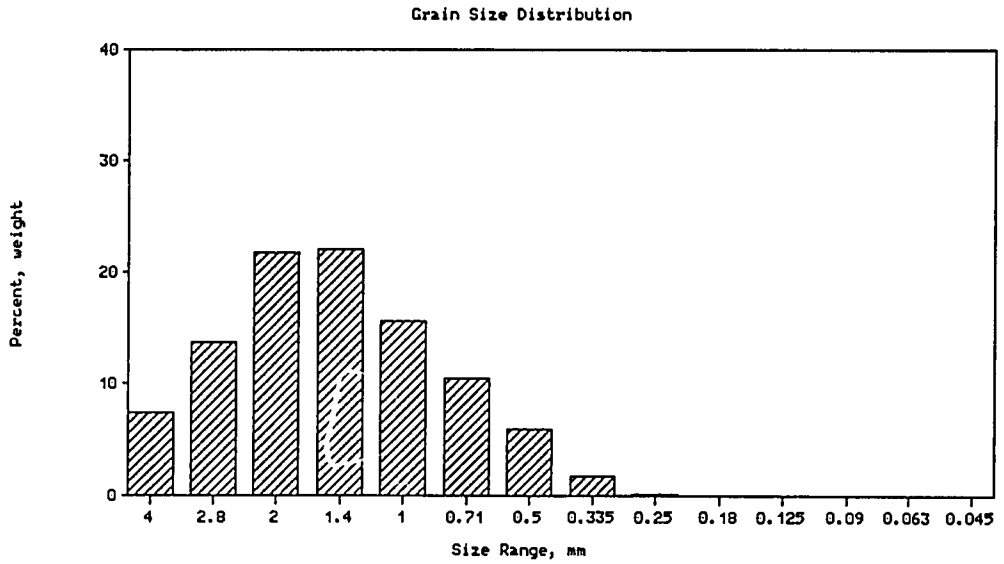




Fig. 10 : Size distribution of channel alluvium, sub-surface. (30 cm depth) sample No. 2Sec1 (Lab. No. 65), Bonwapitse R.



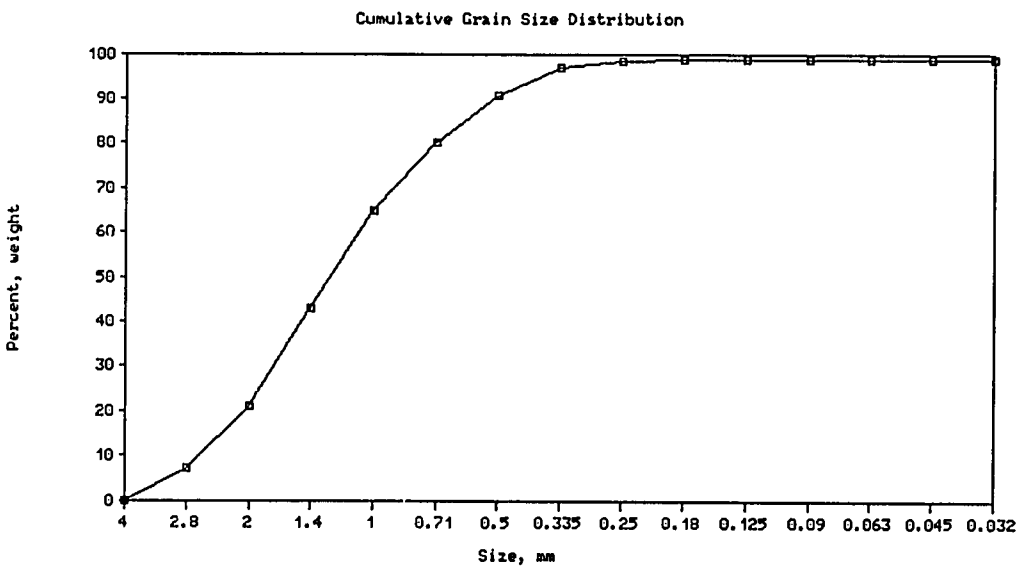




Fig. 11 : Size distribution of channal alluvium, surface sample No. 3Sec2 (Lab. No. 5), Tautswe R.

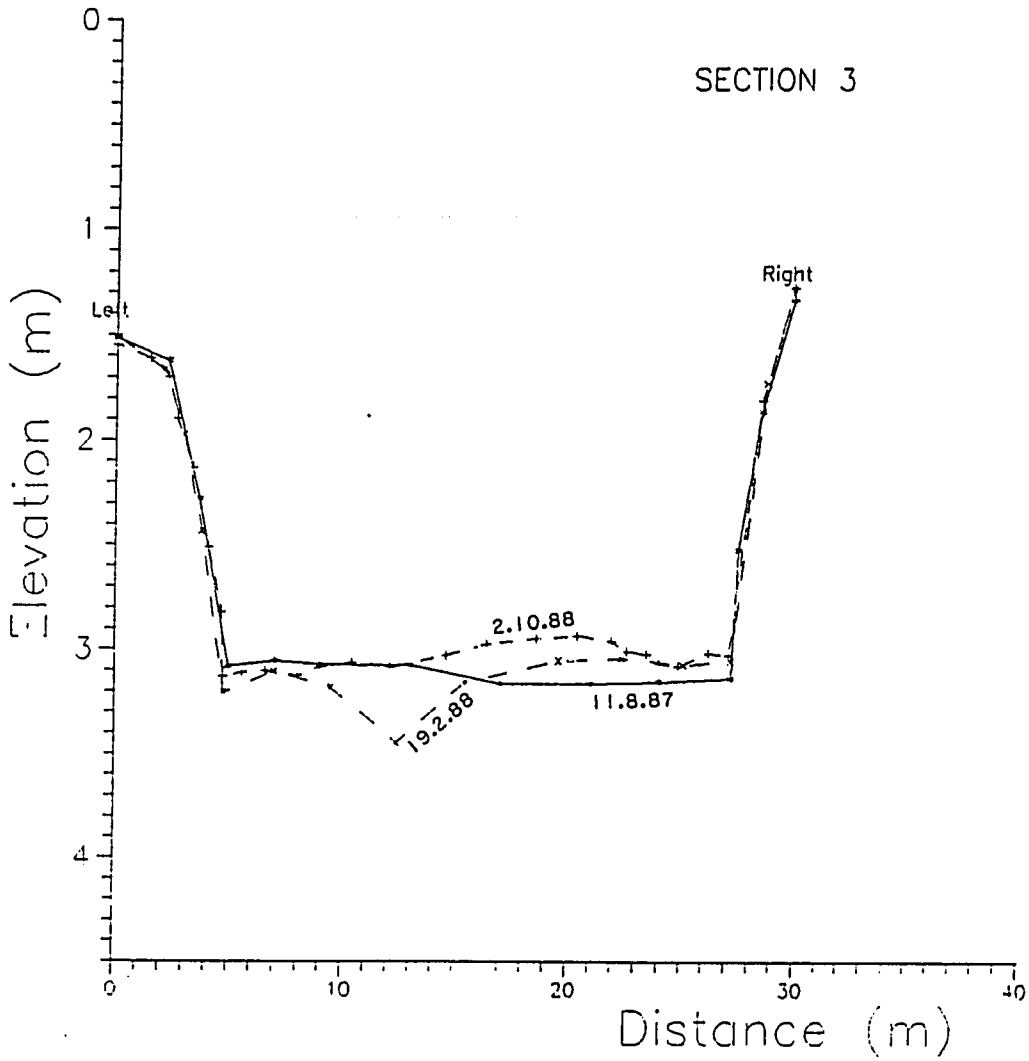



Fig. 12 : Cross section No. 3 (L = 200 m), Metsemotlhaba R. Channal bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

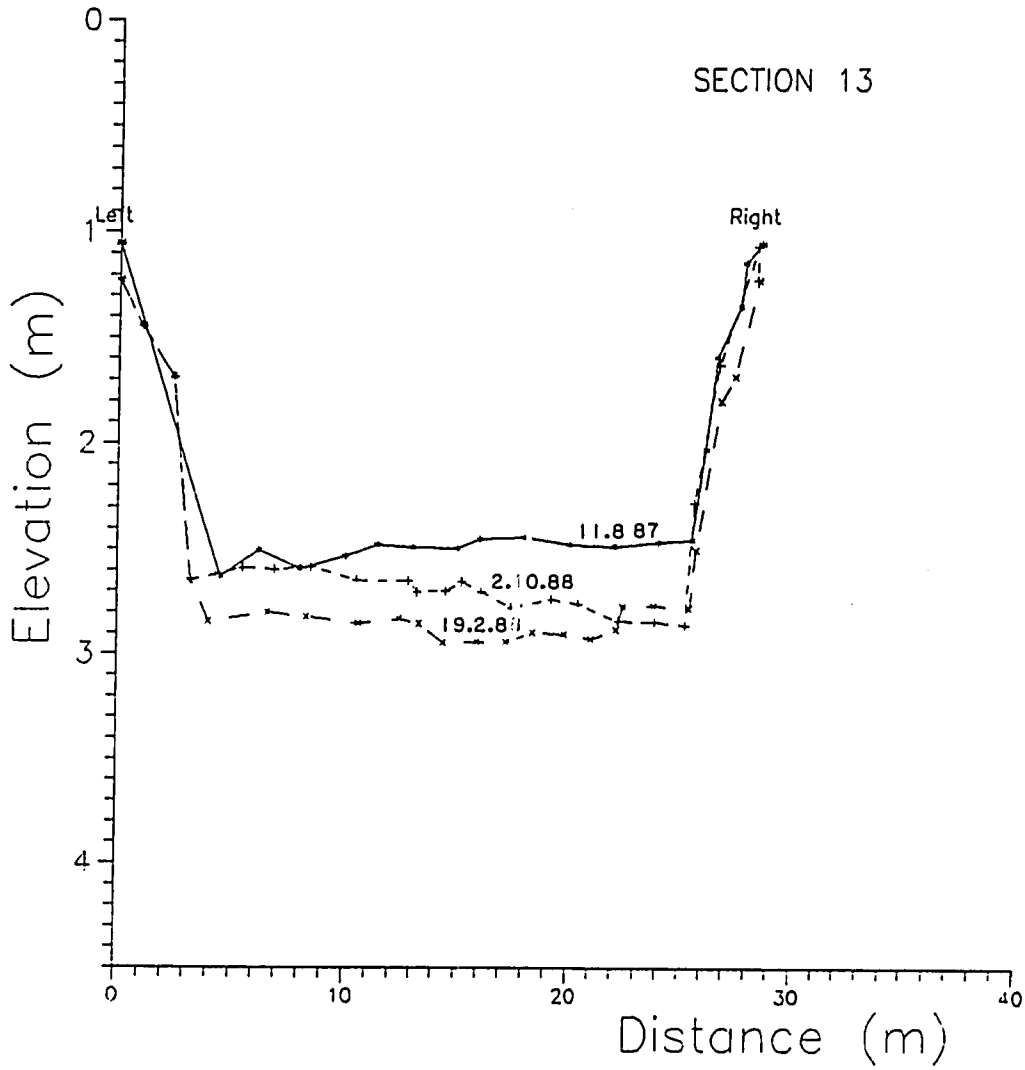



Fig. 13 : Cross section No. 13 (L = 1200 m), Metsemotlhaba R. Channal bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

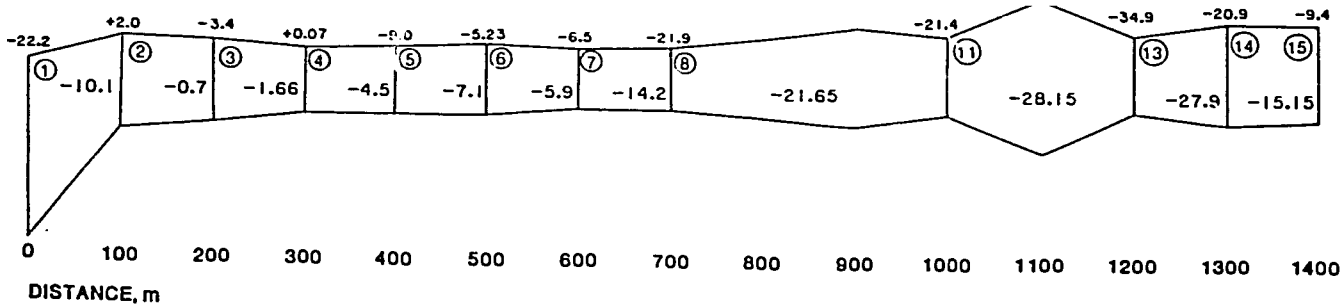



Fig. 14 : Change in river bed level, Aug 1987 to Feb 1988, Metsemotlhaba River.
Based on 12 resurveyed benchmark-based cross sections. Small numbers are aggradation(+) / degradation(-) values for reach between two sections. Section numbers are encircled.
Mean degradation over entire study reach : 14.9 cm.
Upstream section 0 - 100 is excluded.

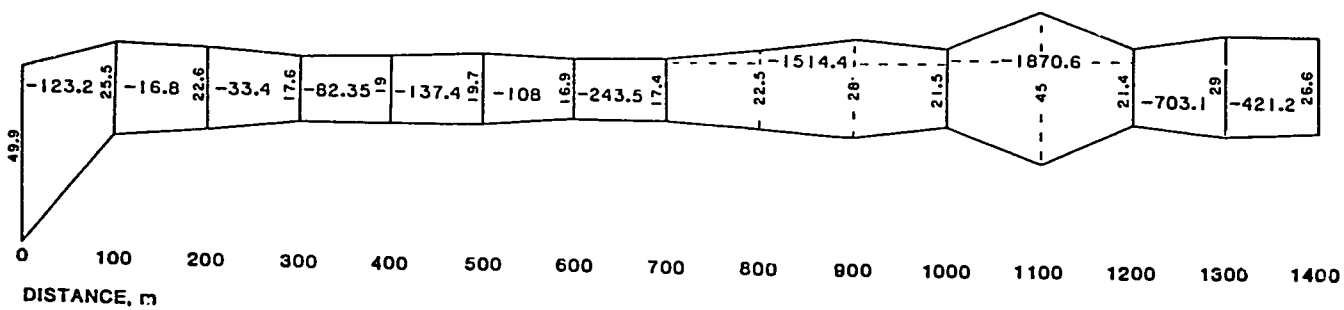



Fig. 15 : Change in volume of alluvial sediment, Aug 1987 to Feb 1988, Metsemotlhaba River.
Based as in Fig. 24. Small numbers are interbank section lengths in meters. Large numbers are volume changes, for each reach between two cross sections, in cubic meters. The total minimum volume exported from study reach (section 100 to section 1400) was 5,130 m3. Reach 0 - 100 was excluded from computation because of bend effects.

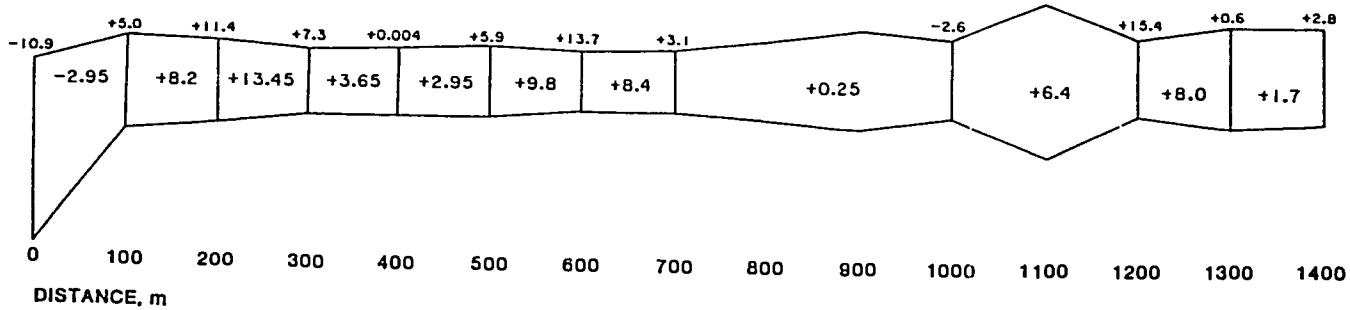



Fig. 16 : Change in river bed level, Feb 1988 to Oct 1988, Metsemotlhaba River.
Based on 12 resurveyed benchmark-based cross sections.
Small numbers are aggradation(+) / degradation(-) values for reach between two sections.
Mean aggradation over entire study reach : 5.4 cm.
Upstream section 0 - 100 is excluded.

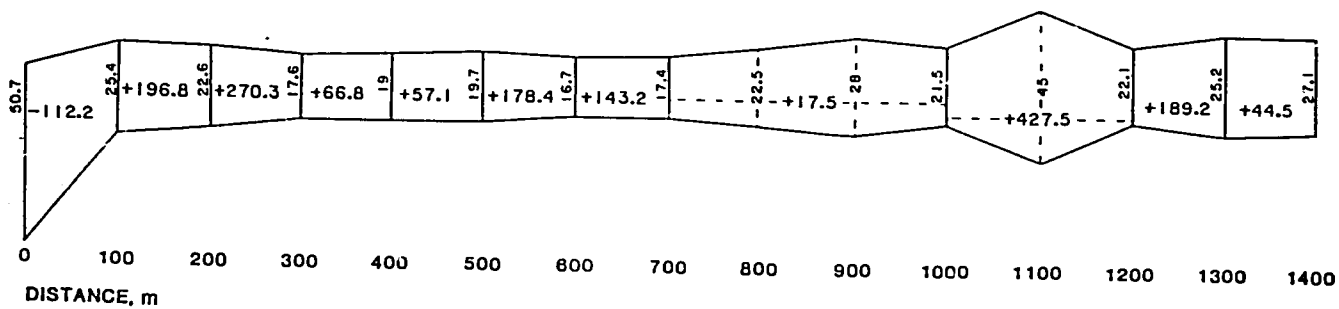



Fig. 17 : Change in volume of alluvial sediment, Feb 1988 - Oct 1988, Metsemotlhaba River.
Based as in Fig. 26. Small numbers are interbank section lengths in meters. Large numbers are volume changes, for each reach between two cross sections, in cubic meters. The total volume moved into study reach (section 100 to section 1400) was 1,590 m3.
Reach 0 - 100 was excluded from computation because of bend effects.

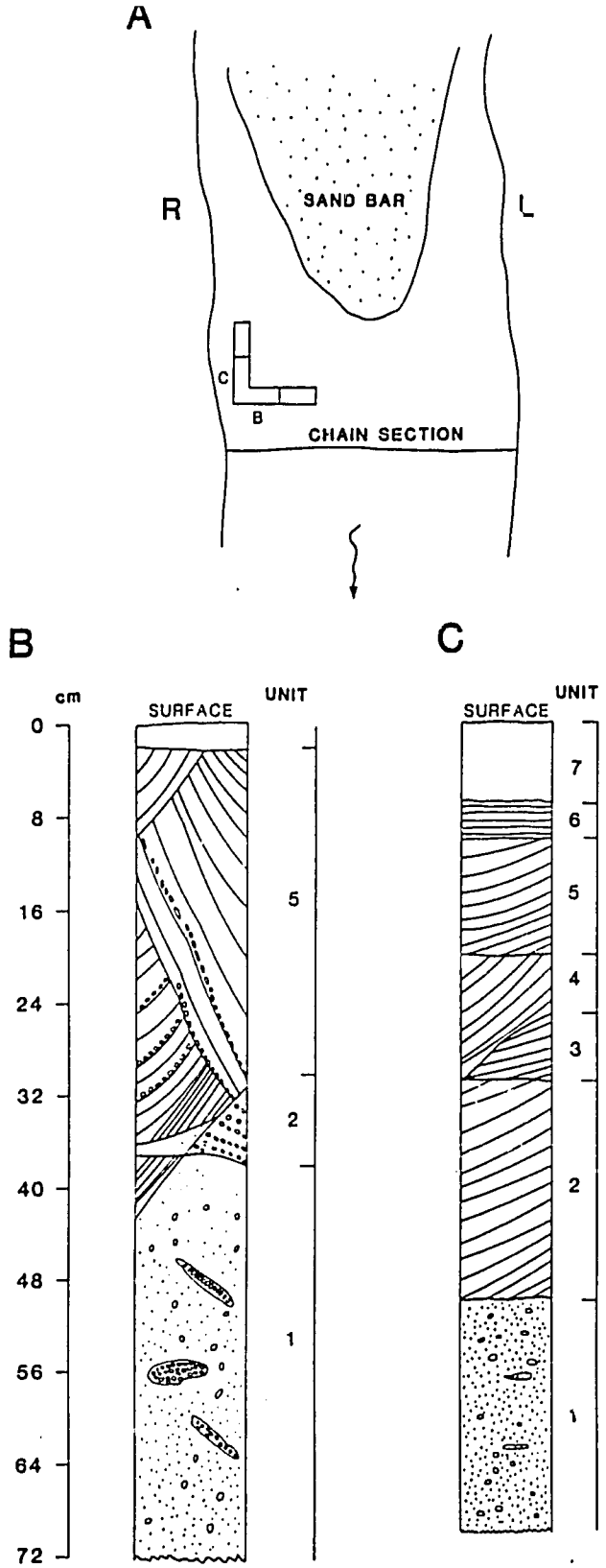
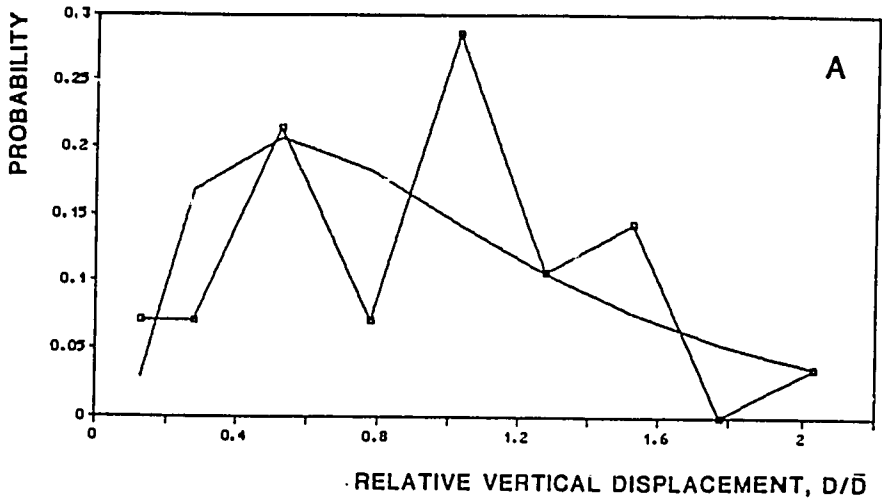
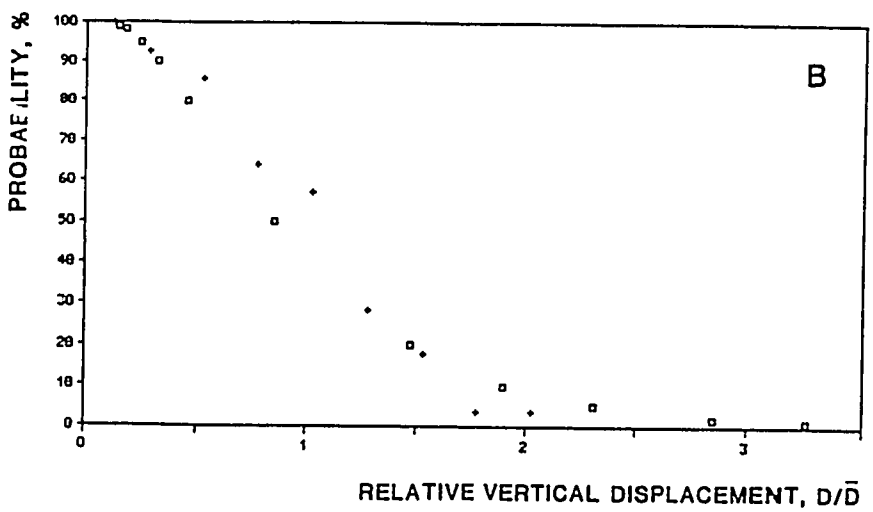



Fig. 18 : Alluvial stratigraphy, Metsemotlhaba R.
A - Location sketch ; trench 3 (at station 275 m)
B - Cross section
C - Longitudinal section

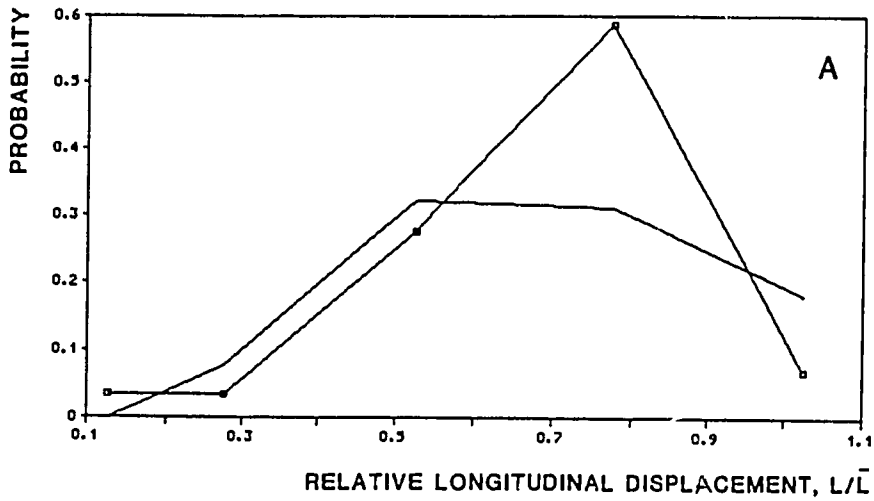



Note : 29 particles recovered. Squares are field data.
Curve is for $\gamma = 0.1$

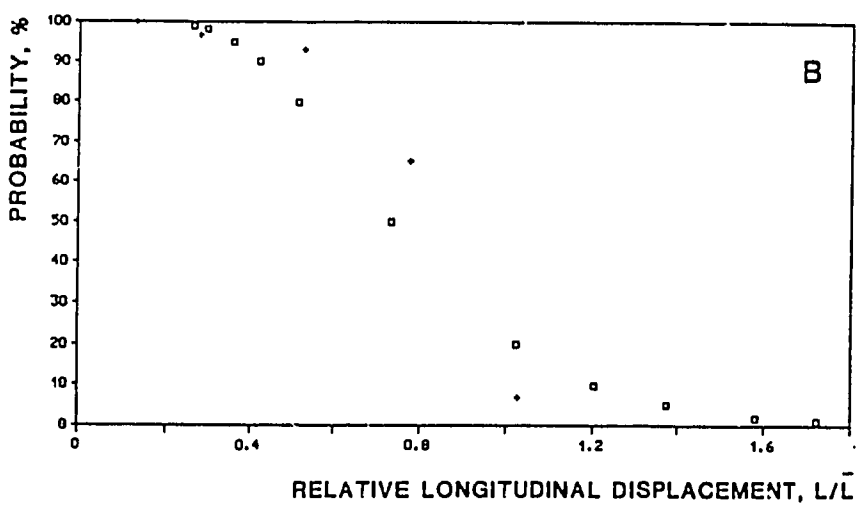



Note : Mean displacement : 28 cm. Crosses are field data.
Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 19 : Burial of tracer particles : field data and fitted gamma distribution. Bonwapitse R., Sep 1987 - Sep 1988

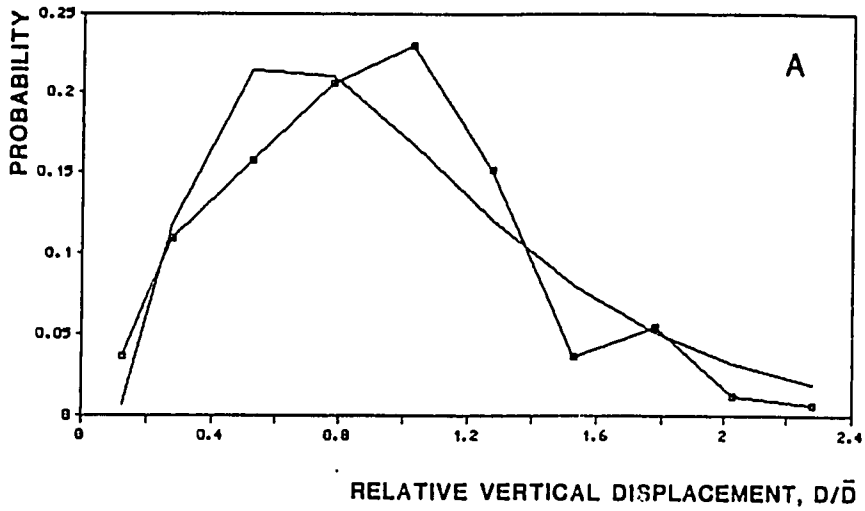



Note : Mean displacement : 924 m. Squares are field data. Curve is for $\gamma = 0.1$

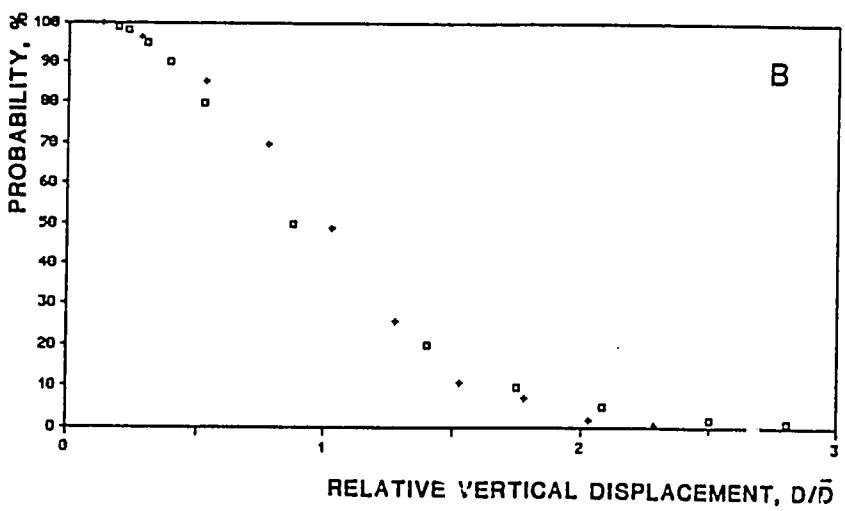



Note : Crosses are field data. Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 20 : Downstream displacement of tracer particles : field data and fitted gamma distribution. Bonwapitse R., Sep 1987 to Sep 1988

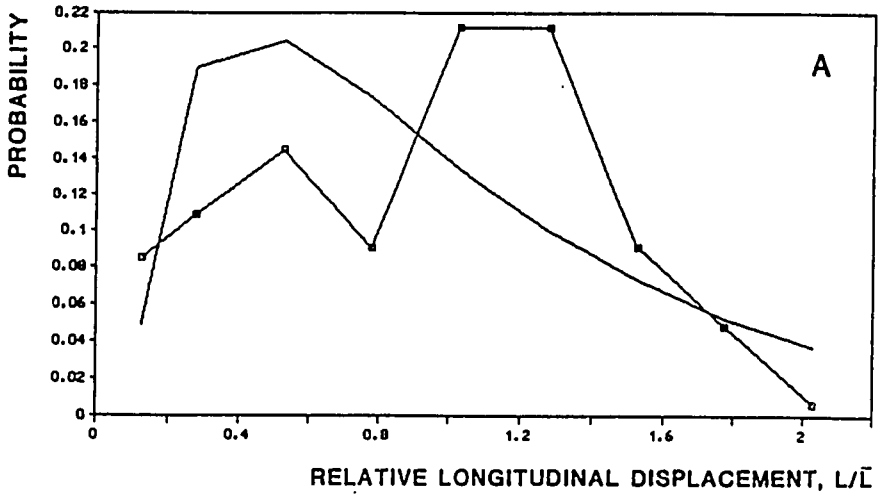



Note : 165 particles recovered. Squares are field data.
Curve is for $\gamma = 0.1$

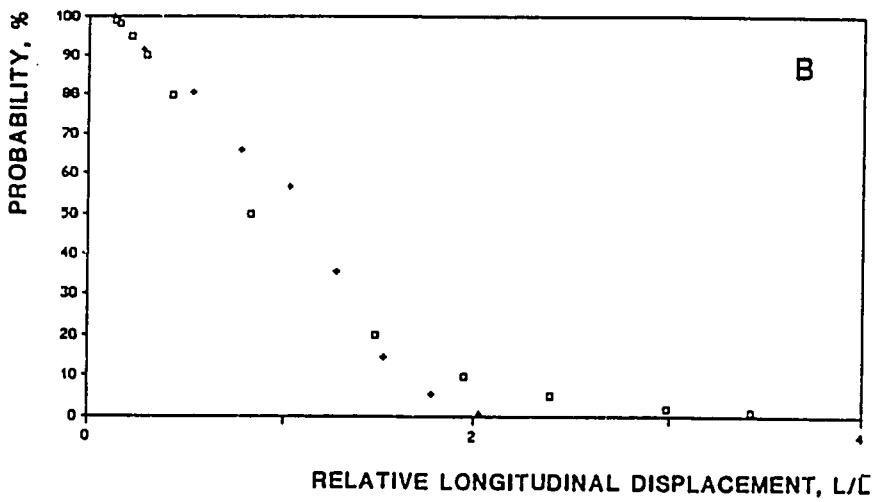



Note : Mean displacement : 44 cm. Crosses are field data.
Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 21 : Burial of tracer particles : field data and fitted gamma distribution.
Metsemotlhaba R., Sep 1987 - Sep 1988




Note : Mean displacement : 1060 m. Squares are field data.
Curve is for $\gamma = 0.1$




Note : 165 particles recovered. Crosses are field data.
Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 22 : Downstream displacement of tracer particles : field data and fitted gamma distribution.
Metsemotlhaba R., Sep 1987 to Sep 1988

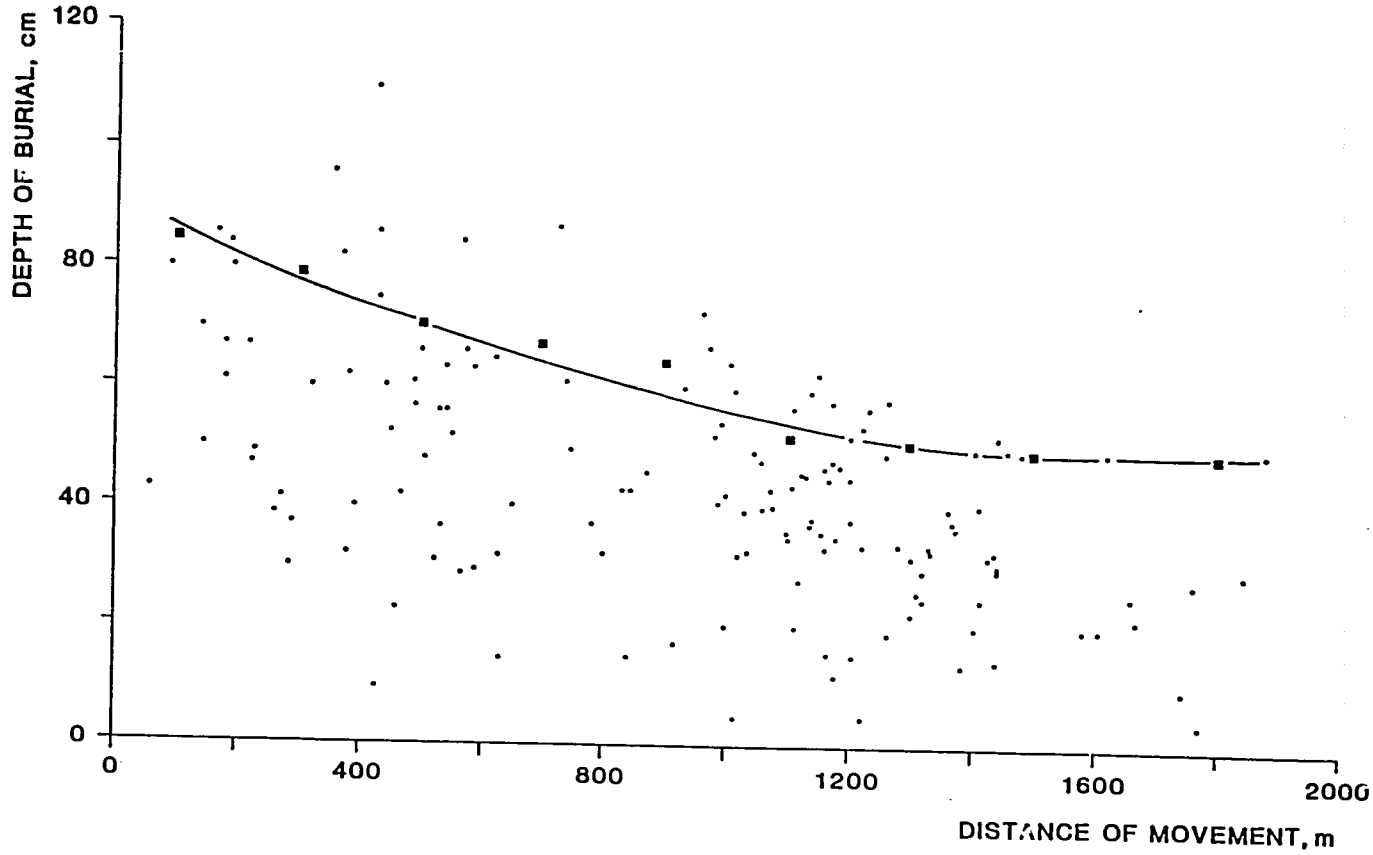



Fig. 23 : Longitudinal and vertical displacement, small particles.
Metsemotlhaba R., Sep 1987 - Sep 1988
Curve, based on squares computed for 200 m long reaches, indicates depth limit of 80% of the particles

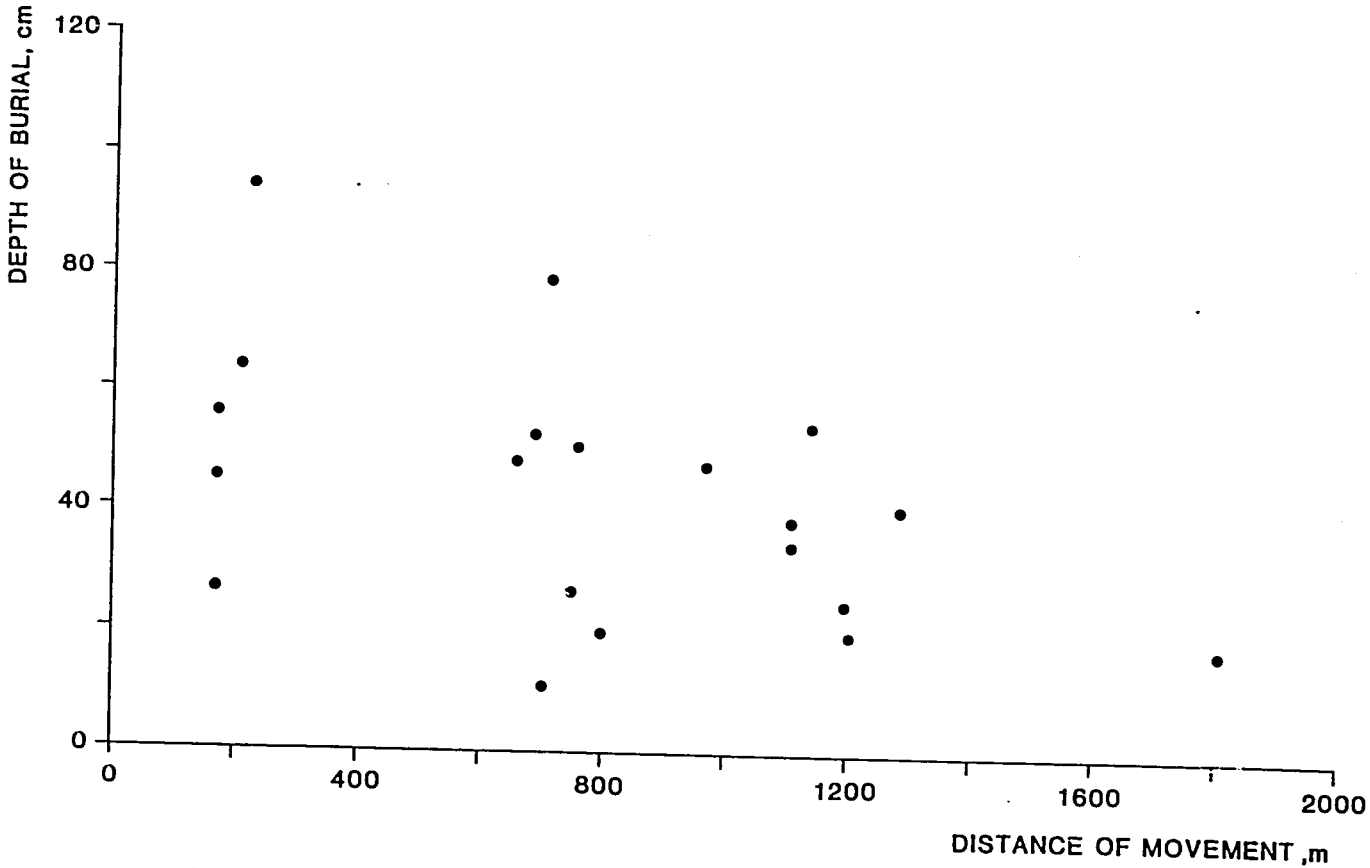



Fig. 24 : Longitudinal and vertical displacement, large particles.
Metsemotlhaba R., Sep 1987 - Sep 1988

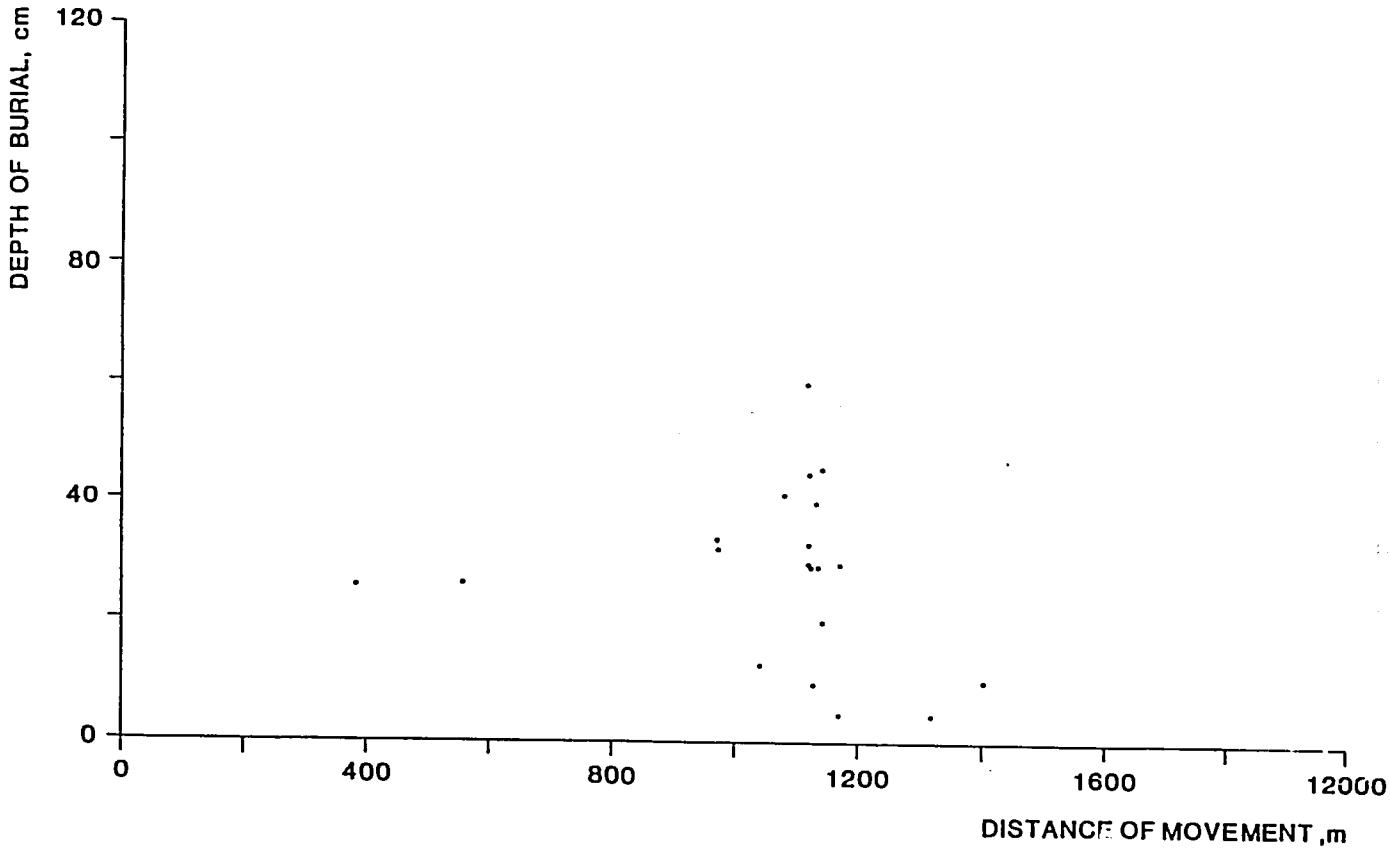



Fig. 25 : Longitudinal and vertical displacement, small particles.
. Bonwapitse R., Sep 1987 - Sep 1988

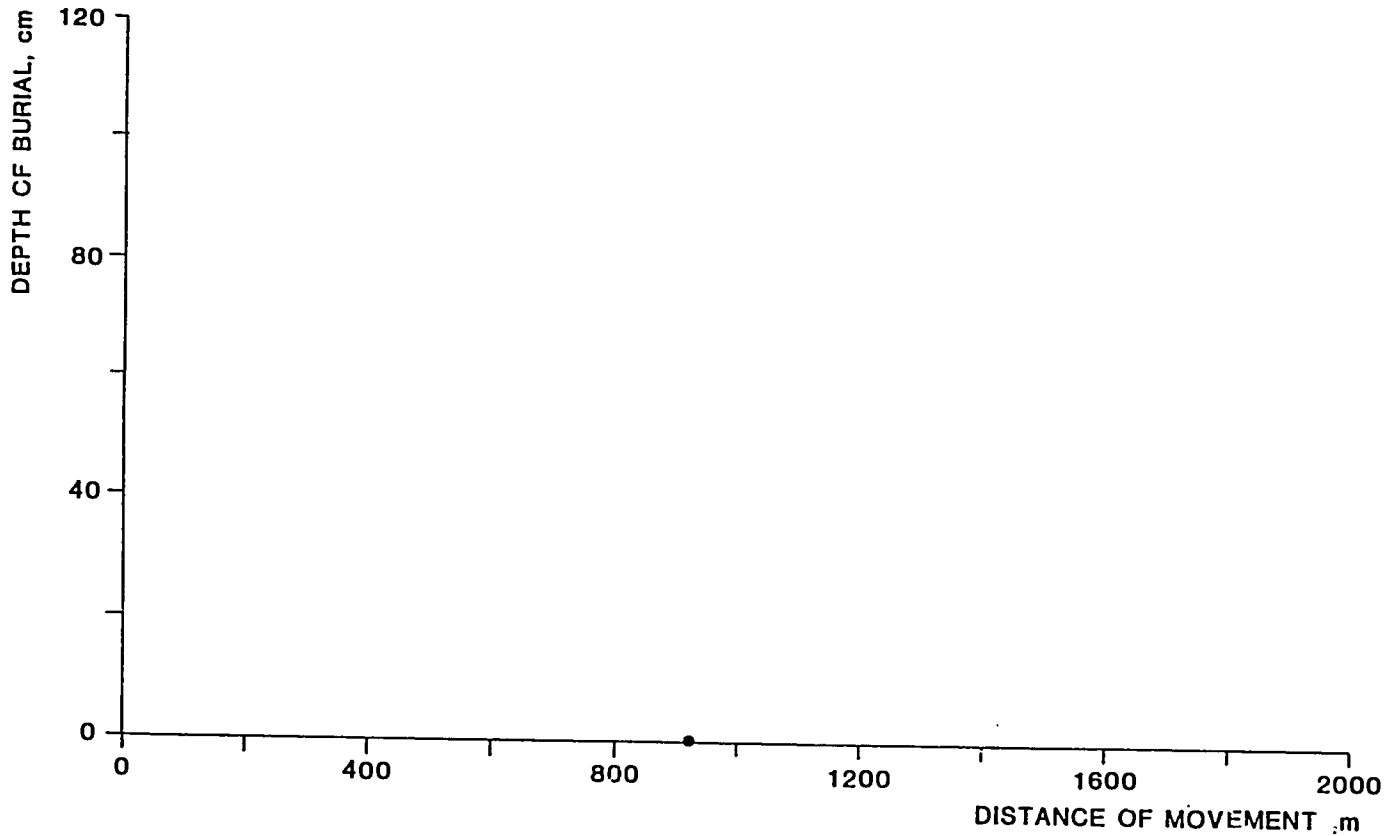
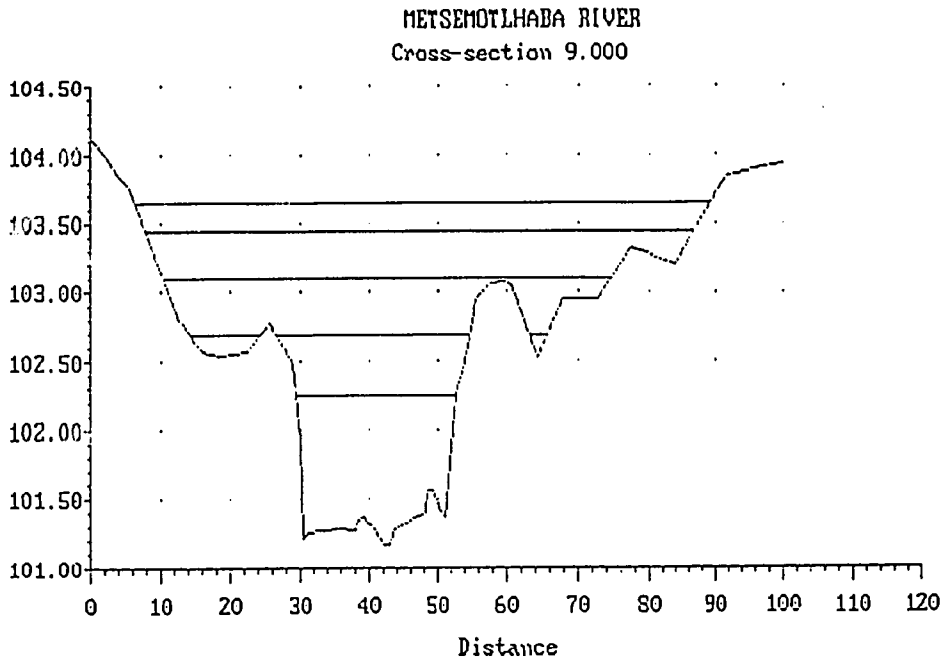



Fig. 26 : Longitudinal and vertical displacement, large particles.
---- Bonwapitse R., Sep 1987 - Sep 1988



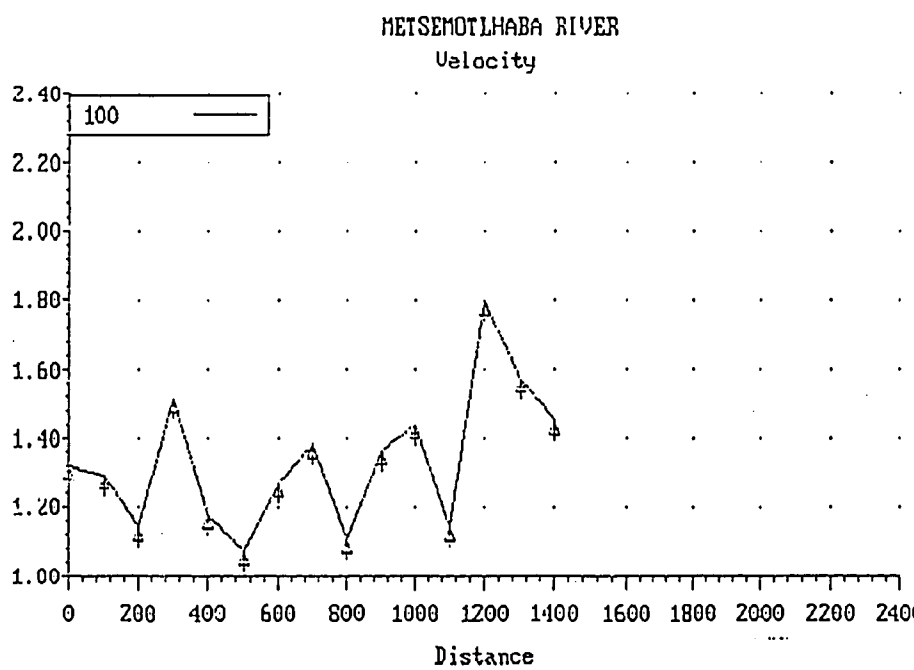




Fig. 27: Hydraulic characteristics, Metsemotlhaba River near Thamaga, Section 9:

(a) HEC 2 computed water levels for discharges of 20, 40, 60, 100 (bold), and 140 m3/sec;

(b) Downstream mean velocity from Section 1 (distance=0m) to Section 15 (distance=1400m).

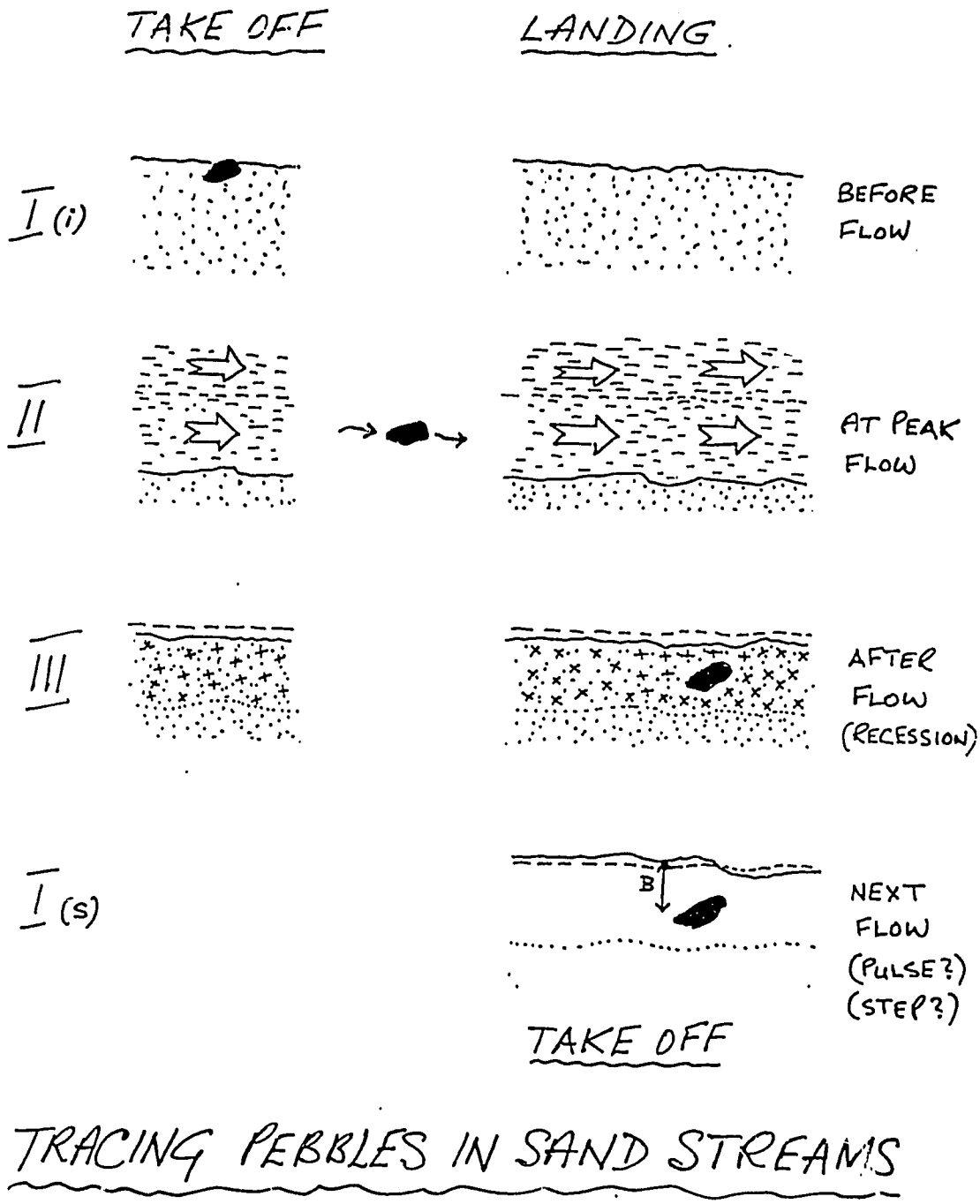



Fig. 28: The use of tracable pebbles in studying erosion and sedimentation in sand streams.

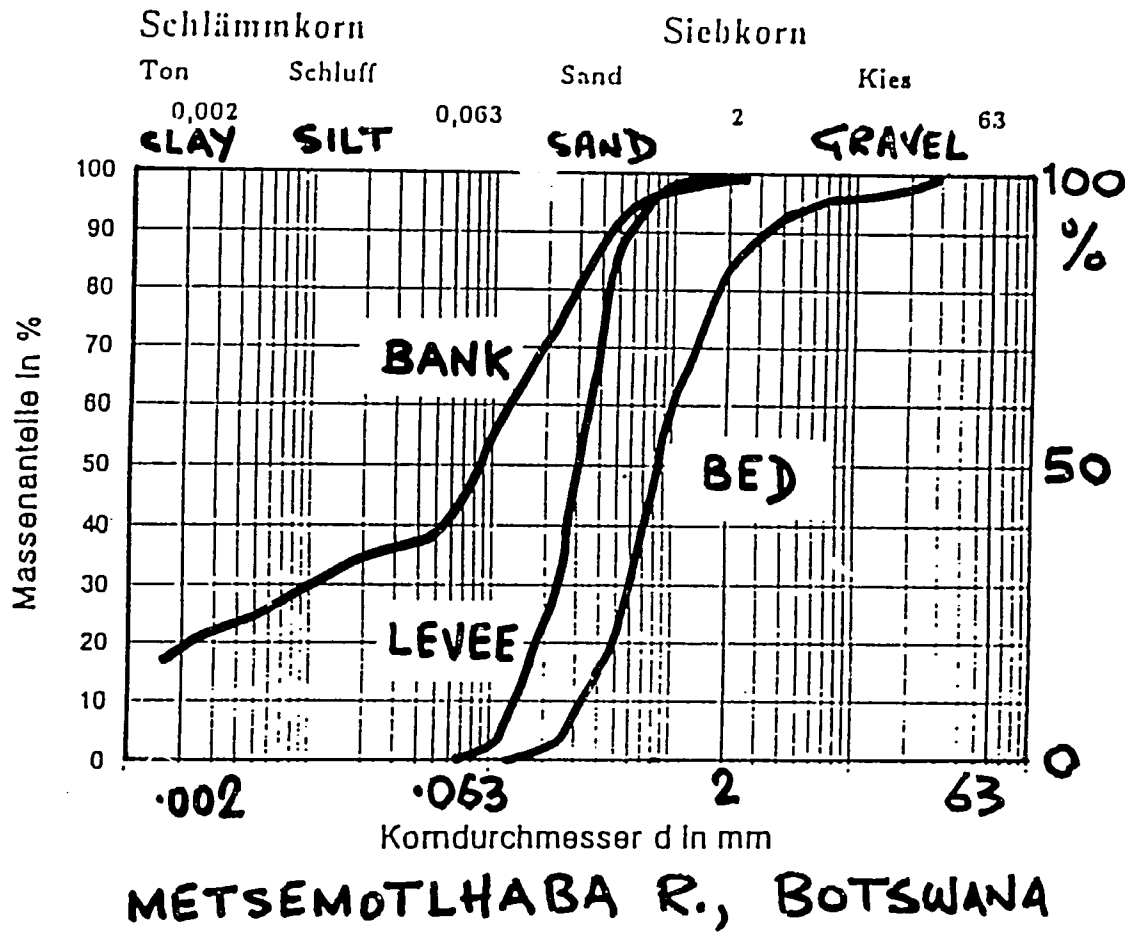



Fig. 29: Representative grain size distribution of bed material, levee (1991) material, and bank material, Metsemotlhaba River.

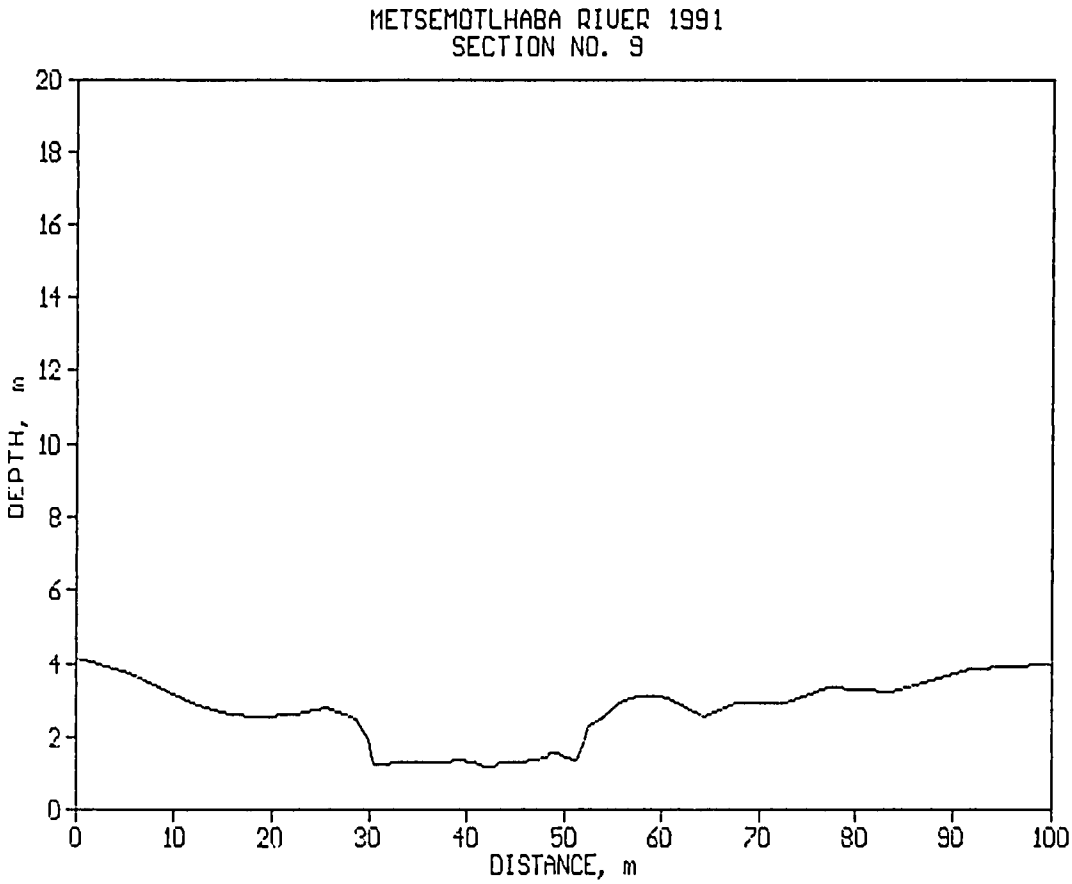



Fig. 30: Section 9, Metsemotlhaba River near Thamaga, after the deposition of sand levees by the 1991 flood.

# green generation: particle trajectories and terminal depth

## Metsemotlhaba River, Botswana (lateral exageration 1:3)

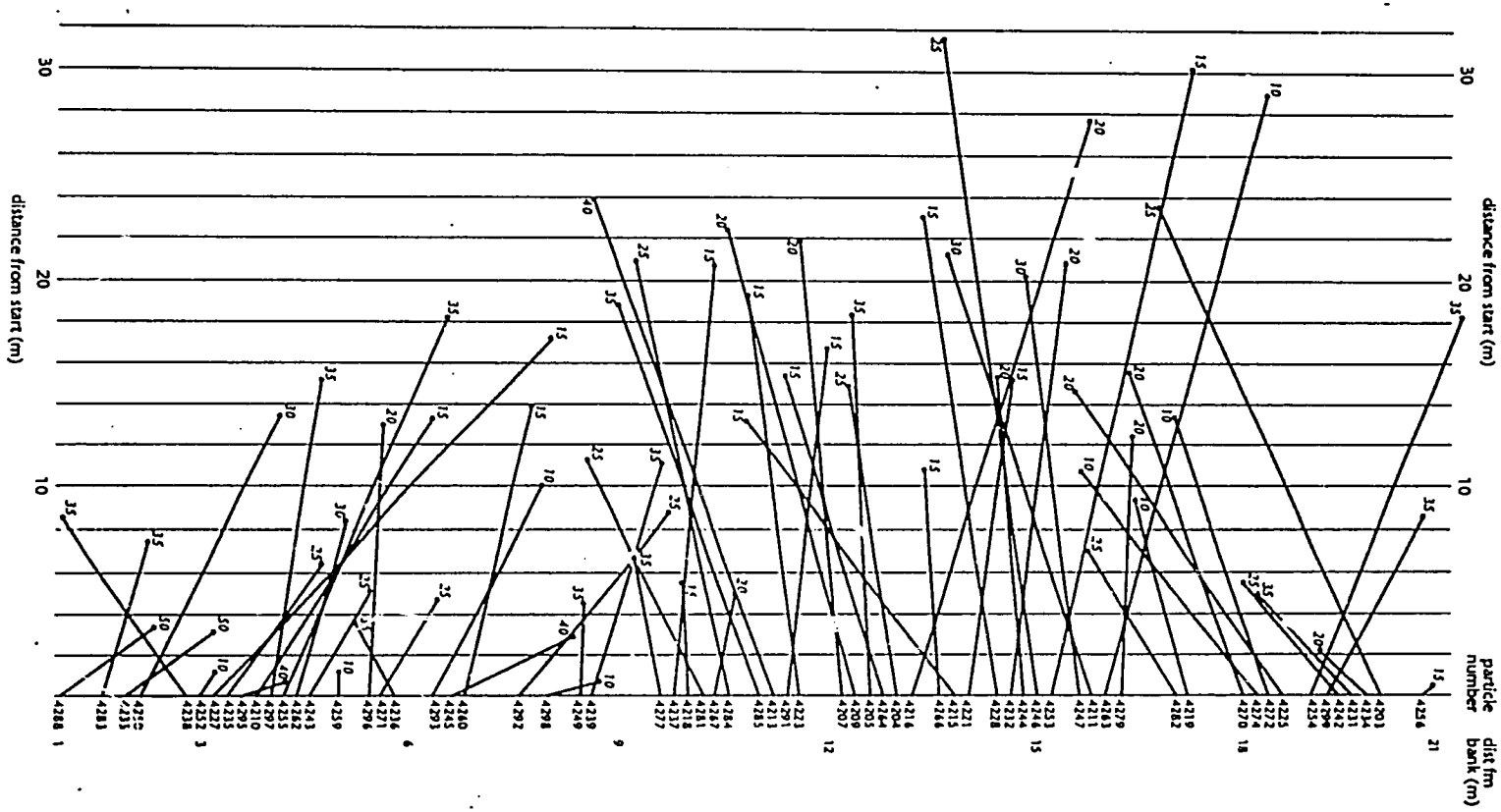



Fig. 31: Low flow pebble dispersion; numbers at end of trajectory lines are depths of burial, in cm.

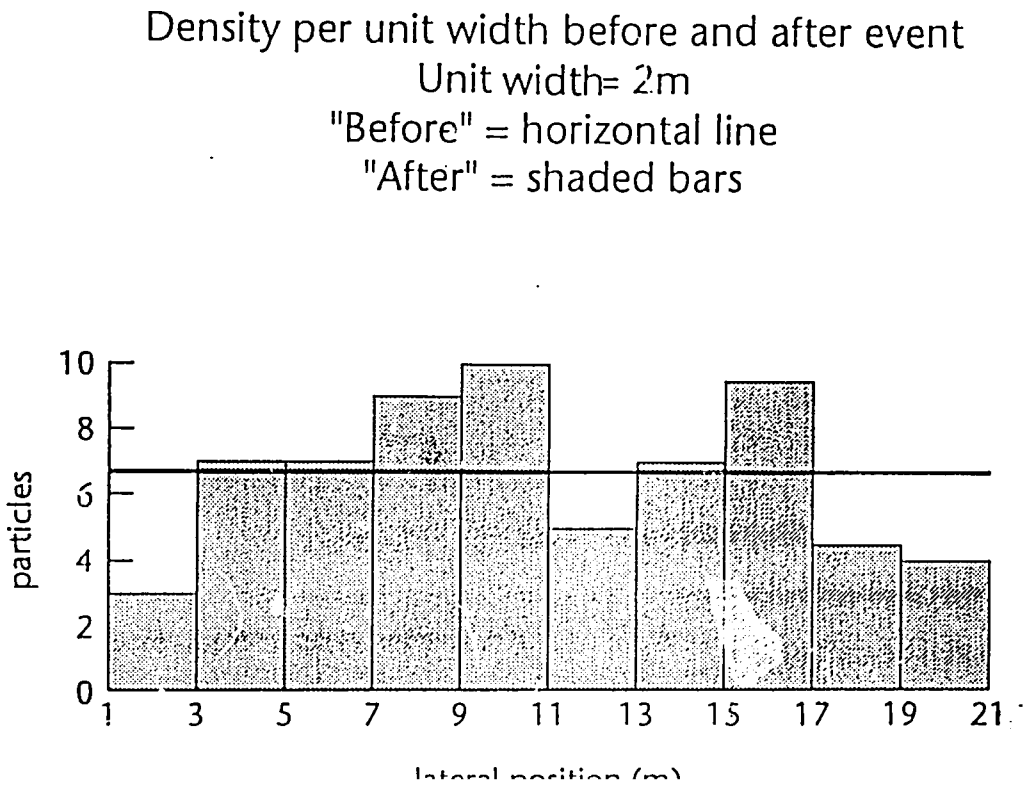



Fig. 32: Low flow pebble dispersion: tendency for concentration in two thalwegs.

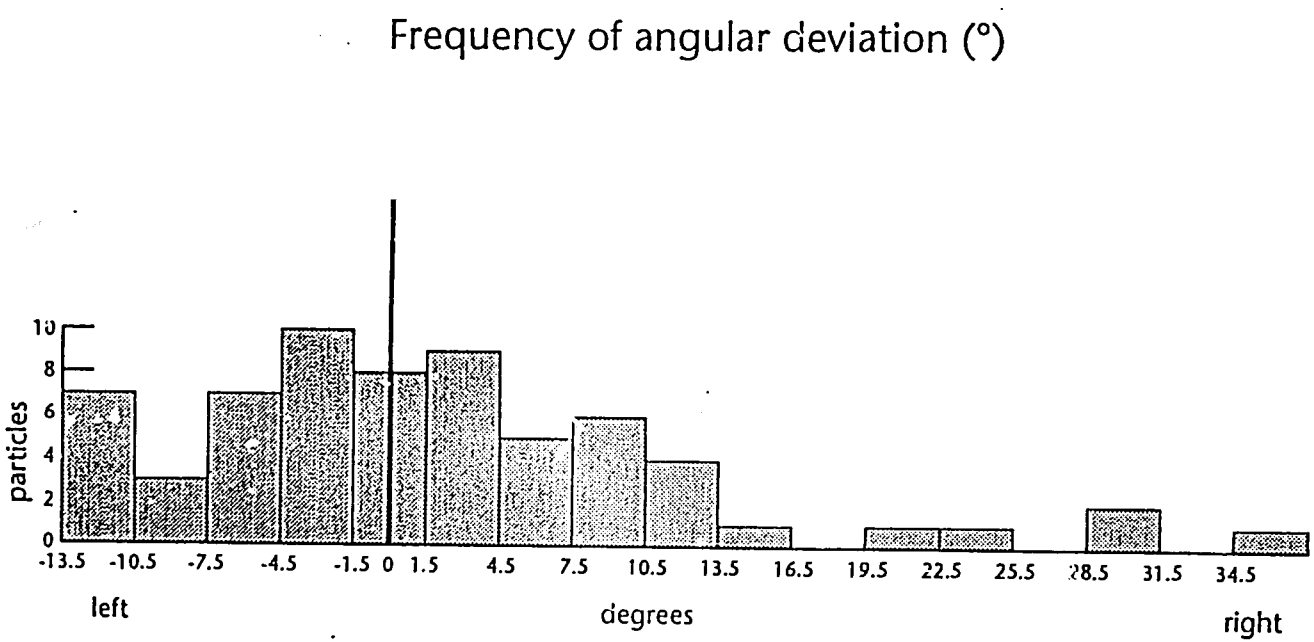



Fig. 33: Low flow pebble dispersion: angular deviation.

green particles: trajectories between +6° and +11°
Metsemotlhaba River, Botswana (lateral exageration 1:3)

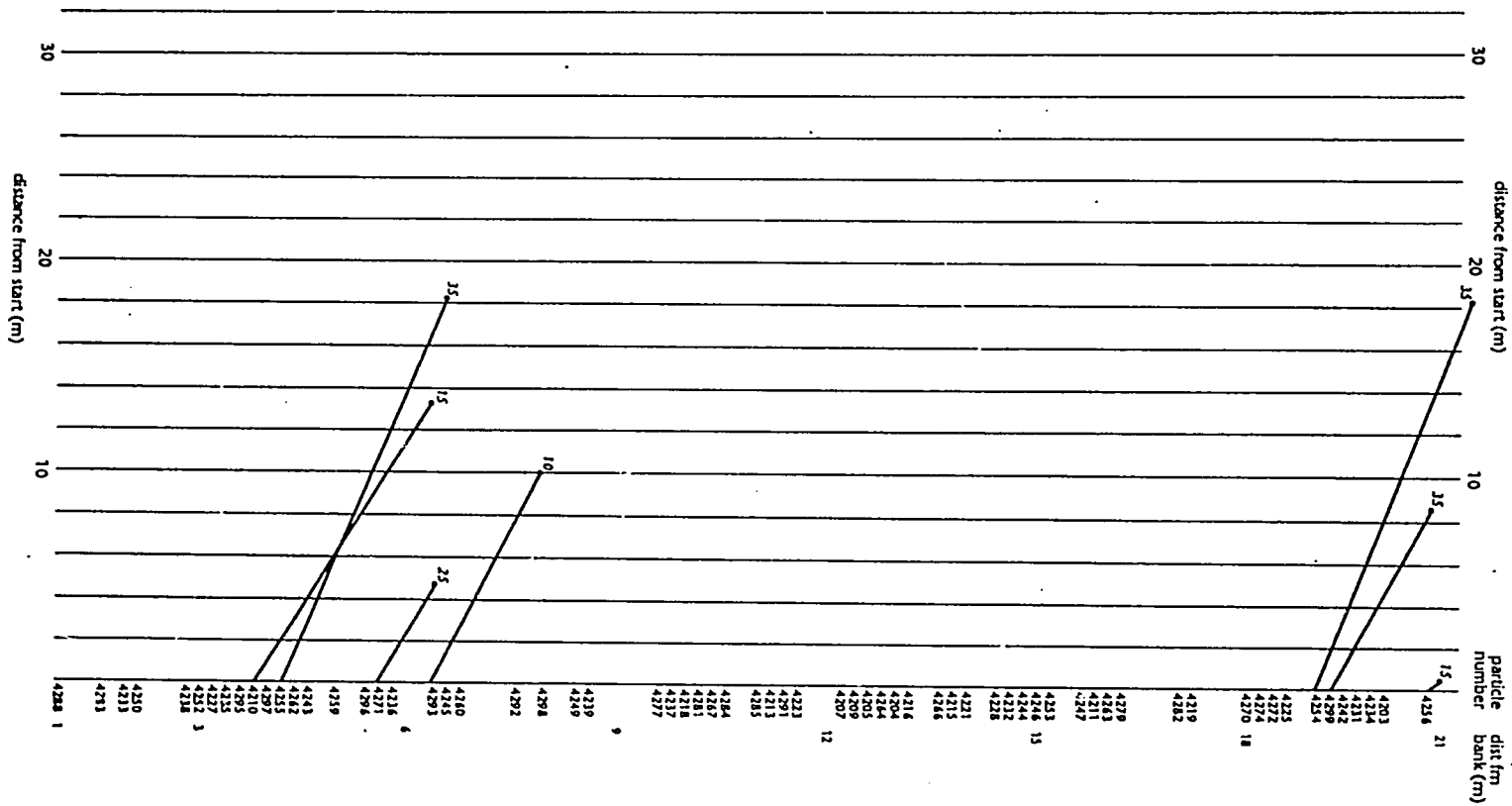



Fig. 34: Low flow pebble dispersion: selective trajectory direction (6°-11° to right).

green particles: very high (≥20°) lateral deviation to right

Metsemotlhaba River, Botswana (lateral exageration 1:3)

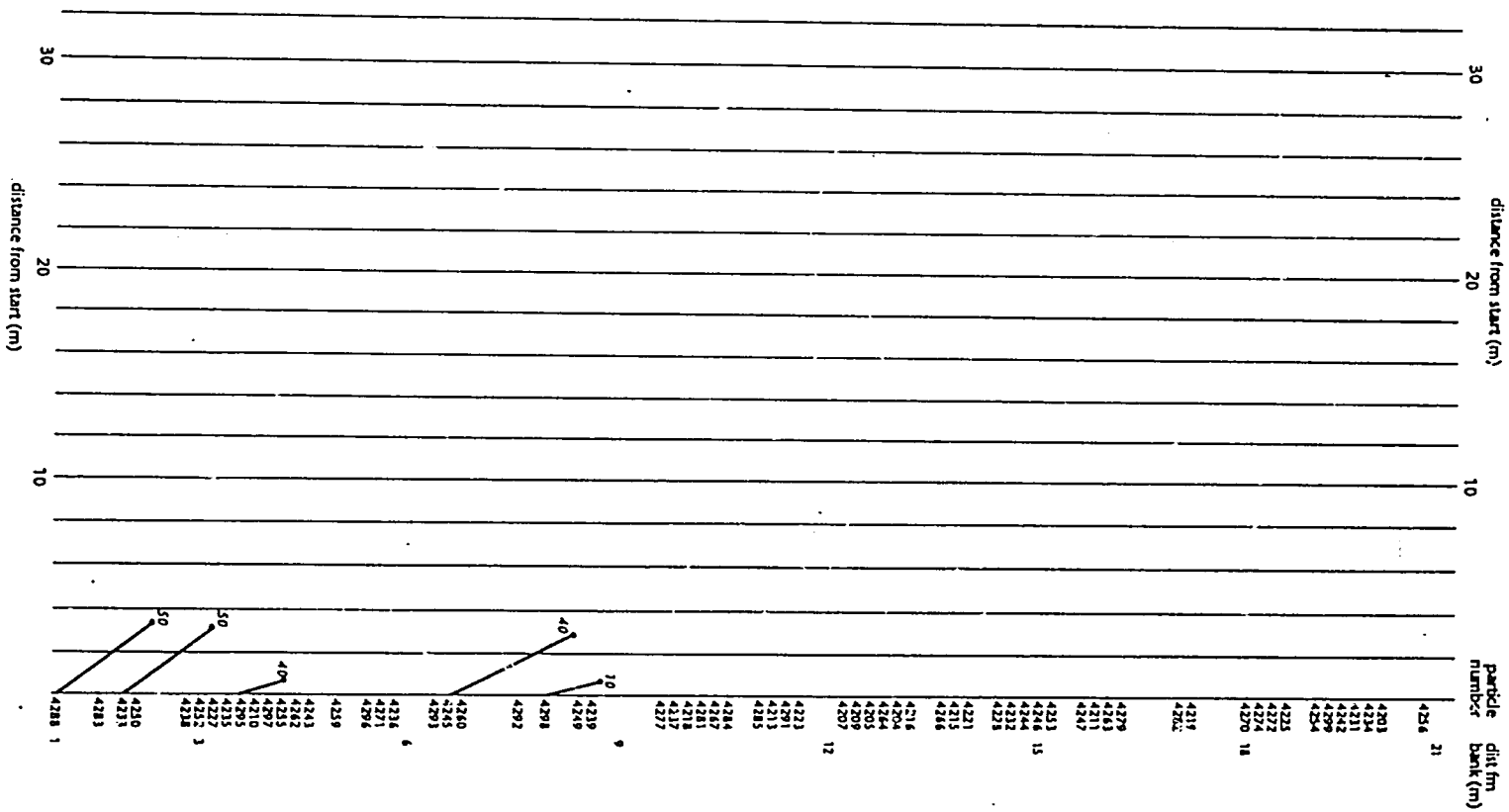



Fig. 35: Low flow pebble dispersion: selective trajectory direction (>20° to right).

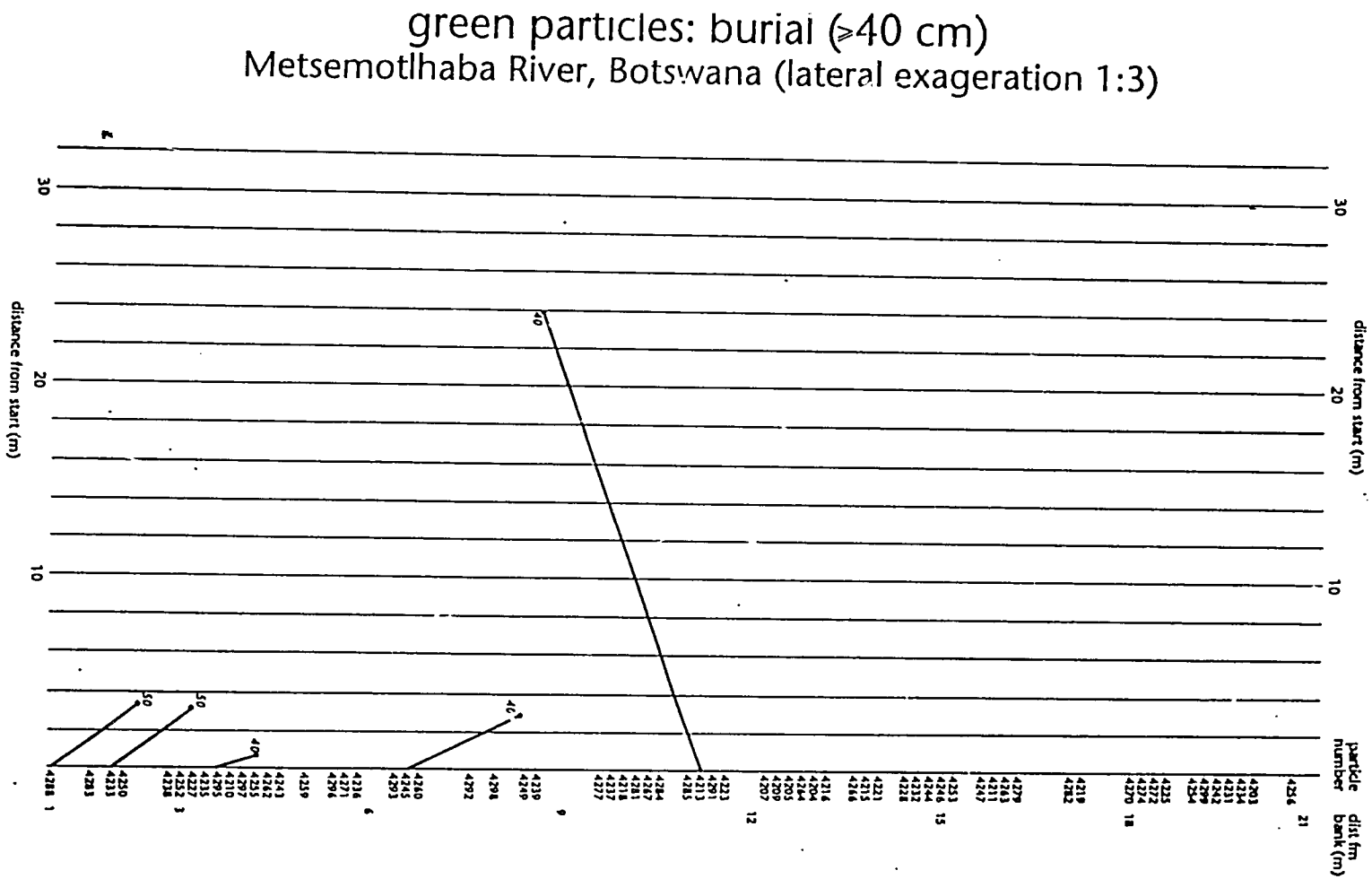



Fig. 36: Low flow particle dispersion: pebbles with very deep (>40 cm) burial.

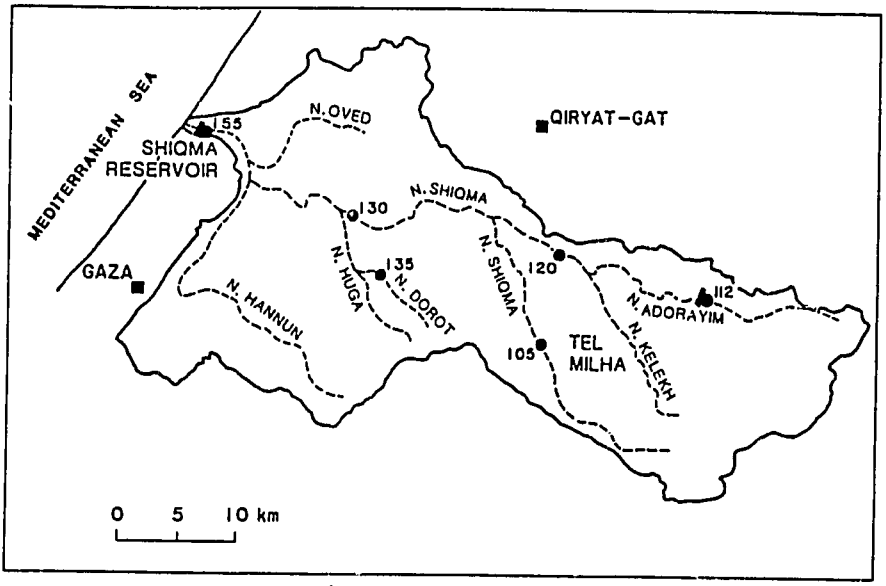



Fig. 37 : Nahal Shiqma catchment : location map

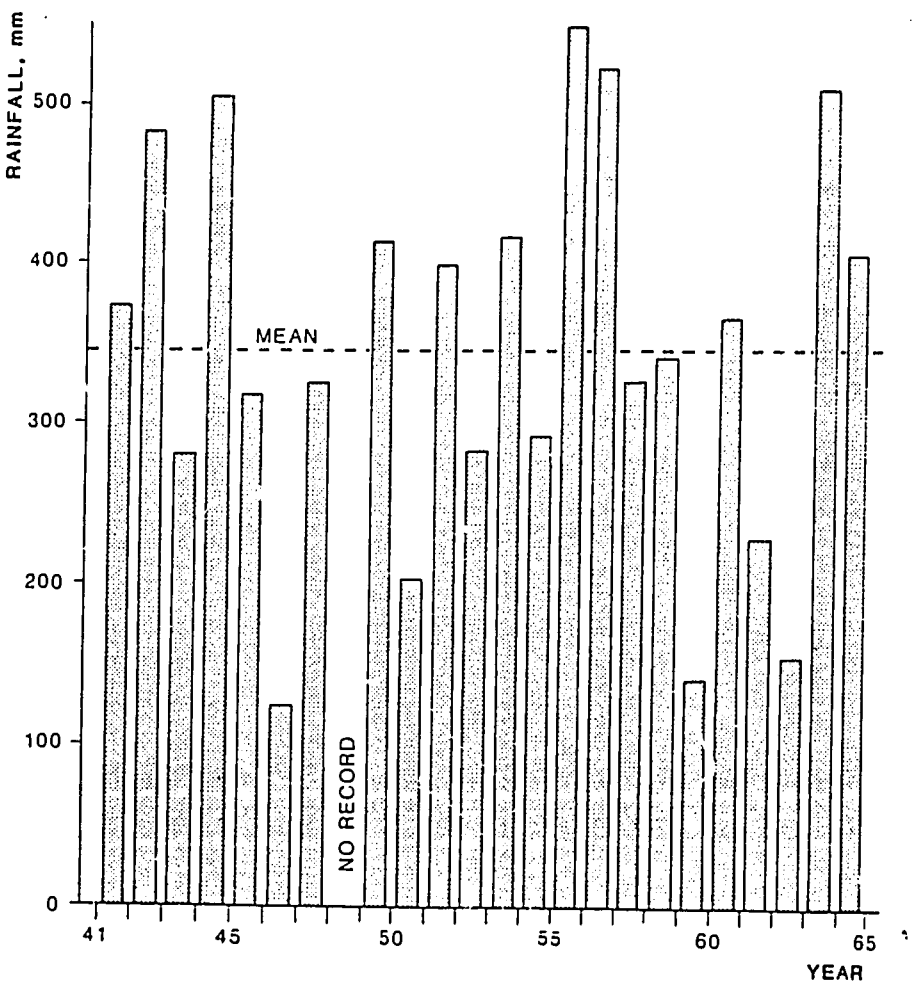



Fig. 38 : Annual rainfall, Dorot, 1941-1965

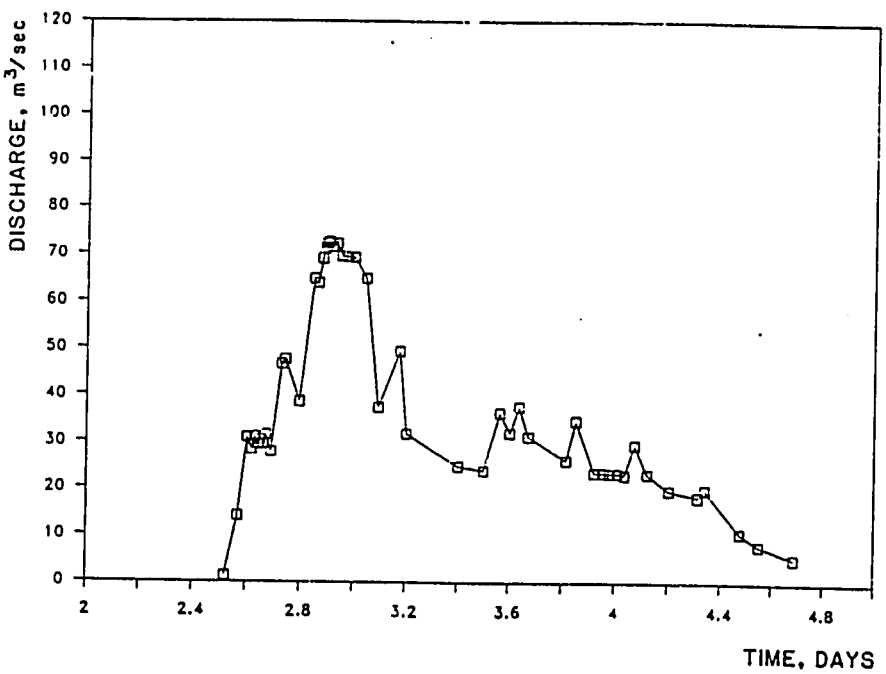



Fig. 39 : Flow of 2 Dec 1963, Nahal Shiqma at Beror Hayil

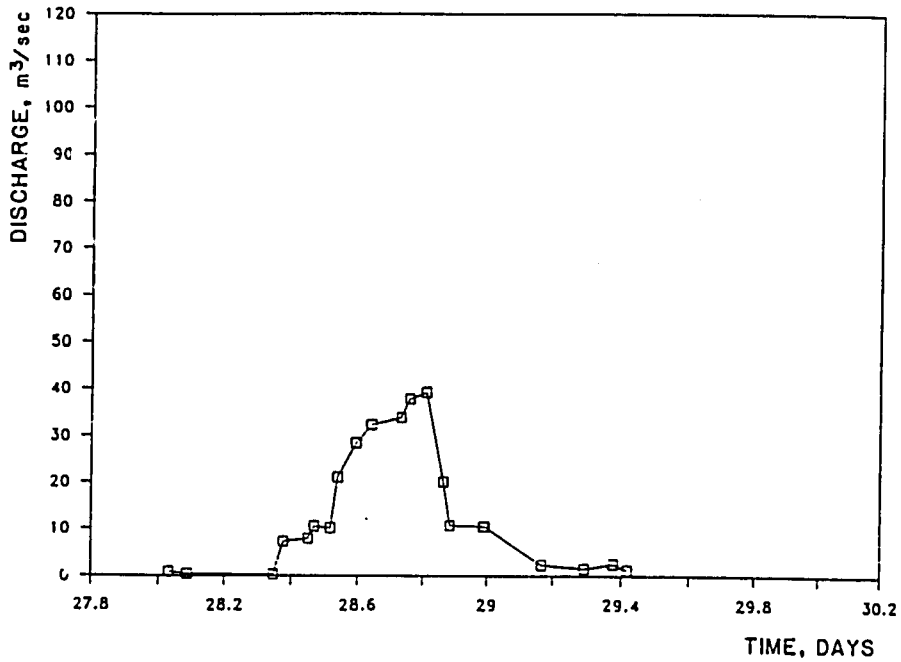



Fig. 40 : Flow of 28 Dec 1971, Nahal Shiqma at Beror Hayil

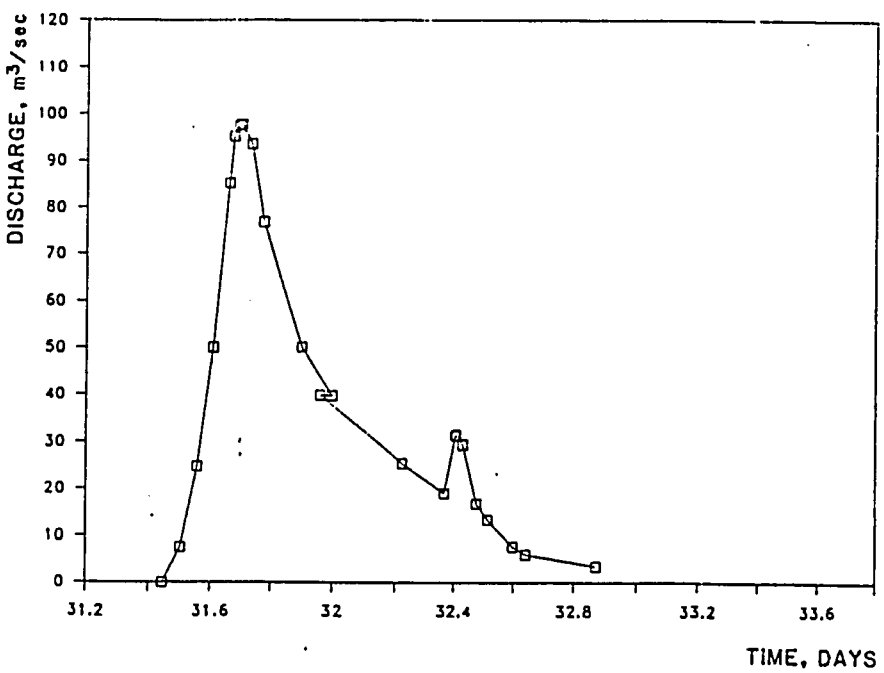



Fig. 41 : Flow of 31 Jan 1974, Nahal Shiqma at Beror Hayil

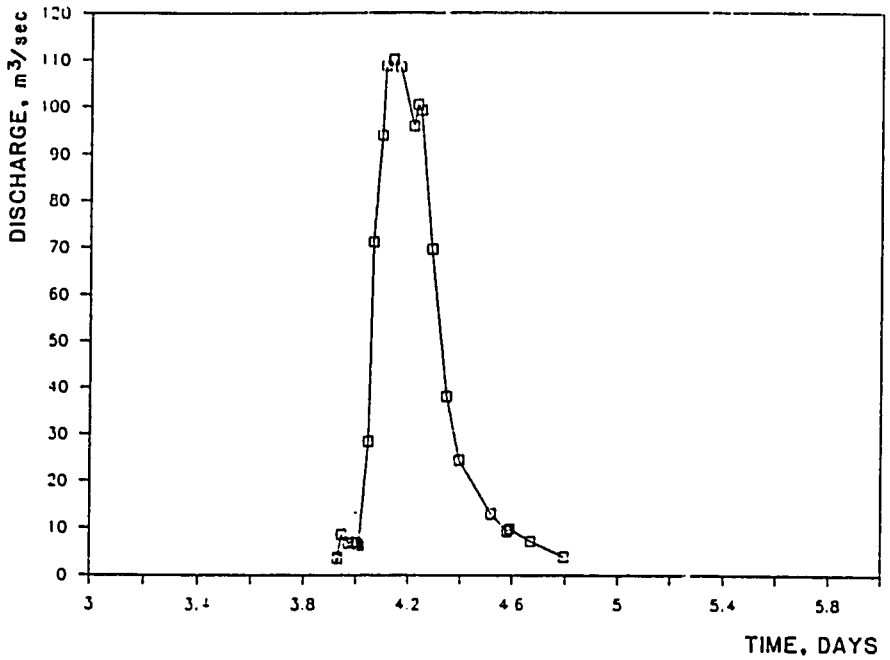



Fig. 42 : Flow of 3 Jan 1978, Nahal Shiqma at Beror Hayil

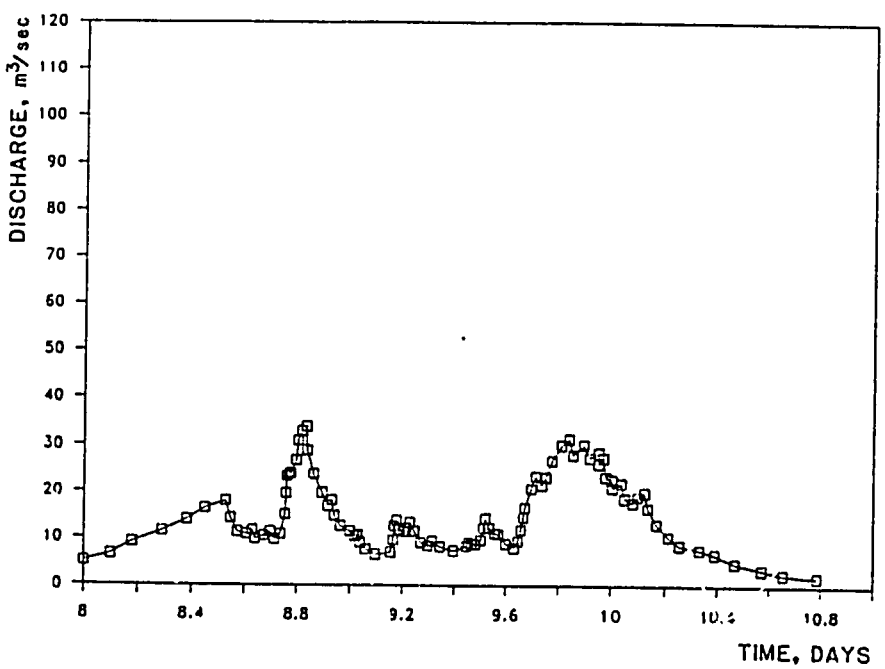



Fig. 43 : Flow of 8 Nov 1986, Nahal Shiqma at Beror Hayil

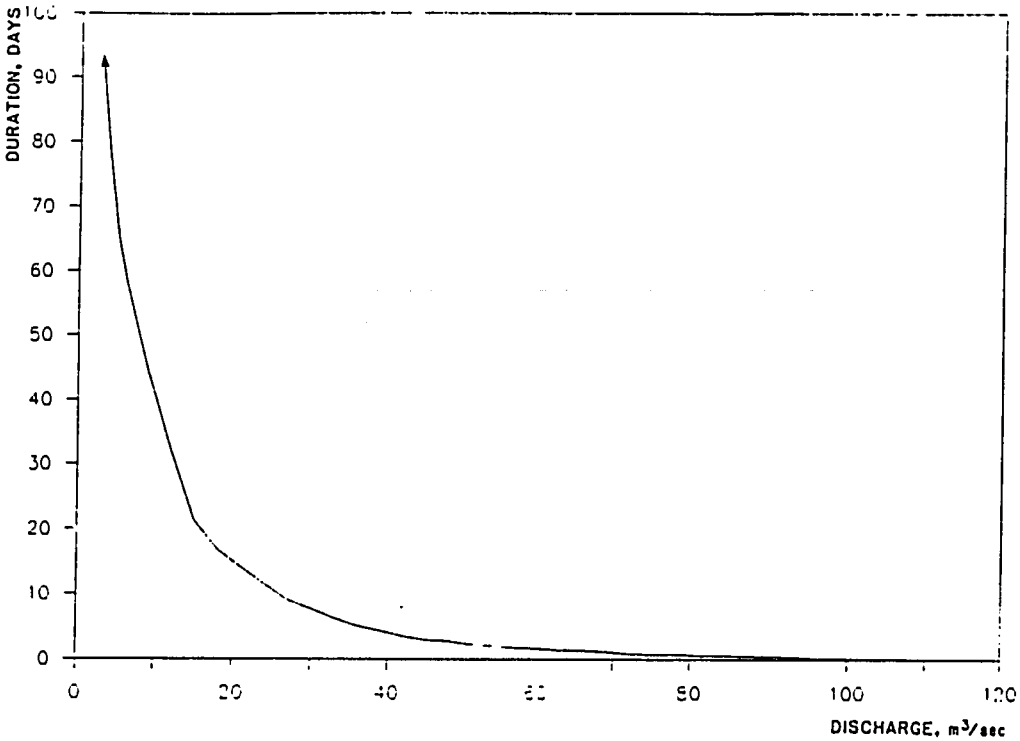



Fig. 44 : Flow frequency, Nahal Shiqma at Beror Hayil, 1960-1987

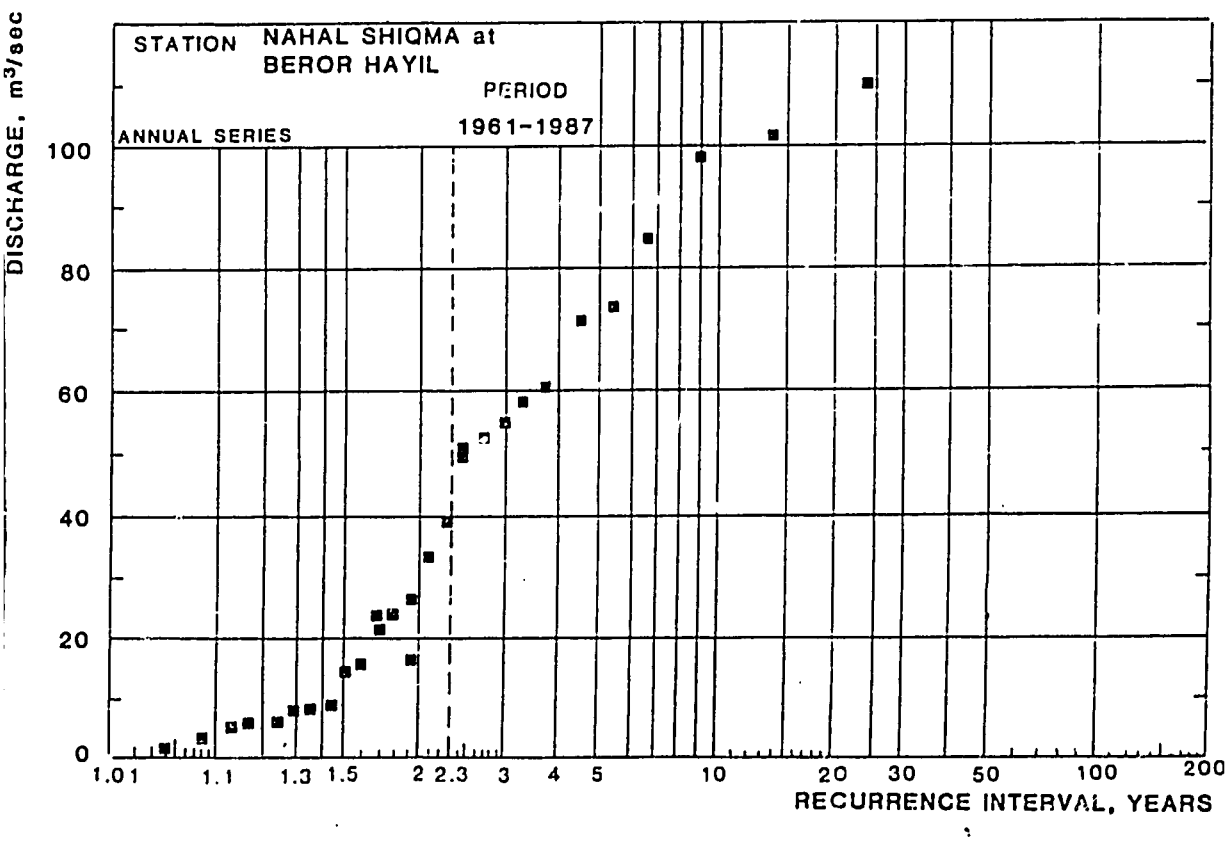



Fig. 45 : Magnitude and frequency of annual flows,
Nahal Shiqma at Beror Hayil, 1960-1987

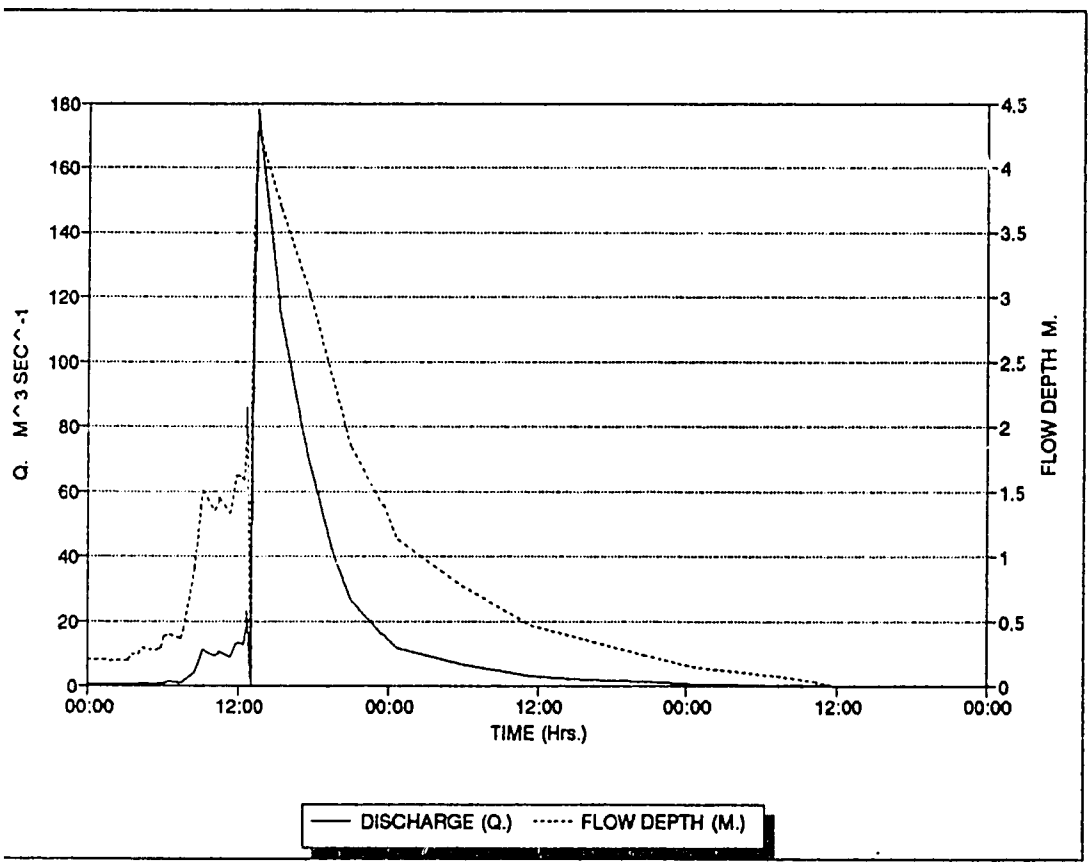



Fig. 46 : Flow of 23-25 Jan. 1991, Nahal Shiqma at Beror Hayil.

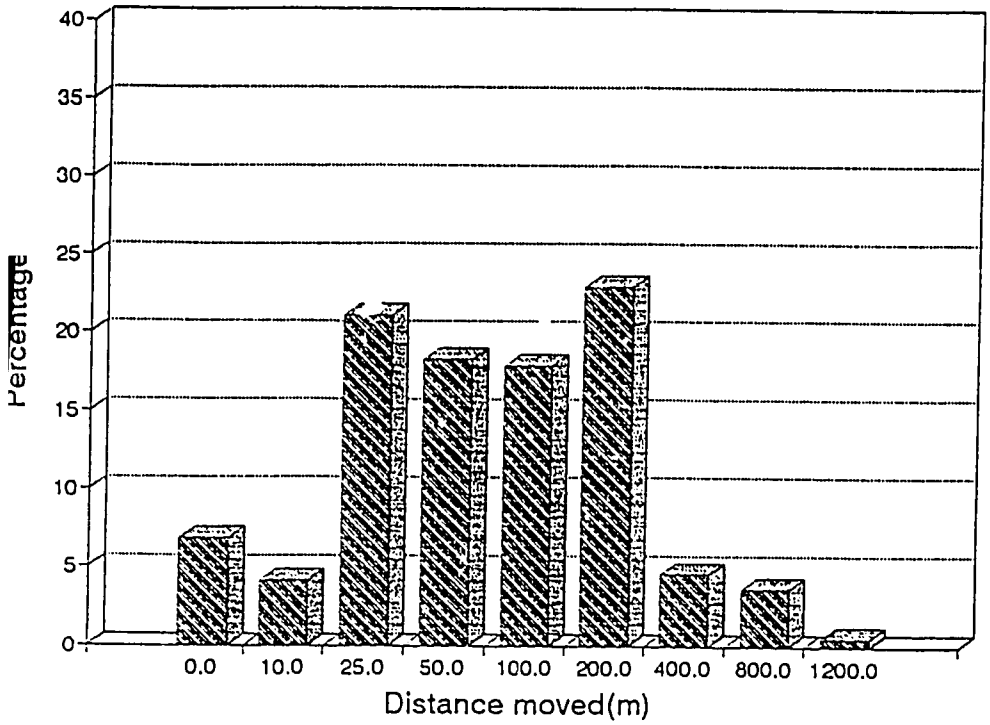



Fig. 47 : Distance moved by trace particles (N=218), Nahal Shiqma, 1987/88.

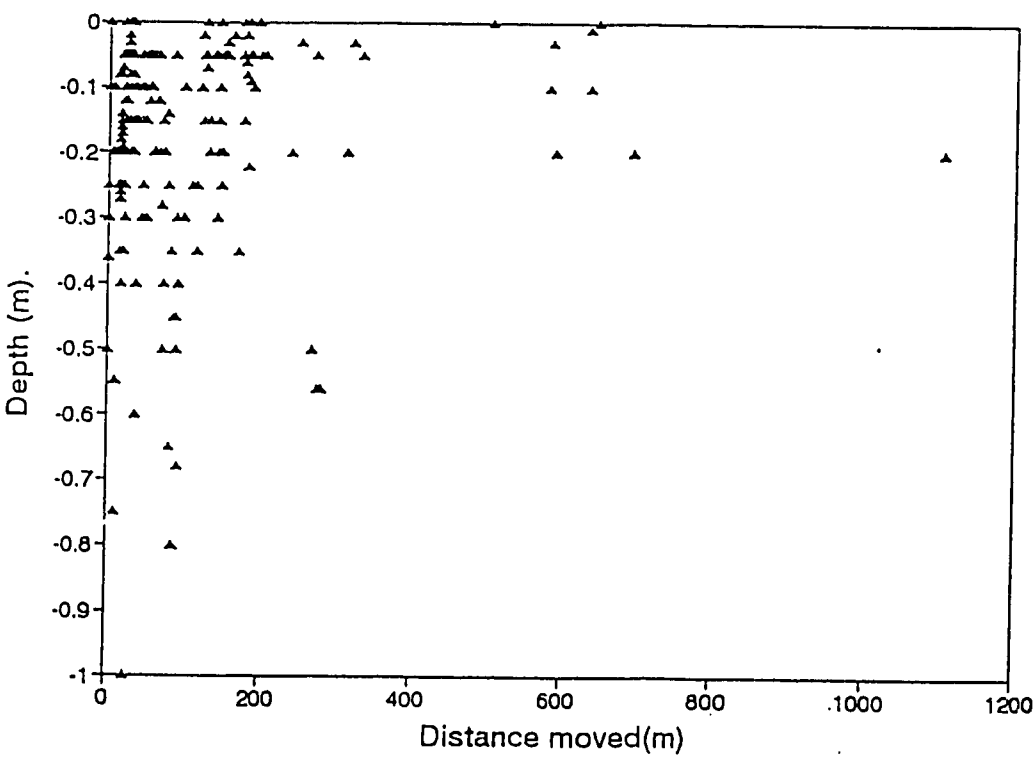



Fig. 48 : Depth of burial v. transport distance, all tracer particles (N=218), Nahal Shiqma, 1987/88.

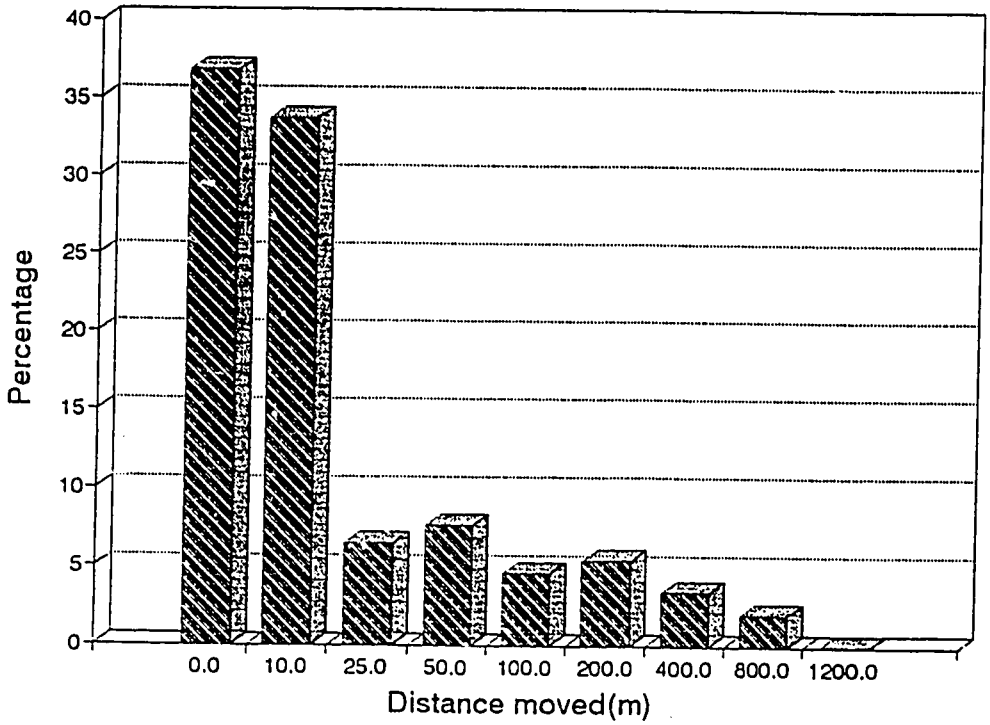



Fig. 49 : Distance moved by trace particles, Nahal Shiqma, 1988/89.

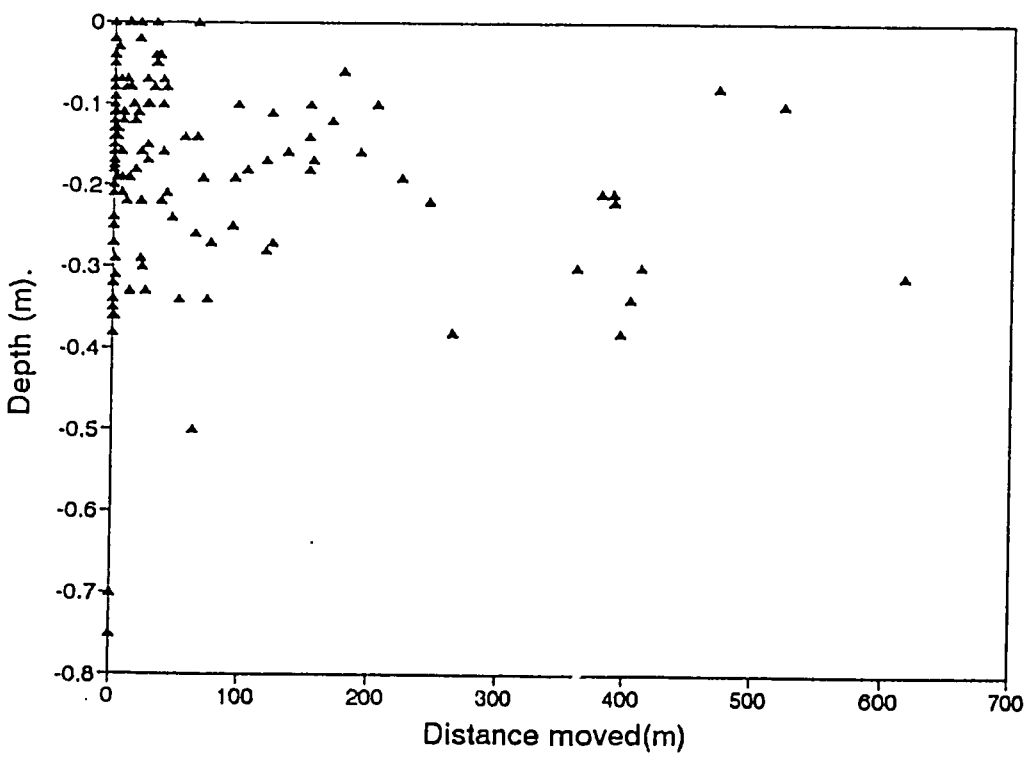



Fig. 50 : Depth of burial v. tranport distance Nahal Shi