US - Israel AID/CDR Program C7-151

FLOODS IN EPHEMERAL STREAMS : EVALUATIONS BASED ON GEOMORPHOLOGY

Contract number DPE-5544-G-SS-6029

Hebrew University reference number 030.7096

INTERIM SCIENTIFIC REPORT

and

PROGRESS REPORT, JUNE - NOVEMBER 1988

Principal Investigator : Asher P. Schick
Department of Physical Geography
Institute of Earth Sciences
The Hebrew University of Jerusalem
Israel

Co-Principal Investigator : Paul Shaw
Department of environmental Science
University of Botswana
Gaborone, Botswana

Rec'd in SCI MAY 3 1 1989

ACKNOWLEDGMENT

It is impossible to thank all individuals and organizations who had helped in one way or the other during the initiation and first field season of the project. We mention only a few : colleagues at the University of Botswana, mainly Drs. Sefe and Ambros ; associates at the Hebrew University, especially Dr. Hassan and Messrs. Grodek, Grossman, Lekach and Sharony ; Mr. Hahn (University of Freiburg) ; Mr. Hentzepeter (University of Amsterdam) ; staff members of the Botswana Water Affairs Department, mainly Messrs. Childe, Khupe and Mollentze ; and AID personnel both in Gaborone and in Tel-Aviv.

CONTENTS

Chapter 1 - Introduction ..... 2 - 3
Chapter 2 - Cooperation aspects 4
Chapter 3 - The site - Geomorphology of the Metsemotlhaba Basin ..... 5 - 7
Chapter 4 - Flow events ..... 8 - 9
Chapter 5 - Particle size distribution 10
Chapter 6 - Cross sections - Metsemotlhaba River .... 11 - 12
Chapter 7 - The longitudinal pattern of bed level changes 13
Chapter 8 - Sediment volumes ..... 14 - 15
Chapter 9 - Sediment tracing and chain records ..... 16 - 20
Chapter 10 - Tha Nahal Shiqma counterpart ..... 21 - 24
Chapter 11 - Main conclusions and Guidelines for the future 25

Appendix A - Progress Report by Dr. Shaw ..... 26 - 27
Appendix B - Abstract of paper submitted to the 4th Benelux Colloquium on Geomorphological Processes and Soils, 1988 ..... 28 - 29
Appendix C - Abstract of paper submittes to the Lanzho (China) IGU/COMTAG Workshop on Loess Geomorphological Processes and Hazards, 1989 ..... 30 - 31

List of Figures

1 - INTRODUCTION

Following the devastating floods of the last rain season (see Appendix A, this report and Progress Report 3), the instrumental set-up on the main project site on the Metsemotlhaba River has now been restored and the flood damage replaced.

The fear that these floods, which were close to the highest recorded or even exceeded them, would disrupt the entire research plan, was exaggerated. 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-sectins also proved revealing. To a lesser extent the chain sectins 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. Although our study is not yet complete, it is clear now that the previously prevalent estimate that there is only little sand movement during flows in the sand rivers is untenable. Our data prove that very large volumes of sand are transported, depths of scour approach, and sometimes exceed, one meter, and particles 2-4 phi units <u>larger</u> than the channel bed sand move hundreds of meters in large floods.

Table 1 summarizes the schedule of the main field operations at the Metsemotlhaba research site for the 1987/88 season in relation to the main flow events.

The occurence of a high-magnitude low-frequency event at the very beginning of our series of observed events poses a problem with regard to establishing relation between sediment tracer dispersion and water discharge characteristics. The future events will elucidate whether this concept can still be useful in reconstracting past flow attributes from tracer data. The

requested no-funding one year project extension is essential not only to obtain a reasonably representative observational series of flow events, but also to give the system a chance to recuperate from the big event effects of 1987/88.

The bulk of this interim scientific report is based on a brief description and discussion on the following topics : Flow events (Chapter 4) ; channel bed grainsize distribution (Chapter 5) ; River cross-sectinal changes (Chapter 6) ; the longitudinal change pattern (Chapter 7) ; scour chains and sediment volume moved (Chapter 8) and sediment tracing (Chapter 9).

Nearly the entire material refers to the main project site on the Metsemotlhaba River ; data from auxiliary sites, especially the Bonwapitse, are occasionally used. Among the Israeli connterpart sites, our main attention in this report is focused on Nahal Shiqma, where sediment tracing experiments have proceeded well (Chapter 10).

The state of the project is evaluated in Chapter 11, which discussed some conclusions and alternatives for the future research period.

Up to now, about 25 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 preformed by the principal investigators and their assistants, each in his own country, on the project, both in the field and in the office. We are keen to reap the results from this large investement by continuing the observations and establishing the interpretations and conclusions in the forthcoming two years.

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 utilisation to discuss the application of the equipment to developing countries. A second party is expected to visit the site in the near future. The site has also been visited by students from the University of Botswana taking hydrology as an optional course. It is also hoped to conduct field visits for Department of Water Affairs technical staff in the near future to familiarise them with the equipment, which is deemed well suited to conditions in Botswana.

The project employs a permanent watchman on-site, and provides employment for up to 4 labourers on a casual basis. The employment of an additional person, in the capacity of observer, is under consideration.

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. Despite the slim chances of finding a suitable candidate for in-research training under the prevailing conditions, we intend to make a special effort in this direction during the period of research left for this project.

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 1,300m 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 km2 area. In the east and south the basin drains 200 km2 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 enters 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 leading 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 characterised by Early Stone Age implements. This line of research, however, has not been followed up.

An alternative explanation 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. 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 Metereological Department. The proposal to construct the dam at Kopong has created a demand for data relating to the hydrology of the Metsemotlhaba.

REFERENCES :

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

4 - FLOW EVENTS

The seven flow events which occurred on the Metsemotlhaba River, 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 events 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. In future, with the restoration of our ENMOS gauges at the site and the successful measurement of a few events simultaneously at the site and at the WAD gauge, it is hoped to establish a discharge correlation between these two sites. Meanwhile, despite factors like the possibility of local sources such as small-diameter rain cells, e.g. 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 can be approximated by 80% of the peak value at Thamaga.

Fig. 4 is a preliminary 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 11 year period shown. Massive sand and tracer gravel transport, as indicated by our study, is probably limited to the 2-3 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 6-7 events in 43 years in which very substantial amounts of sediment have been 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 0.26 and the Manning roughness coefficient indicated by the data was a very high 0.126. 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 when walking on it.

Three suspended sediment samples collected on 14 Feb 1988 at a discharge level of 6.6 m3/sec yielded a concentration of about 1 g/l for the two surface samples and of 3 g/l for a depth of 0.30 m (2 cm above the channel bed). During a flow 0.30 m deep, two samples were collected for suspended sediment. The top sample, taken near the water surface, had 12% sand and 88% silt-clay. The bottom sample, taking 5 cm above the moving dunes, had 40% sand and 60% silt-clay. The concentration of sand only was roughly ten times larger in the bottom sample than in the top sample.

5 - PARTICLE SIZE DISTRIBUTION

The Metsemotlhaba River at the project site has a fairly consistent and symmetric sand 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 2 mm (Figs. 9-11).

These data are in agreement with the findings of the Swedish SIDA team (Nord, 1985, ibid.).

The figures shown are only a small fraction of the data collected. It is our intention to include in the final report of this research, a detailed description and interpretation of the sand size characteristics, especially of the Metsemotlhaba, and to evaluate their relation to past and current geomorphic processes.

6 - CROSS SECTIONS - METSEMOTLHABA RIVER

Figures 12-23 show the results of three recurrent benchmark based surveys done before (11.8.87), after (2.10.88) and in the middle of (19.2.88) 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 (Fig. 12) 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. Most of a large point bar, which 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 has 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 (Fig. 12) 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 (Figs. 13-19). The downstream half (L = 700 m to L = 1,400 m) is represented by five sections (Figs. 19-23).

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. 14) and of up to a cumulative 0.52 m for both periods (section 8, Fig. 19) 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. 24). 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 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 (Fig. 26). Values of aggradation ranges 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 substantial aggradation, such as at L : 300-500, L : 700-1,000, 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 1) 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. 25 and 27, 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 condition.

Strictly speaking, these volumes cannot be regarded beyond doubt as representing sediment exported from the study reach or moving into the reach, since, theoretically, the origin or destination of any individual sand particle may be within the 1,400 m long study reach. However, other evidence points to a long-distance transport of the sand particles. This includes the sedimentological evaluation of seven trenches such as Fig. 28, which disclose a high level of activity. This aspect will be presented in the final report of this project.

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 (Dec 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). Each of the scour and fill values operating in a sand river like the Metsemotlhaba is much larger than the residual value of net aggradation or degradation. Thetechniques of evaluating scour chain data and redeposited tracer sediment are used in this study and their evaluation proves that this is indeed the case (Chapter 9).

9 - SEDIMENT TRACING AND SCOUR CHAIN RECORDS

As reported in progress report 2 (Feb 18, 1988), some 1,400 pebbles were injected into the channel beds of the Metsemotlhaba, Bonwapitse and Tanpye Rivers. About 1,100 of them were small synthetic magnetized pebbles, weight 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 (Progress Reported ibid). In this chapter some of the results obtained from the monitoring of the tracers and chains will be described.

Bonwapitse River

The tracer dose injected in September 1987 included 73 large particles (numbered 600 and over) and 200 small particles (identified by numbers up to 600). The catastrophic flood which occured 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 no significant difference in horizontal displacement between the large and the small particles.

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 the 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 149 large and 595 small particles. The high magnitude event of December 1987 was the first following the injection and entrained all 741 particles. The 165 recovered at the end of the season constitute 22.3%. 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 yet been evaluated. However, in both rivers, as well as in the second auxiliary site on the Tautswe River not discussed in this report, the December 1987 was clearly of prime importance in moving sediment.

Three-dimensional distribution

From previous tracer studies involving coarse sediment (Hassan, 1988) it was concluded that gamma distributions fit well both longitudinal and vertical dispersion patterns of tracer particles, both vertically (burial) as well as longitudinally (downstream). Figs. 29 and 31 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 from 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 not 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. 30 and 32, respectively, show similarly fair to poor fits with the expected gamma distributions. We assume, as a 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 as 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 who continue to move, settle in environments that have already been filled, and tend therefore -- at the end of the event -- to be in shallowely buried locations.

Fig. 33 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. 33 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 generalized vertical position of the bed at the time of arrival of the fasest 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. 33) during 15-25 hrs of high flow (Table 1, event of 22 Dec 87), a meam 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 their number is small. In contrast, the patterns for the Bonwapitse tracers suggest a bore-like flood translocation of the tracers, with a clear concentration around D = 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 Fig. 25 & 27 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.

10 - THE NAHAL SHIQMA COUNTERPART

Nahal Shiqma has 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.

Following are several characteristric rainfall intensities typical of the Nahal Shiqma area. Data are in mm/hr :

Probability/ Duration, min.	80%	50%	20%
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. 130 at Beror Hayil (Fig. 37). As evident from a frequency - duration analysis (Fig. 44), flows at discharge levels capable of moving sand (assume 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 >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 of at least some of the Botswana sand streams like the Metsemotlhaba. The similarity seems to apply also to characteristics of peak discharges (Fig. 45), though the short length 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.

Project activity : In preperation for the rain season 1987-8, 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 man. The catchment area to the study reach is 510 km2 and the channel slope was found to be 0.184% .

Nine cross sections were surveyed along the study reach and four chain sections, totalling 14 one meter 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 following events were recorded during that season at the IHS station at Beror Hayil, 3.5 km upstream of the study reach :

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 was from 20 to 850 m. Vertical displacement (=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 suggests that even moderate flows have the capacity to entrain, transport, and bury particles which are several phi units larger than the D50 of the channel bed material. This material is exclusively sand, and it is possible that this is due to lack of adequate supply of coarse material. This is one question to be investigated in the current subsequent season.

For the 1988/89 season the Enmos water level recorder has been installed on site and is operating satisfactorily. Regular post-event tracer surveys have been initiated. In addition, 25 boulders, weight 4-5 kg each, have been placed in the study reach. A comprehensive correlation between vertical and horizontal displacements of the tracers and the event characteristics are planned as part of the MSc thesis of Shlomo Sharony.

Table 1 : Schedule of field operations, Metsemotlhaba research site, and 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	
	August 1987 - Installation of sections, chains, tracers ; Stratigraphic trenches.				
22 Dec 87	97(130?)	25	19	14	
8 Jan 88	1.3	0	0	0	
11-18 Feb 88	40	68	0	0	#
	February 1988 - Resurvey of sections ; Post-flood survey ; Low-flow measurements.				
3-11 Mar 88	60	30	8	0	##
11-15 Mar 88	33	13	0	0	##
	Sep-Oct 1988 - Resurvey of sections ; Survey of tracers ; Stratigraphic trenches.				

* 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.

\# Composed of 3 distinct and roughly equal sub-events
Composed of 2 distinct and nearly equal sub-events

11 - MAIN CONCLUSIONS AND GUIDELINES FOR THE FUTURE

Three main tentative conclusions emerge from the work of the first two years of the project :

First, on the general science level, coarse sediment tracing in a sandy matrix has to be viable and correlate, together with other geomorphic and sedimentologic criteria, with the magnitude and frequency of the flows which cause them to move.

Second, on a 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. We have a dynamic system which erodes at an appreciable rate the available sand volume, which may be a non-renewable resource of prime importance to the Botswana livestock industry.

Third, the difficulties involved in running a process-based field study in an LDC country like Botswana are very large. Despite the efficient cooperation between the visiting PI and the resident PI and the proximity of a science base at the University of Botswana, the caliber of the local observing staff and the lack of intermediate research-oriented personnel posed severe limitations. Our effort to bridge this gap has been based partly on a larger than usual field presence of the senior staff and on high-tech instrumentation has been only partially successful. It was hampered to a large extent by the fact that our very first event was one of a 10-20 years recurrence interval. However, the experience gained augments the chances to do a better job in the next two years.

Essentially the method of research has proved appropriate. Of the parts of the system destroyed by the December 1987 flood, the upper station on the Metsemotlhaba has already been rehabilitated. New scour chains will be installed in the coming fall, to replace the 90% loss by deep scour during the flood.

APPENDIX A

1st December 1988

Department of Environmental Science,
University of Botswana,
P/Bag 0022,
Gaborone,
Botswana.

US-ISRAEL CDR PROGRAMME C7-151
FLOODS IN EPHERMERAL STREAMS : EVALUATIONS BASED ON GEOMORPHOLOGY

PROGRESS REPORT 4 : June 1988-December 1988

cc: Professor Schick, HUJ,
US-AID, Gaborone.

The following progress has been made on the implementation of the above project in Botswana:

Following the unexpected and somewhat extreme conditions experienced during the last rain season, work has concentrated on restoring the project to full operational order, and or recovering

and interpreting the wealth of data available from the experimental sites.

A party for HUJ, comprising Professor Schick, Dr Hassan and Mr Hahn visited Botsawana from 24th to 7th October. Field work concentrated on the Metsemotlhaba site, which was resurveyed and a comprehensive check made on the magnetic tracer and chain lines. Two days were also spent at the Bonwapitse site, where similar procedures were carried out. The results of this work are detailed elsewhere. Equipment in the field was also tested, and arrangments made for the more satisfactory reading and handling of data. One of the two stations on the Metsemotlhaba is in

working order, and data is being collected during the present rain season.

All of the equipment lost in the December flood of last year has now been recovered, with the exception of the upstream gauge, which lay below the level of the water table, a feature that has persisted at an unusually high level throughout the dry season. It was decided to replace the gauge with a simpler design in October, but this has been delayed by an early flood in late October, which again raised the water table too high to allow excavation of the foundations. The water table lies at 1 m depth at present, and the gauge will be installed mid-December if hydrological conditions allow.

Thamaga received 100 mm of rain in October and a minor flood occurred over a period of seven days. Subsequently conditions have been much drier. The downstream gauging site is working well at the present time.

The current phase of dam design and construction on Botswana's sand rivers (the Shashe, Matloutsie and Lotsane Rivers) to augment the water supply for eastern Botsawana, has uncovered large gaps in our knowledge of sediment transfer in this type of river, and has renewed interest in the project by the Department of Water Affaies and other organisations. Unfortunately manpower in DWA is still overextended in the light of current monitoring and project needs, so it has still not proved possible to indentify suitable postgraduate candidates. It is, however, being used for undergraduate training at the present time.

Dr Paul Shaw

APPENDIX B

Abstract of paper submitted to the 4th Benelux Colloquium on Geomorphological Processes and Soils, April - May 1988

FLOODS IN EPHEMERAL STREAMS - EVALUATIONS BASED ON GEOMORPHOLOGY

A.P. Schick*, P. Shaw#, T. Grodek*, and M.A. Hassan*

* The Hebrew University of Jerusalem
# University of Botswana

In seasonal or ephemeral streams, labelled particles several phi-units larger than the median bed material, if traced after consecutive events of fluvial dispersion, provide information on the hydrologic characteristics of these events. Geomorphic observations on size, shape, and material of bed, banks, and evaluations of recent and older floodmarkers, as well as historical and concurrent information, provide supportive information. Both approaches can be combined to develop a technique of estimating the flow history and flooding characteristics of ungauged non-perennial rivers. This technique is of substantial potential value in those developing countries which have inadequate or low-quality gauging records.

A pilot project designed to experimentally calibrate the procedure has been set up on several ephemeral sand rivers in Botswana, paralleled by several similar grained streams in Israel. Hundreds of magnetized pebbles were emplaced in experimental stream reaches and their three-dimensional fluvial dimentional fluvial dispersion is being monitored. Detection to depths one meter and more enables evaluation of scour and fill, supported at some of the sites by data from scour chains.

The experimental layout installed at the site in Botswana, the Metsemotlhaba River, and several of the auxiliary sites in both countries, are desecribed and discussed. Several preliminary results and probable result scenarios are evaluated.

APPENDIX C

Abstract paper submitted to the Lanzhou (China/IGU/CPMTAG) Workshop on Loess Geomorphological Processes and Hazards, May - June 1989

FLUVIAL PROCESSES IN LOW - AND MEDIUM - ORDER STREAM CHANNELS IN LOESS TERRAINS -- EXAMPLES FROM SOUTHERN ISRAEL

A.P. Schick, M.A. Hassan, S. Sharoni
The Hebrew University of Jerusalem, Israel

As fluvial order increases in drainage systems of loessial terrains, stream channels dominated by gullying and piping gradually give way to semi-stable, high-bank channels characterized by a relatively resistant bed composed of lag-depositsd sand and occasionally gravel. The dynamic behaviour of these channels is often of a controlling importance on the development of the entire fluvial system.

With the objective of understanding these controls, the movement of coarse sediment particles in the fifth order stream channel of Nahal Shiqma is being studied. Gravel of various sizes, introduced into the channel bed after magnetization, are being used, with subsequent three-dimensional recovery. Morphological changes resulting from event-by-event imbalances of scour and fill, studied with the aid of chains, and from bank caving, are juxtaposed with the transport data.

It is apparent from preliminary results that coarse particle movement considerably exceeds values expected from theoretical and

practical studies. Therfore, it is not only the loessy sediment which moves through the system very effectivelly -- practically all of it as wash load -- but also the sand fraction as well as the coarser particles move substantially. This conclusion is of importance with regard to the understanding of the quasi-equilibrium state of such systems, as well as in relation to applications such as channel stabilization and rivercourse crossings.

LIST OF FIGURES

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

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. 1 (L = 0 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. 2 (L = 100 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 14 : Cross section No. 3 (L = 200 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 15 : Cross section No. 4 (L = 300 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 16 : Cross section No. 5 (L = 400 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 17 : Cross section No. 6 (L = 500 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 18 : Cross section No. 7 (L = 600 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 19 : Cross section No. 8 (L = 700 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 20 : Cross section No. 11 (L = 1000 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 21 : Cross section No. 13 (L = 1200 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 22 : Cross section No. 14 (L = 1300 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 23 : Cross section No. 15 (L = 1400 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

Fig. 24 : 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. 25 : 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. 26 : 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. 27 : 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. 28 : Alluvial stratigraphy, Metsemotlhaba R.
A - Location sketch ; trench 3 (at station 275 m)
B - Cross section
C - Longitudinal section

Fig. 29 : Burial of tracer particles : field data and fitted gamma distribution. Bonwapitse R., Sep 1987 - Sep 1988

Fig. 30 : Downstream displacement of tracer particles : field data and fitted gamma distribution.
Bonwapitse R., Sep 1987 to Sep 1988

Fig. 31 : Burial of tracer particles : field data and fitted gamma distribution.
Metsemotlhaba R., Sep 1987 - Sep 1988

Fig. 32 : Downstream displacement of tracer particles : field data and fitted gamma distribution.
Metsemotlhaba R., Sep 1987 to Sep 1988

Fig. 33 : 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. 34 : Longitudinal and vertical displacement, large particles.
Metsemotlhaba R., Sep 1987 - Sep 1988

Fig. 35 : Longitudinal and vertical displacement, small particles. Bonwapitse R., Sep 1987 - Sep 1988

Fig. 36 : Longitudinal and vertical displacement, large particles. Bonwapitse R., Sep 1987 - Sep 1988

Fig. 37 : Nahal Shiqma catchment : location map

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

Fig. 38 : Flow of 20 Jan 1961, Nahal Shiqma at Beror Hayil

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

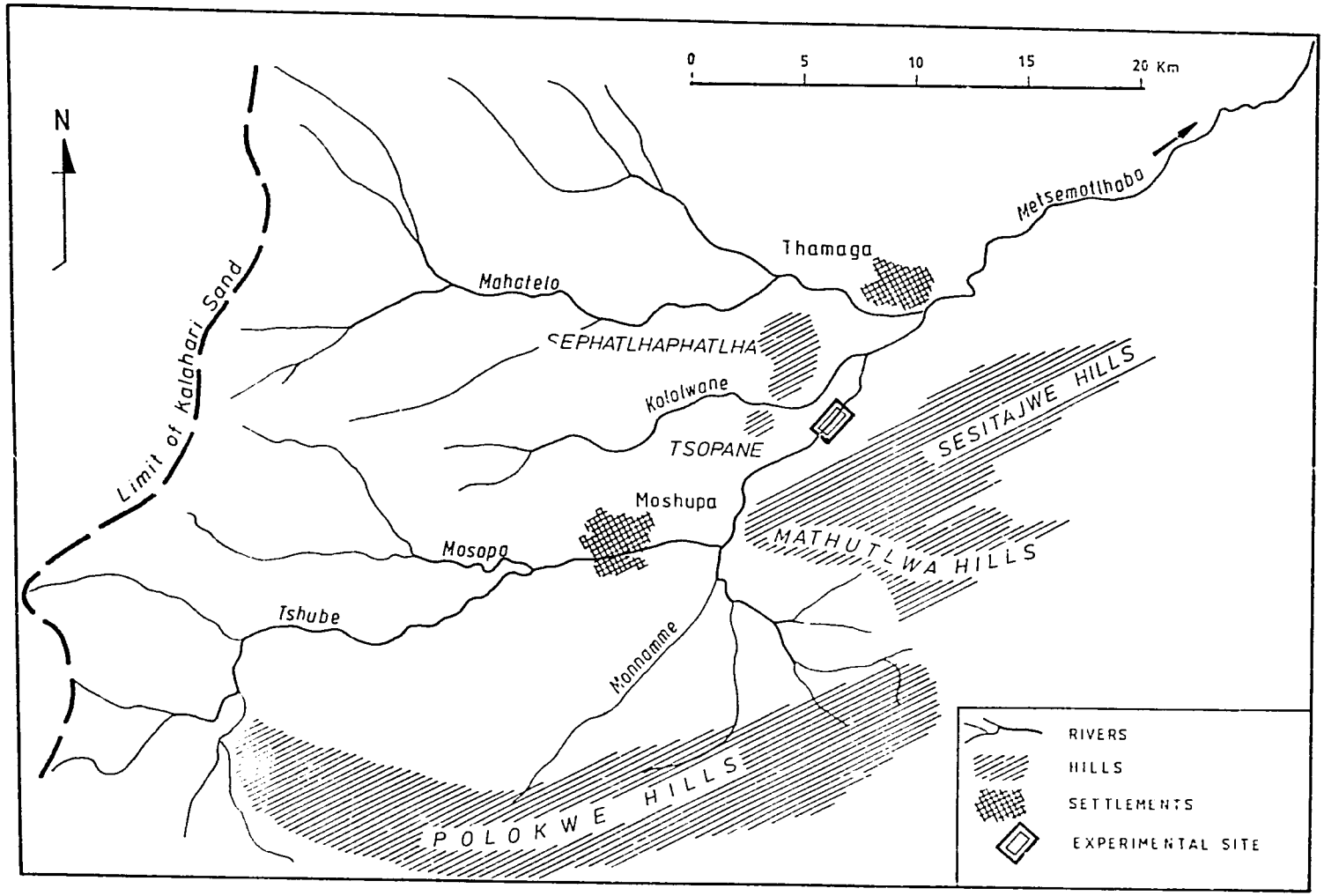


Fig. 1 : Location map : the Upper Metsemotlhaba catchment

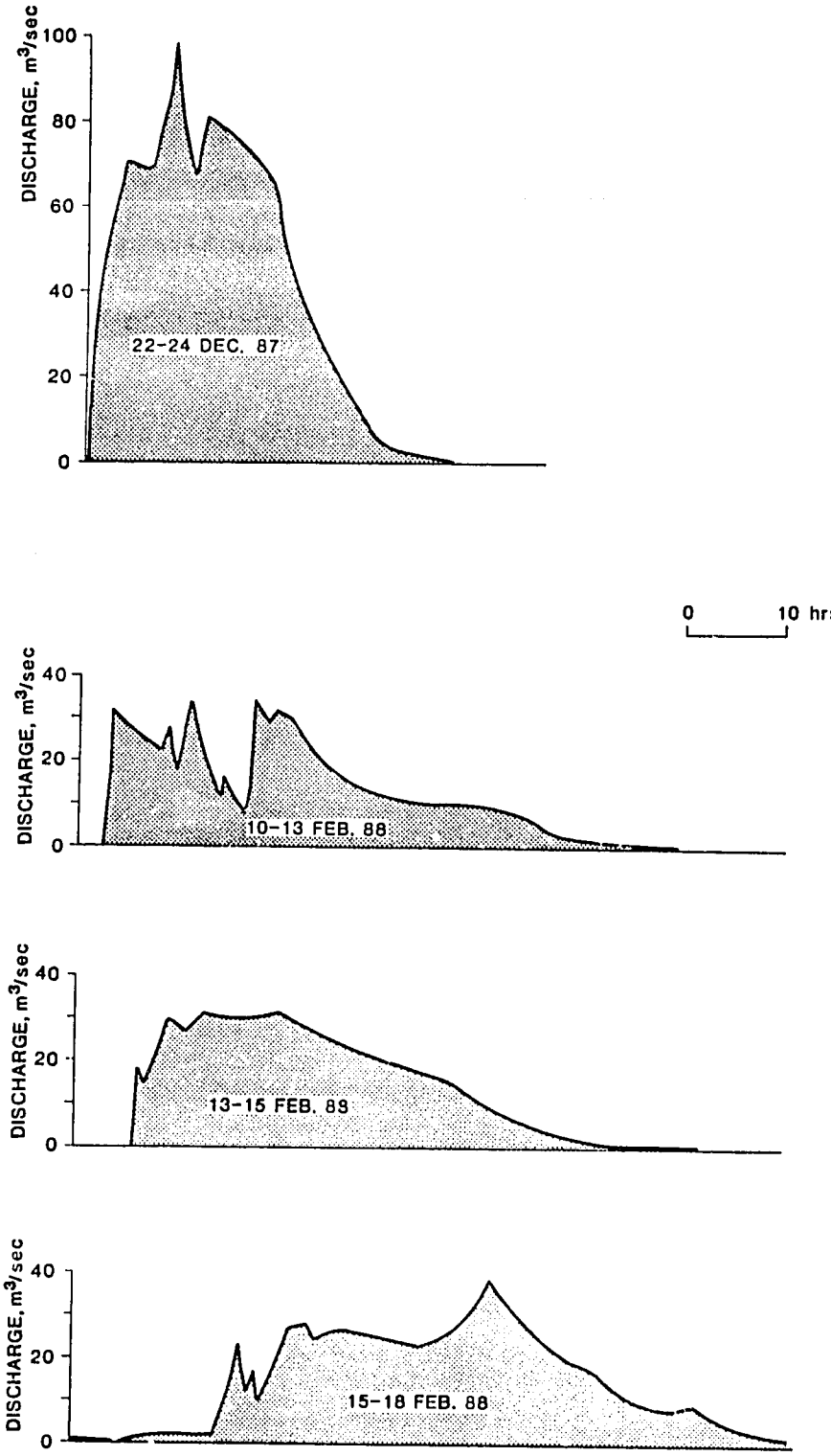


Fig. 2 : Generalized flow record, first observation period, Sep 1987 - Feb 1988
Metsemotlhaba R. at Thamaga, WAD Station 2421

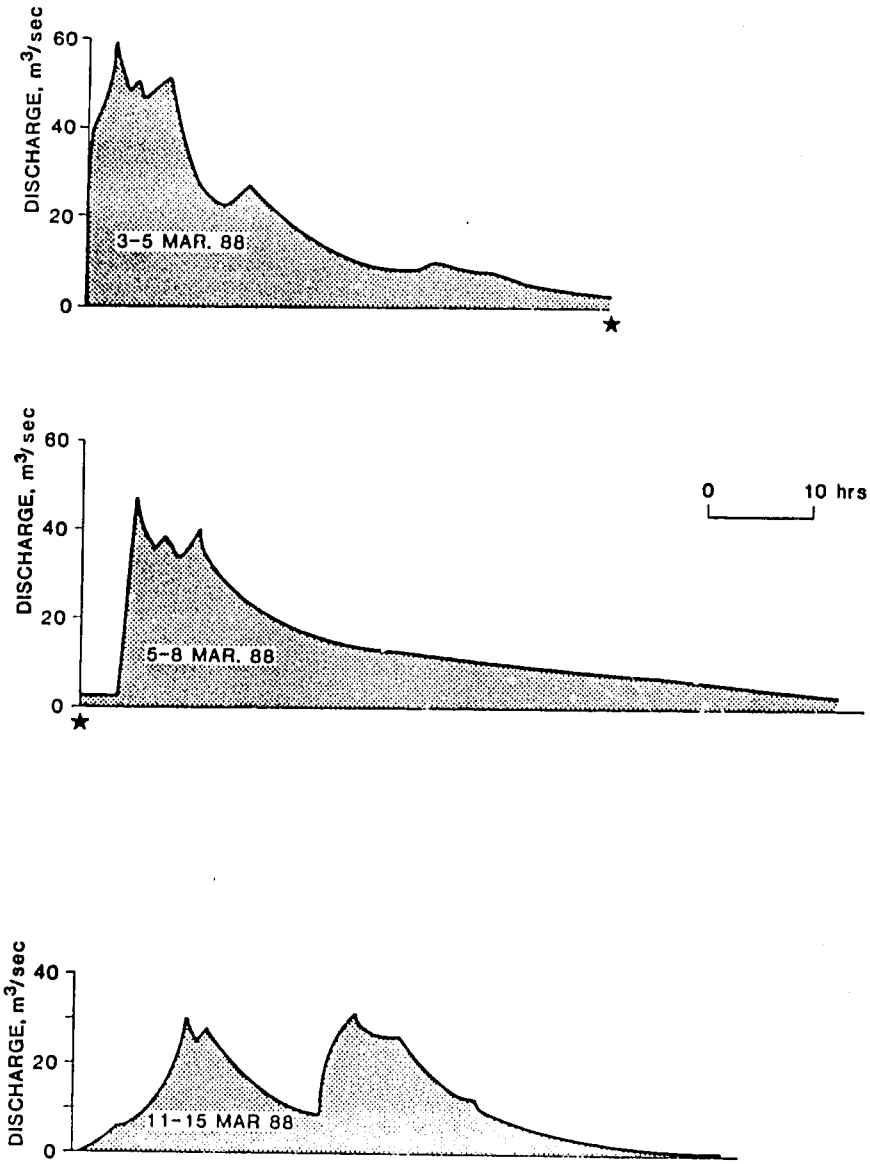


Fig. 3 : Generalized flow record, second observation period, Feb - Sep 1988
Metsemothlaba R. at Thamaga, WAD Station 2421

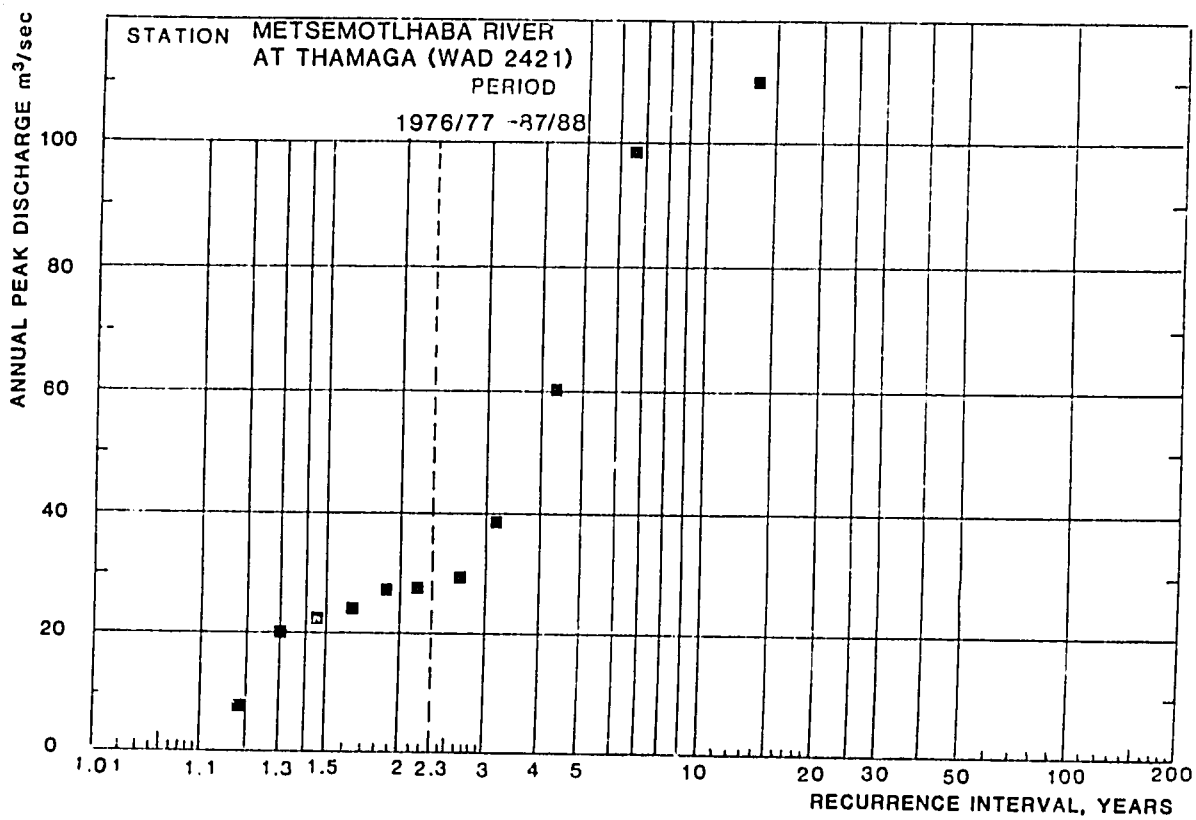
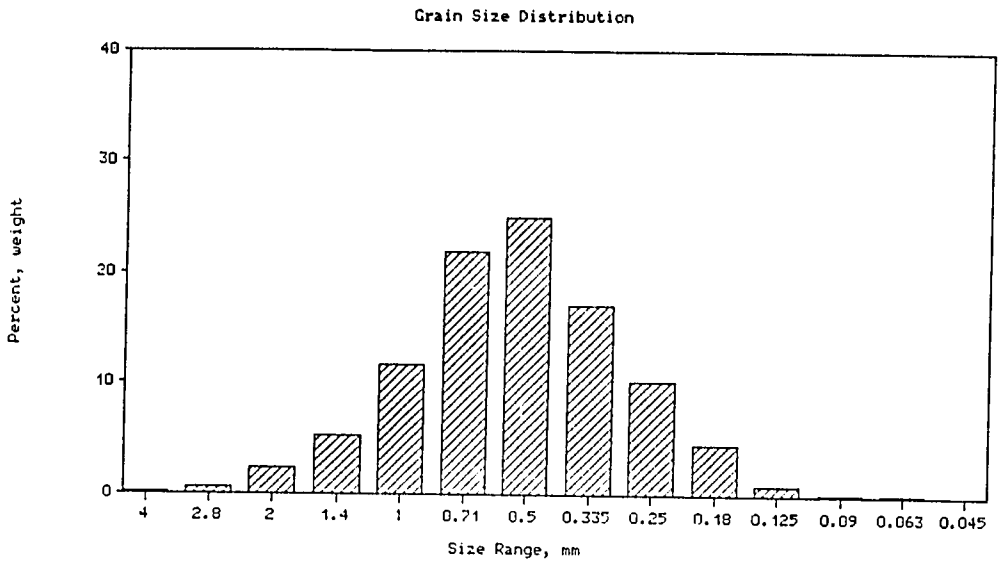


Fig. 4 : Annual peak flows, Metsemotlhaba R. at Thamaga, WAD Station 2421



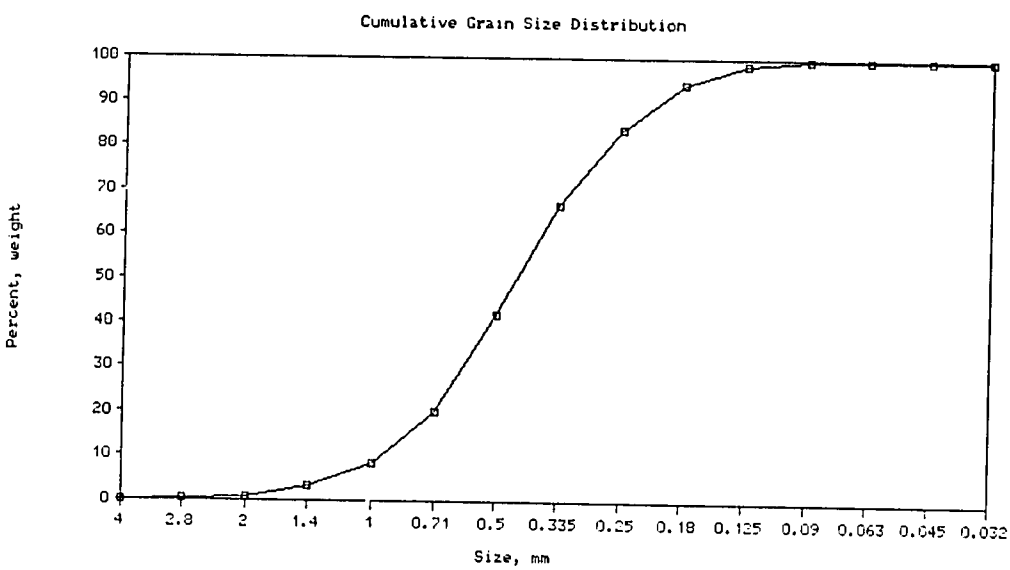
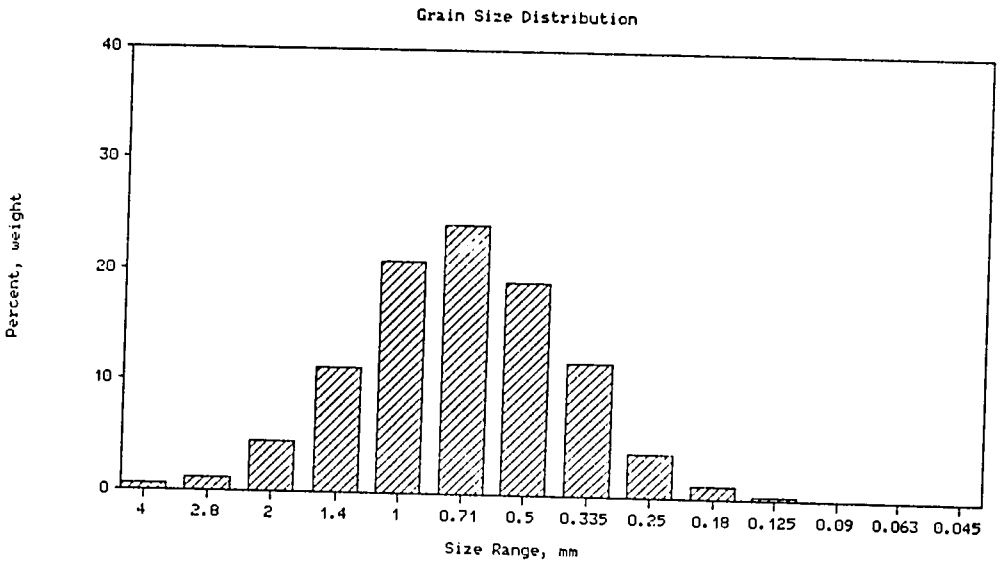


Fig. 5 : Size distribution of channel alluvium, surface sample No. 3W6 (Lab. No. 15), Metsemotlhaba R.



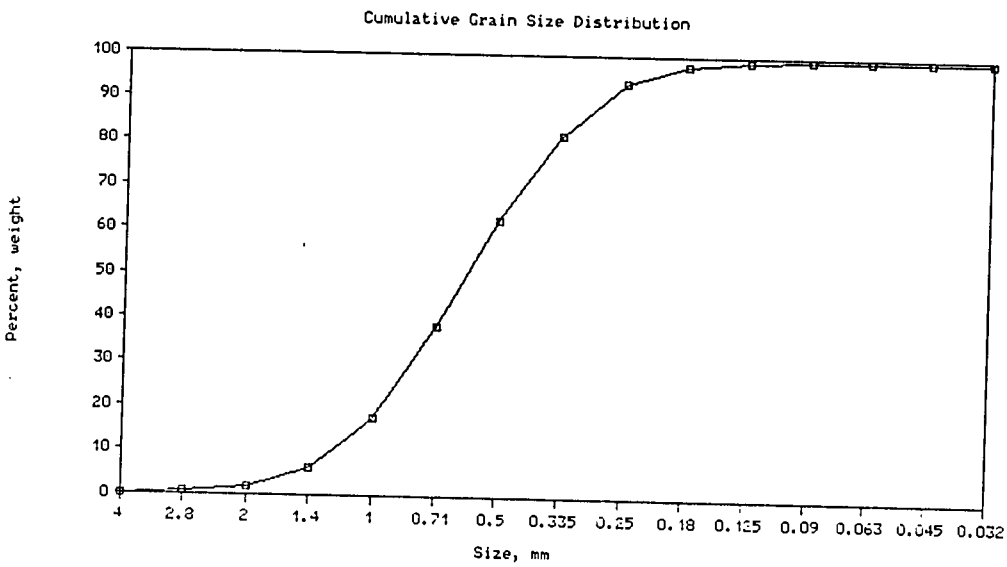
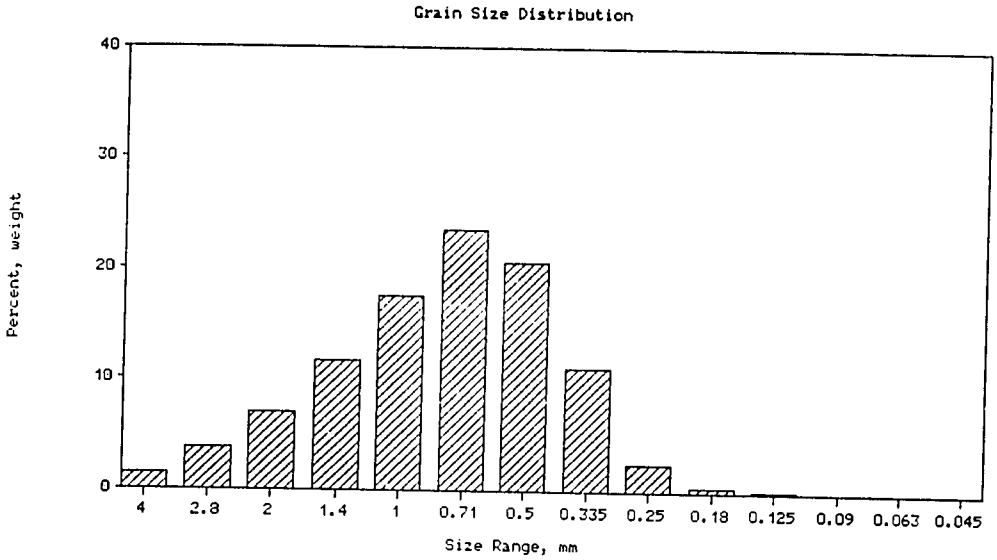


Fig. 6 : Size distribution of channel alluvium, sub-surface sample No. 3W5a (Lab. No. 11), Metsemotlhaba R.



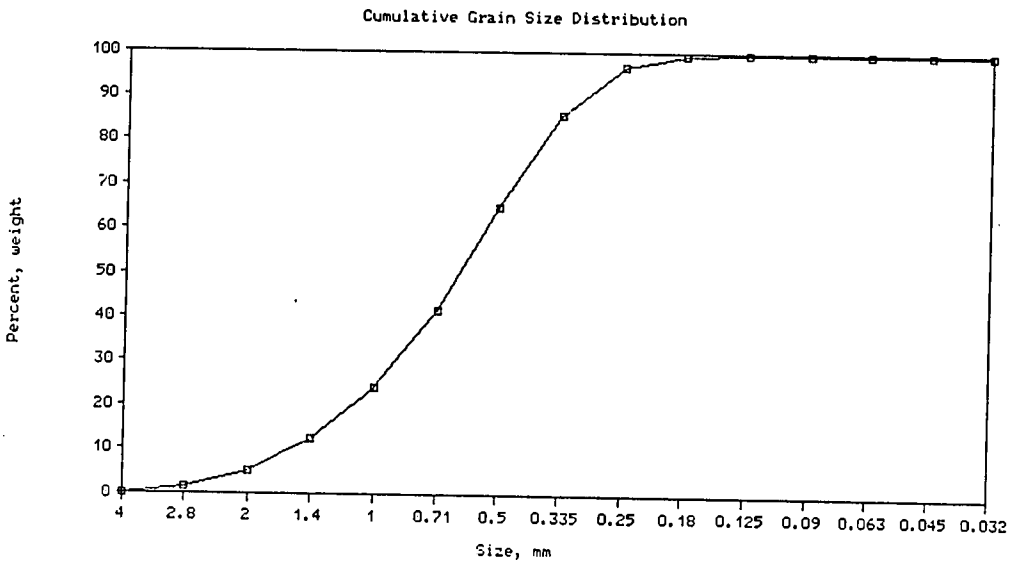
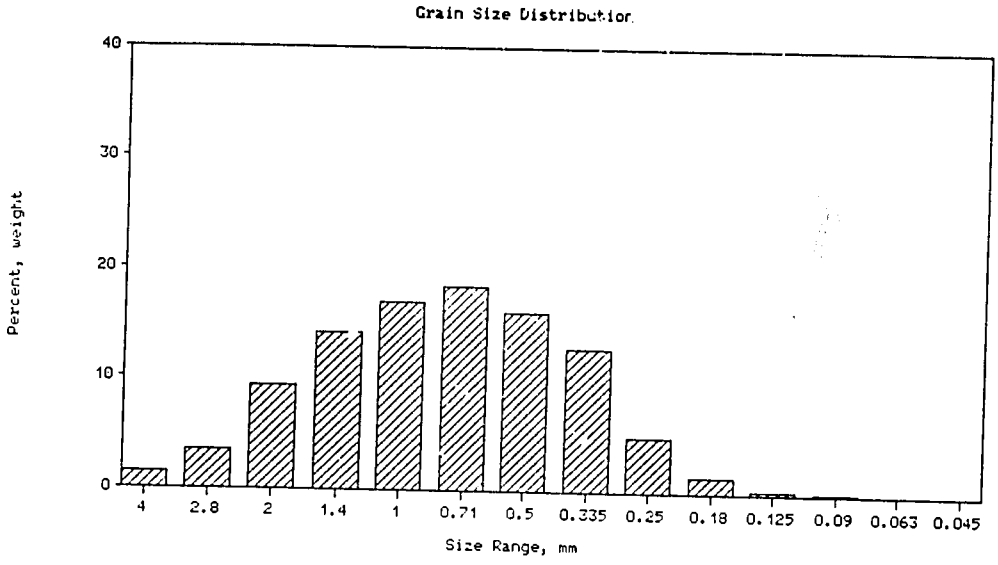


Fig. 7 : Size distribution of channel alluvium, sub-surface sample No. 3W7 (Lab. No. 23), Metsemotlhaba R.



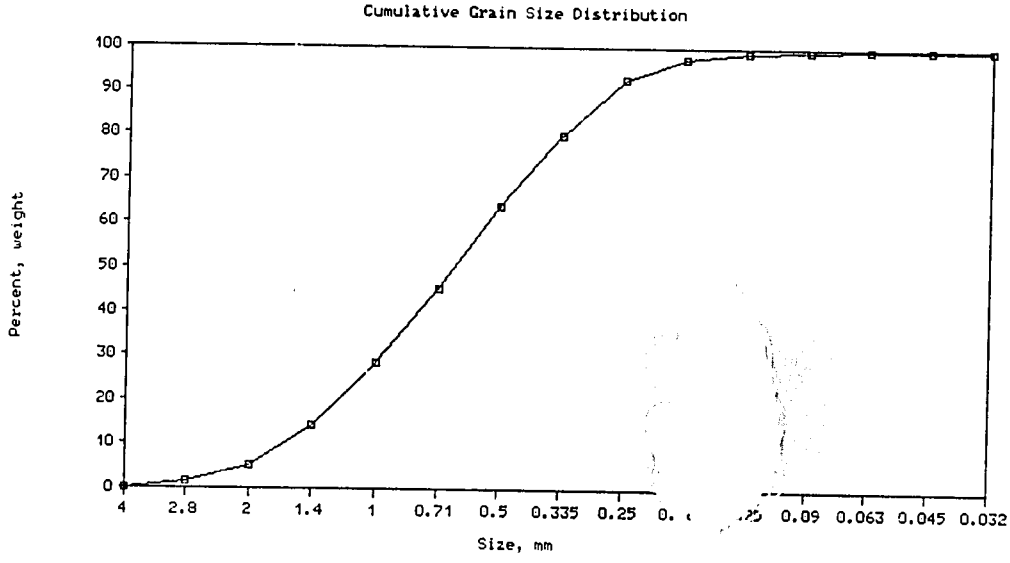
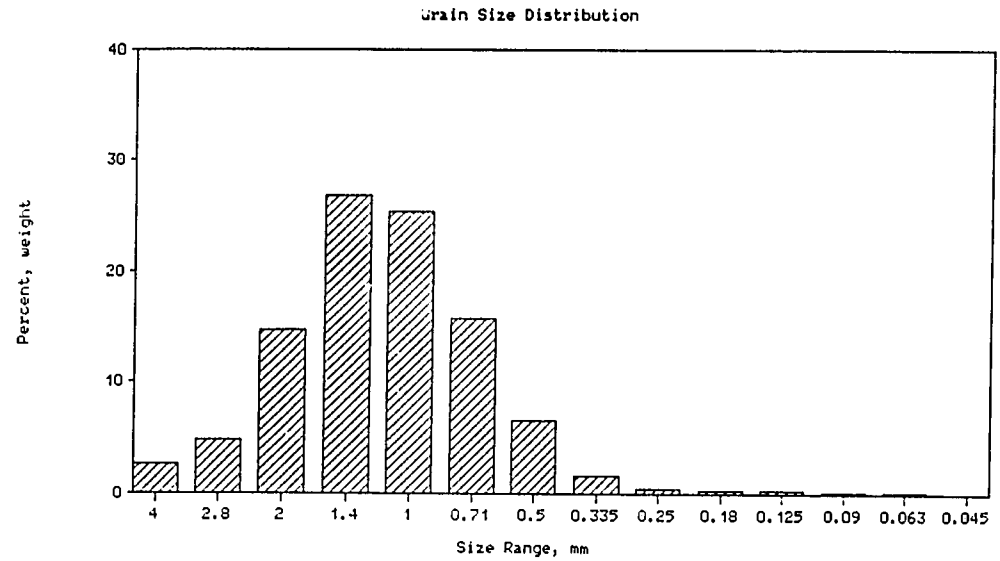


Fig. 8 : Size distribution of channel alluvium, sub-surface sample No. 3W4 (Lab. No. 51), Metsemotlhaba R.



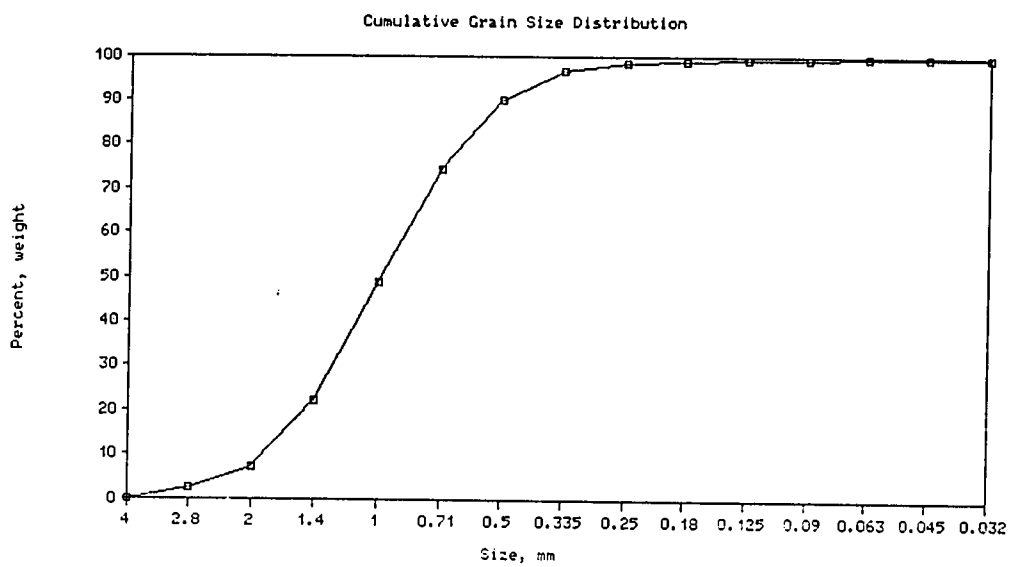
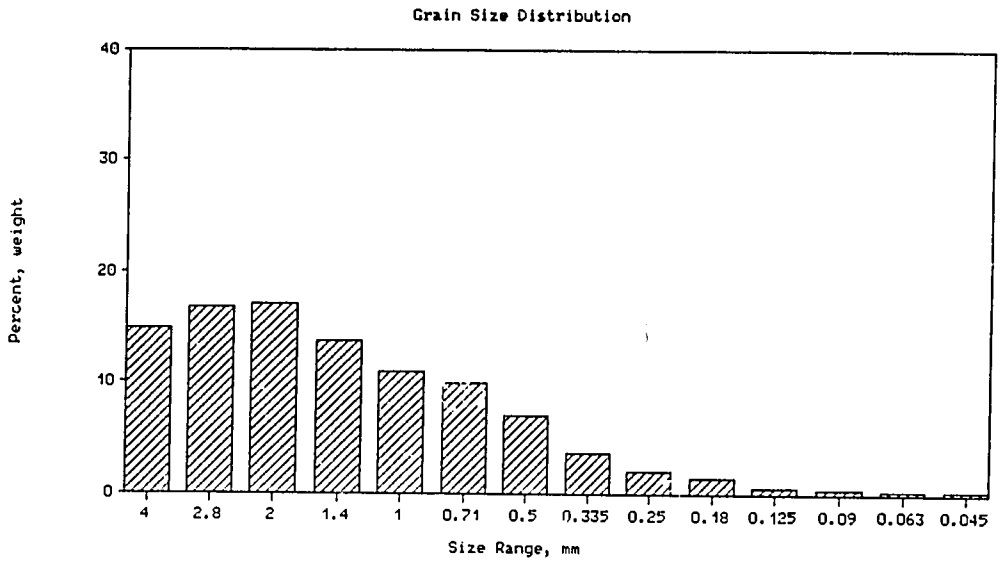


Fig. 9 : Size distribution of channel alluvium, surface sample No. 2Sec1 (Lab. No. 31), Bonwapitse R.



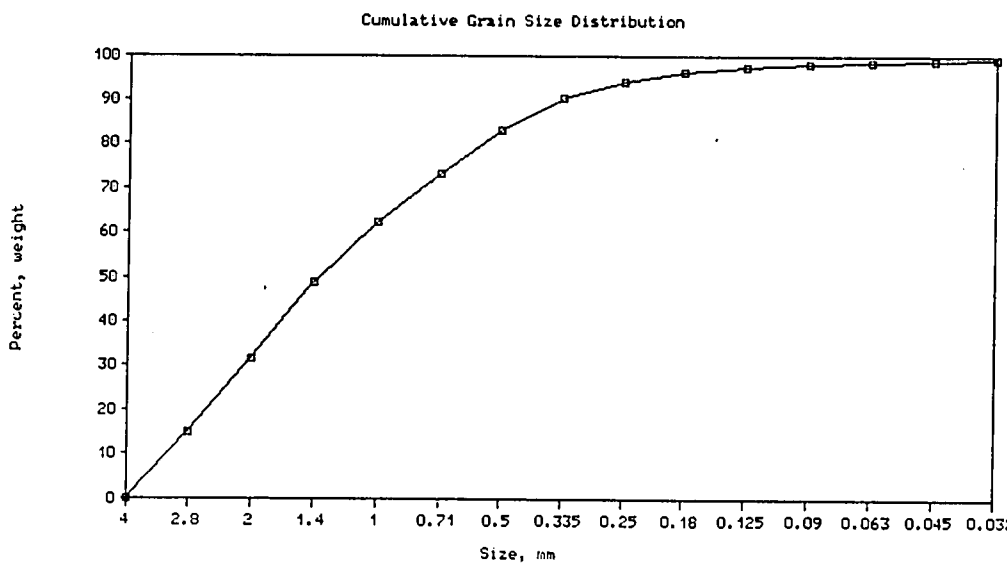
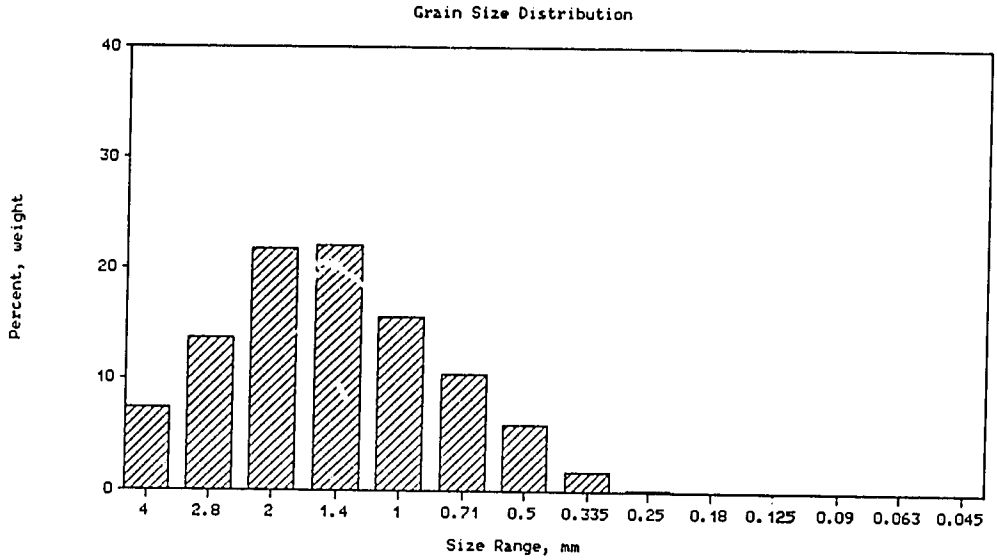


Fig. 10 : Size distribution of channel alluvium, sub-surface (30 cm depth) sample No. 2Sec1 (Lab. No. 65), Bonwapitse R.



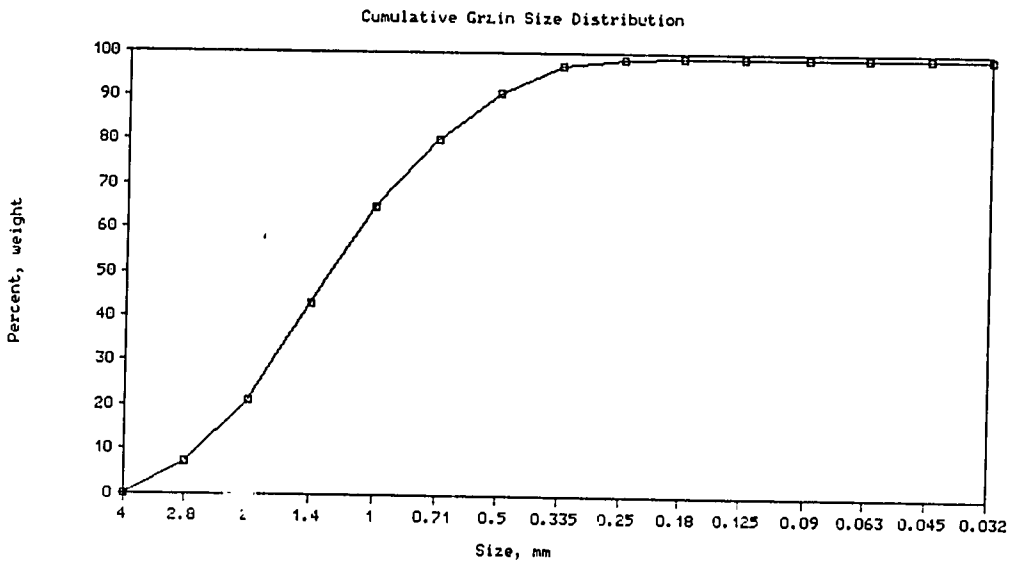


Fig. 11 : Size distribution of channal alluvium, surface sample No. 3Sec2 (Lab. No. 5), Tautswe R.

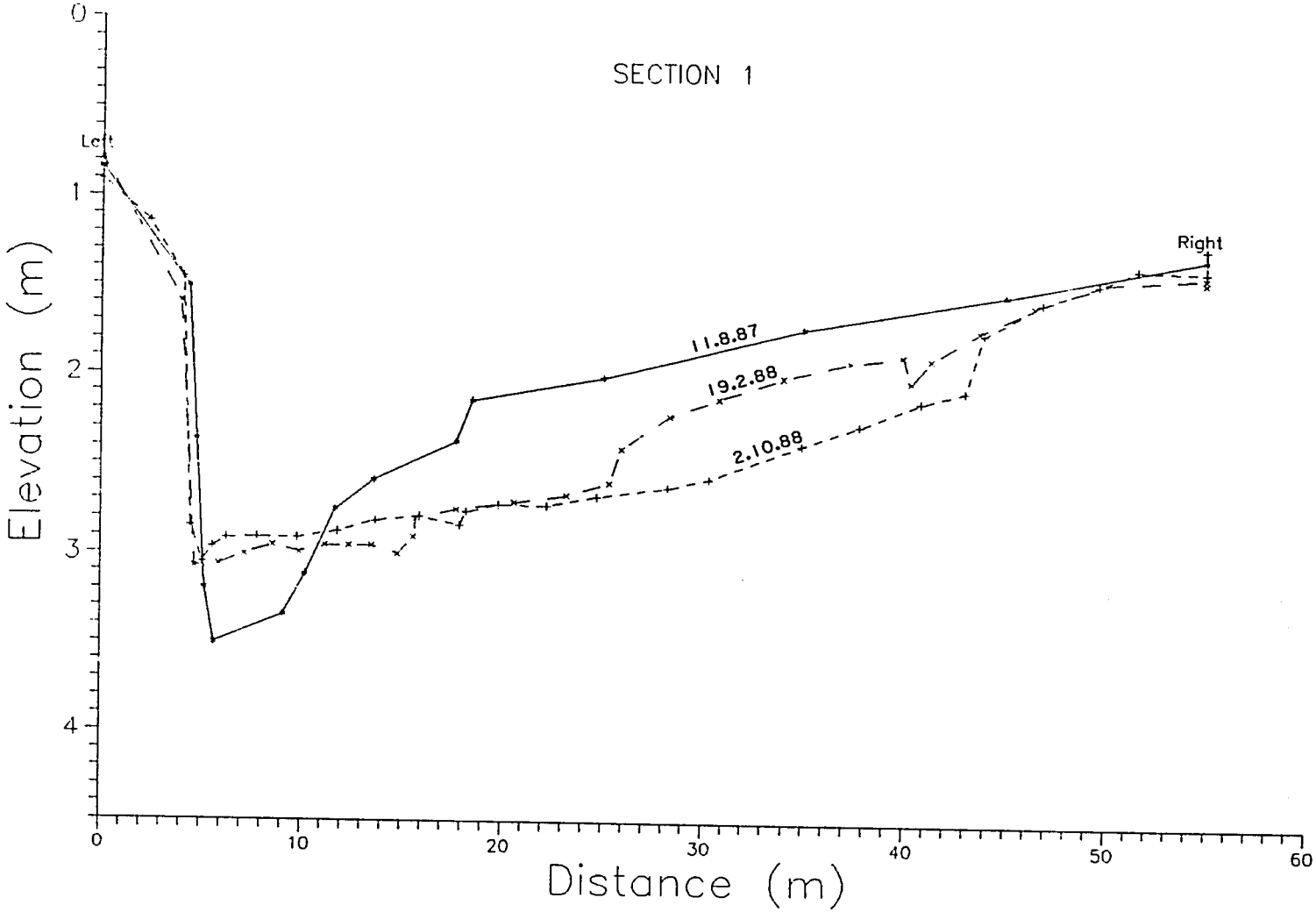


Fig. 12 : Cross section No. 1 (L = 0 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

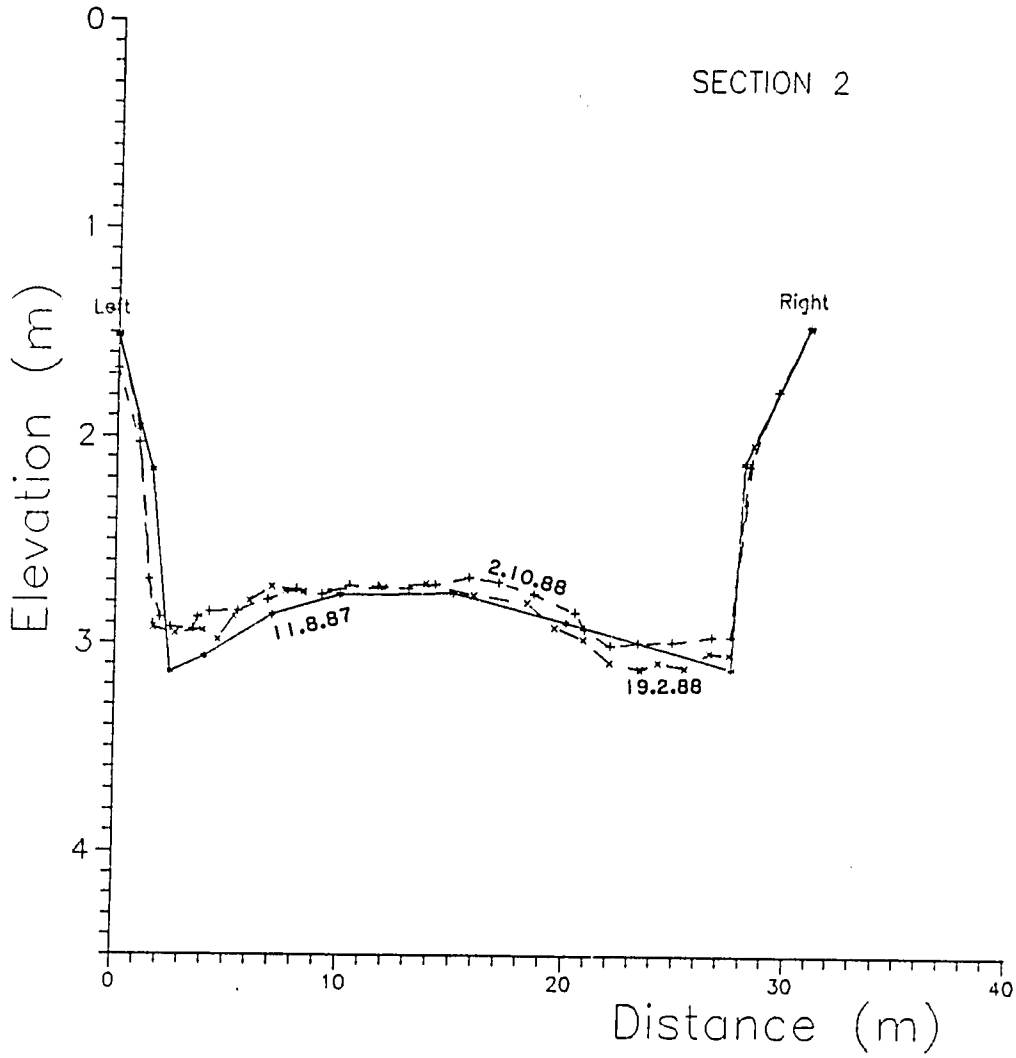


Fig. 13 : Cross section No. 2 (L = 100 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

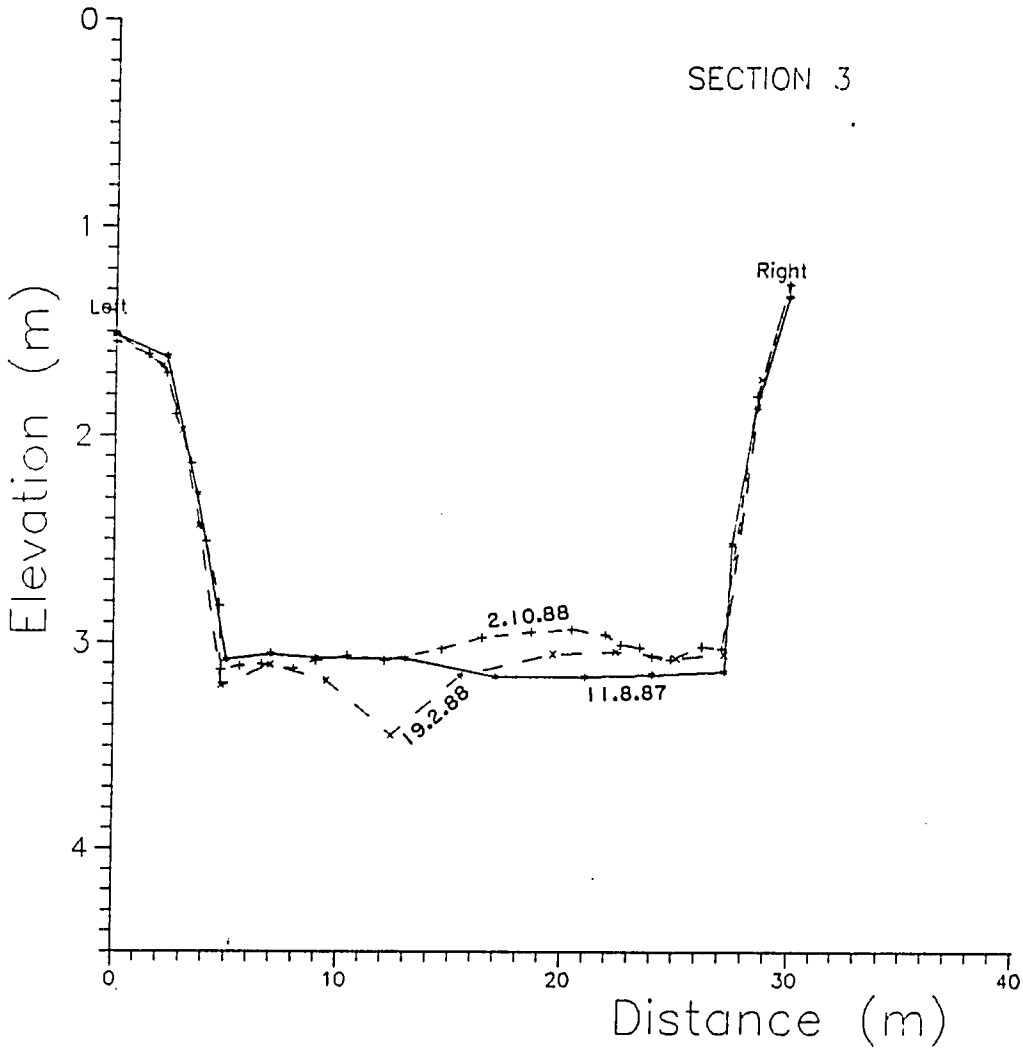


Fig. 14 : Cross section No. 3 (L = 200 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

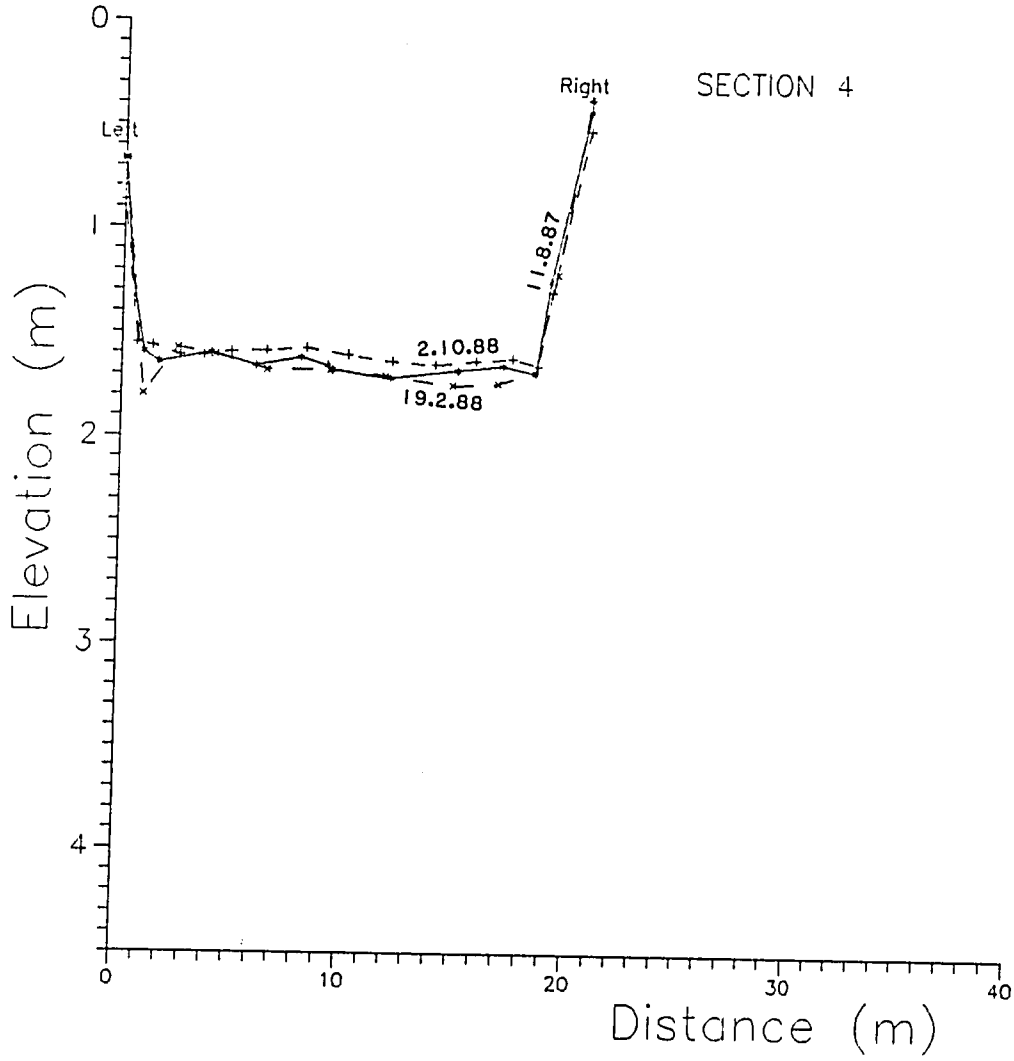


Fig. 15 : Cross section No. 4 (L = 300 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

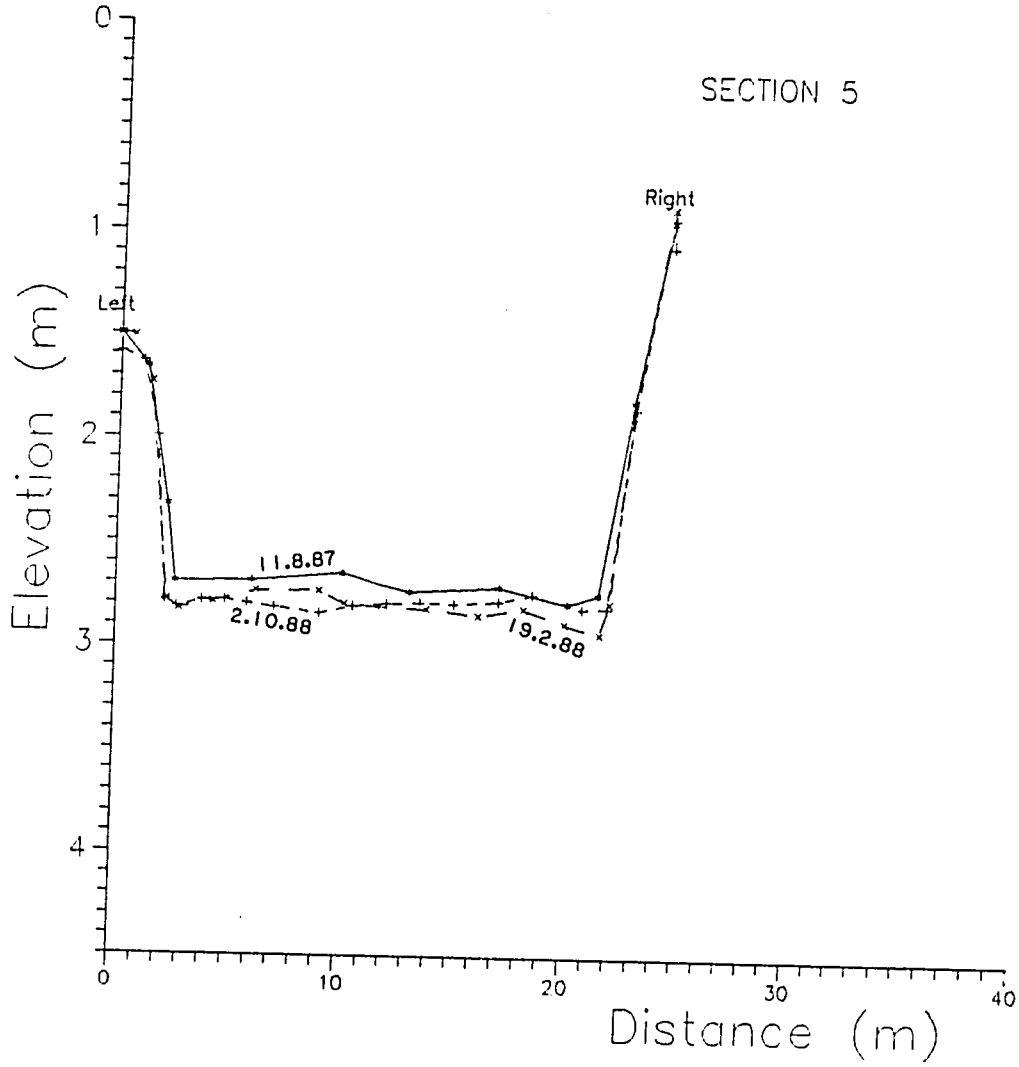


Fig. 16 : Cross section No. 5 (L = 400 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

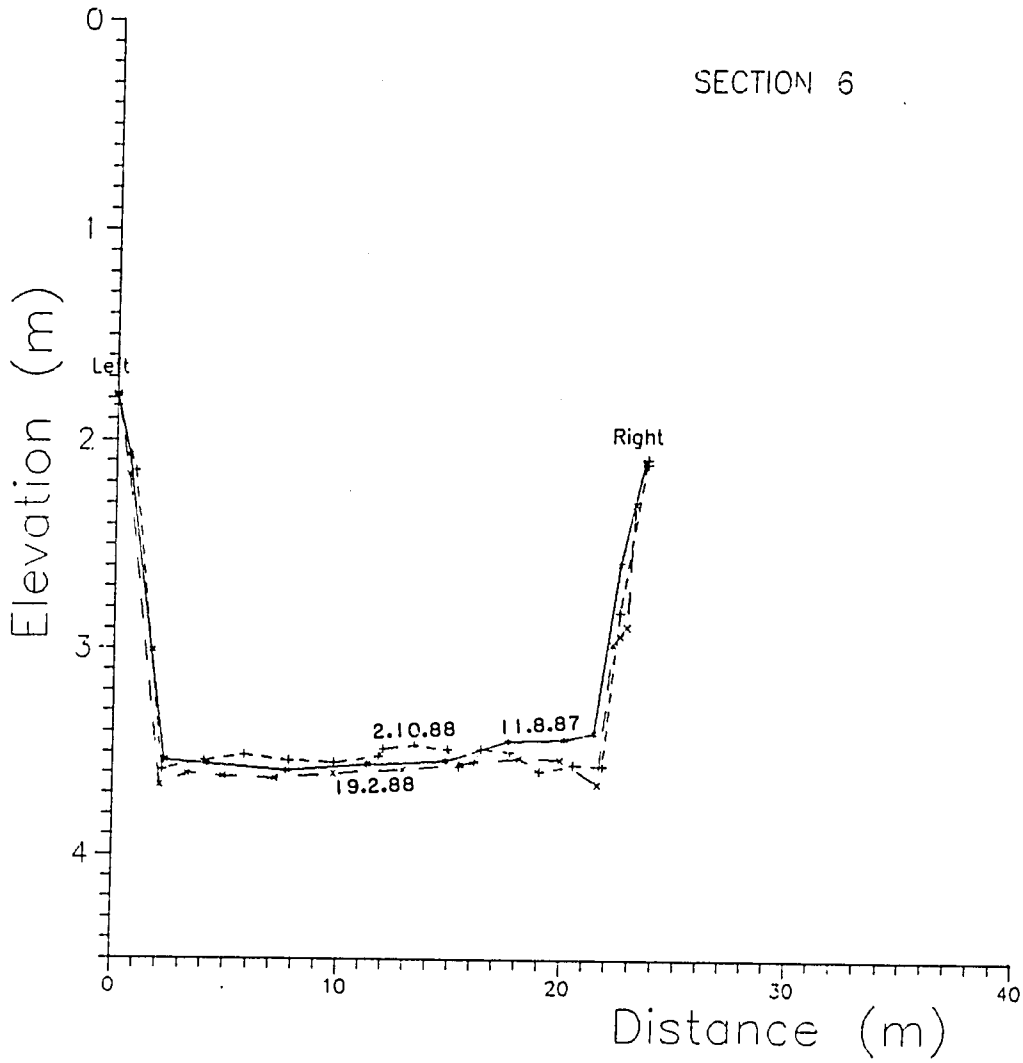


Fig. 17 : Cross section No. 6 (L = 500 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

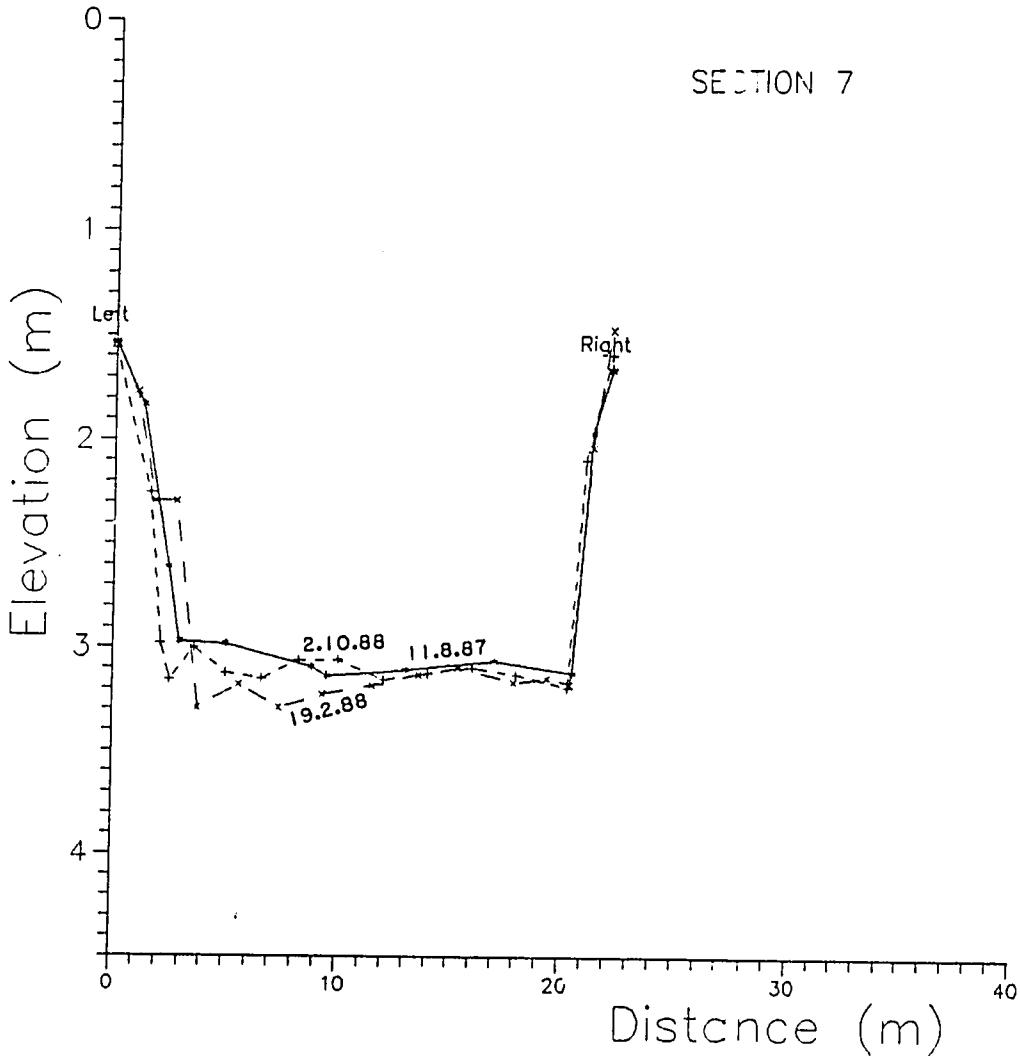


Fig. 18 : Cross section No. 7 (L = 600 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

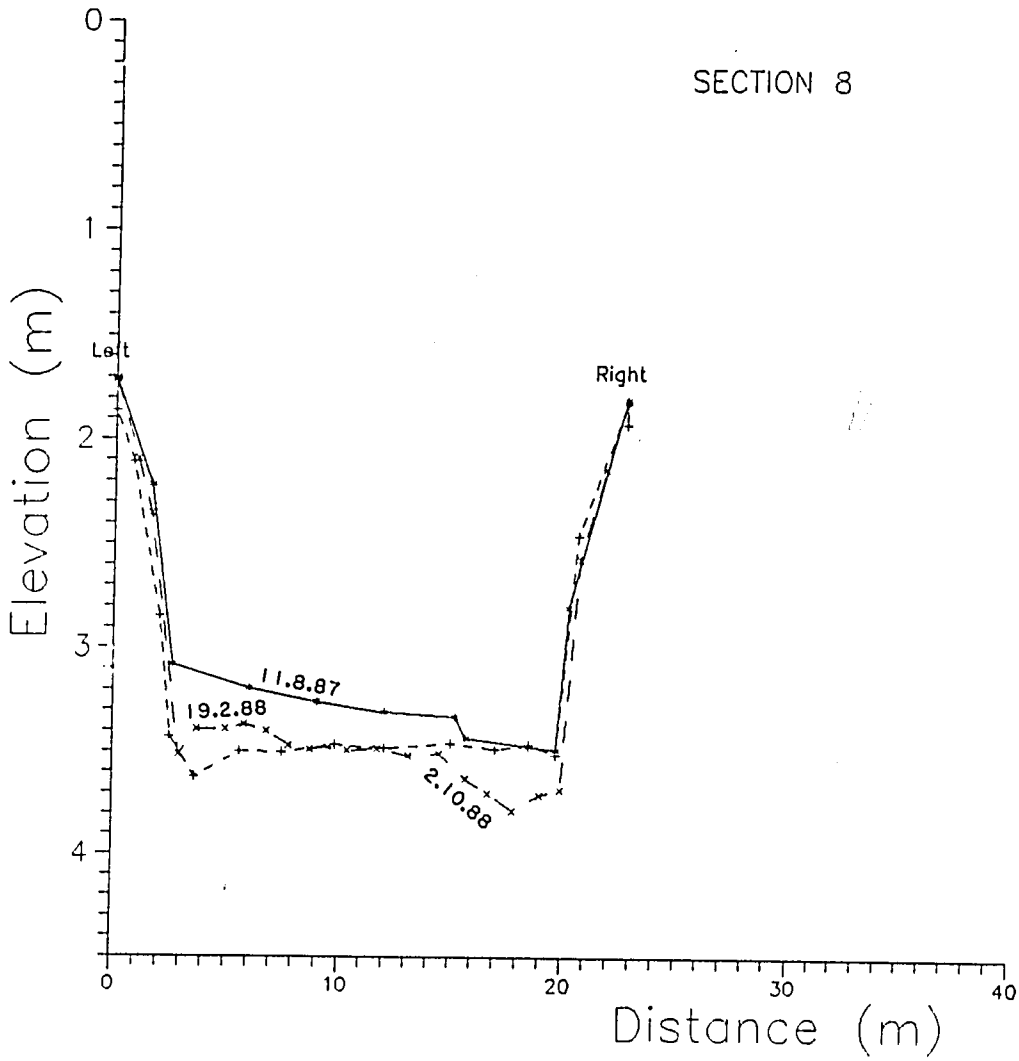


Fig. 19 : Cross section No. 8 (L = 700 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

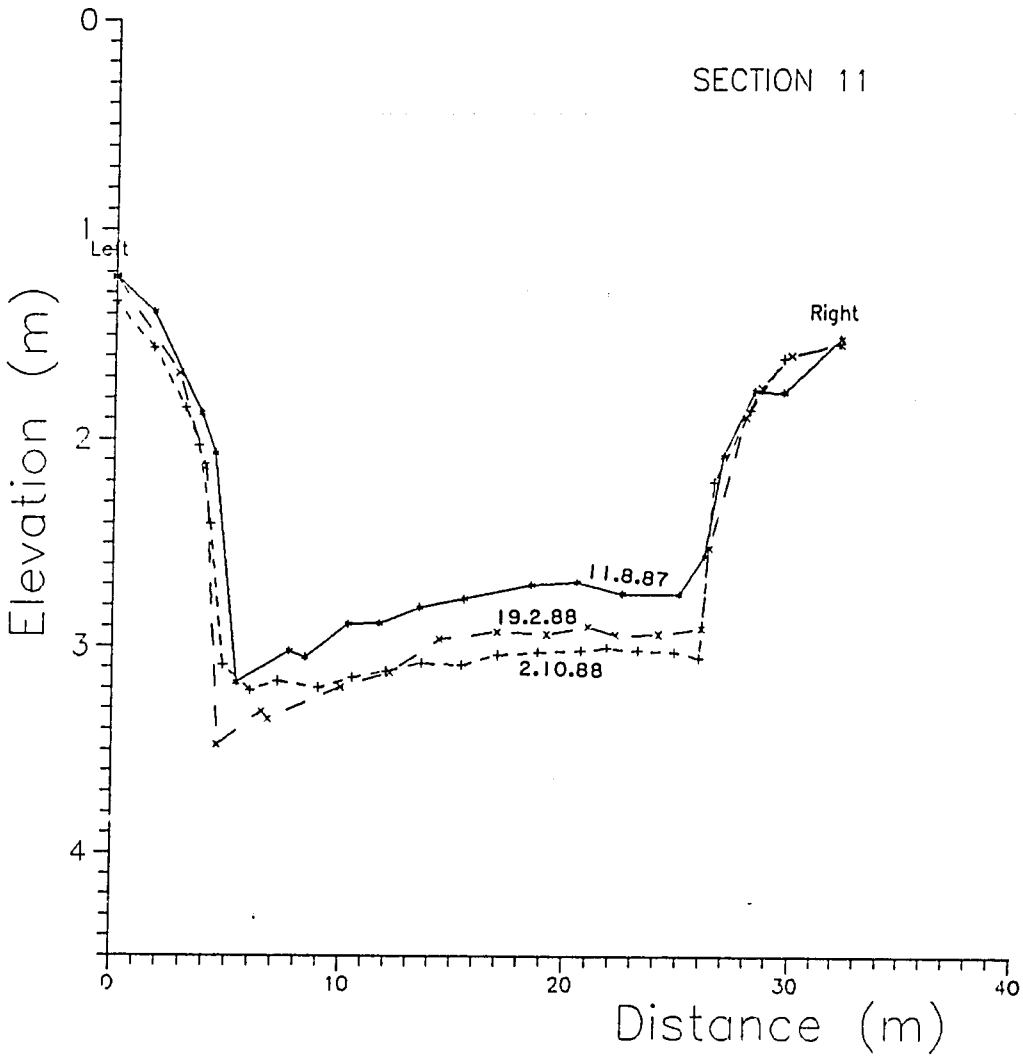


Fig. 20 : Cross section No. 11 (L = 1000 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

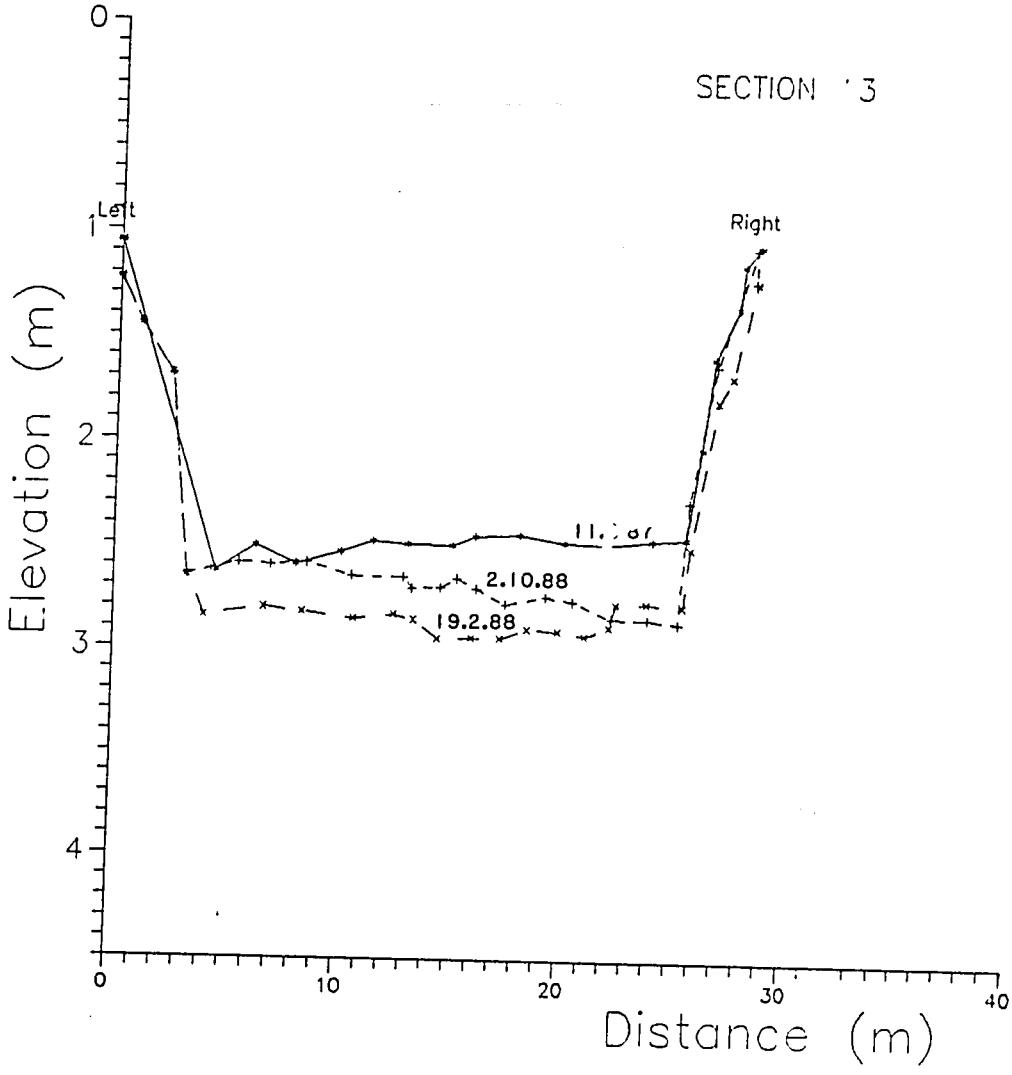


Fig. 21 : Cross section No. 13 (L = 1200 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

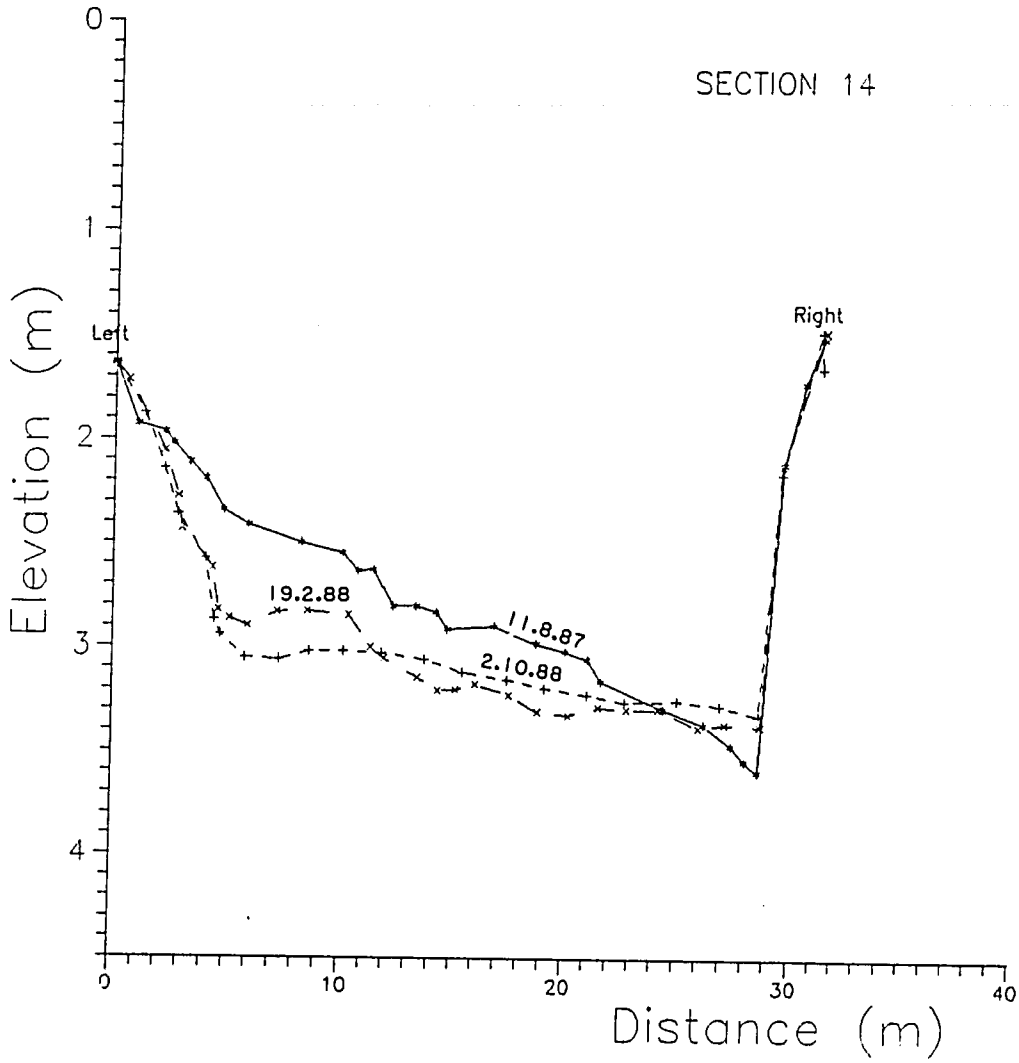


Fig. 22 : Cross section No. 14 (L = 1300 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

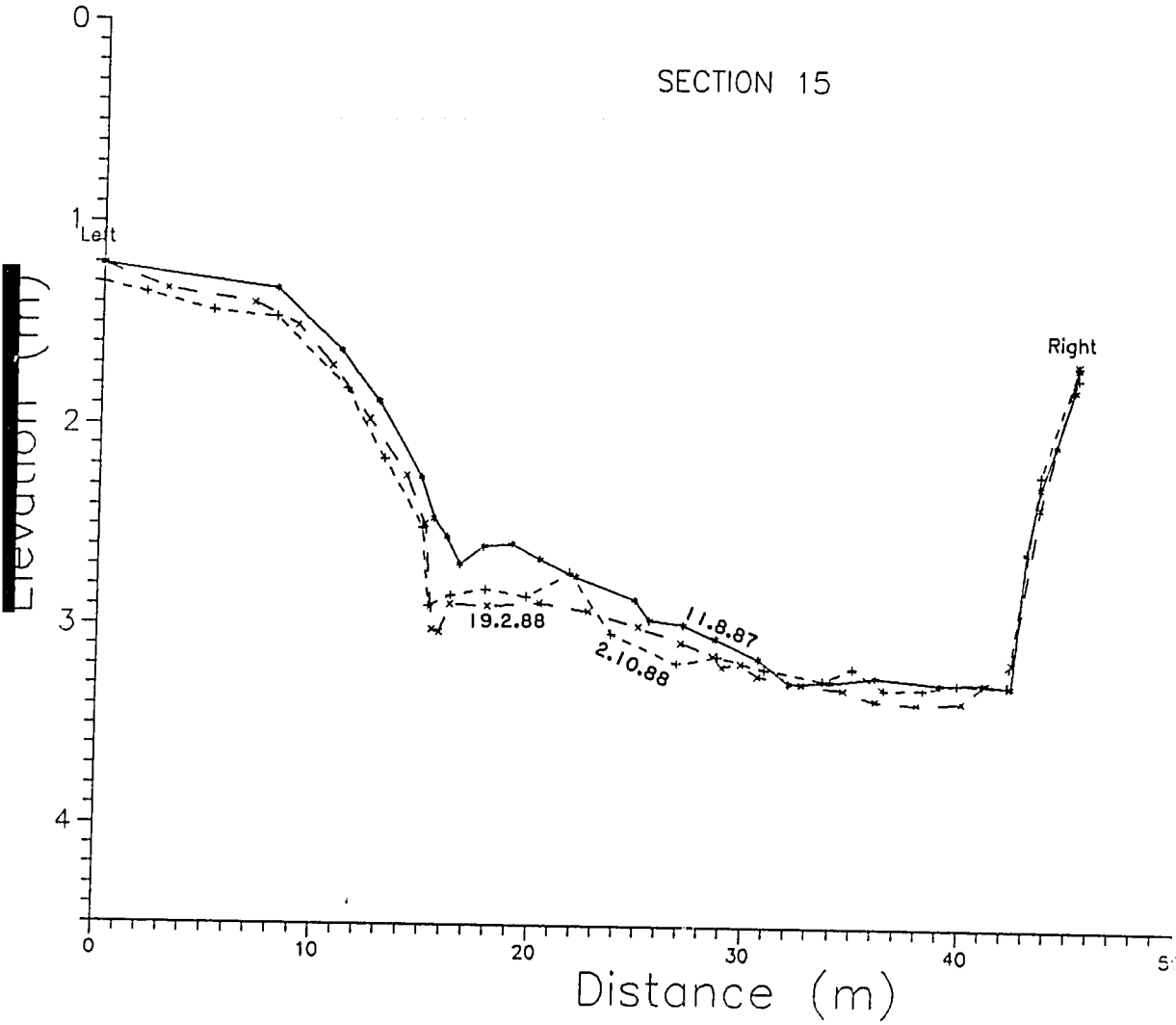


Fig. 23 : Cross section No. 15 (L = 1400 m), Metsemotlhaba R. Channel bed as surveyed before first observation period (Aug 87), after first observation period (Feb. 88), and after second observation period (Oct 88).

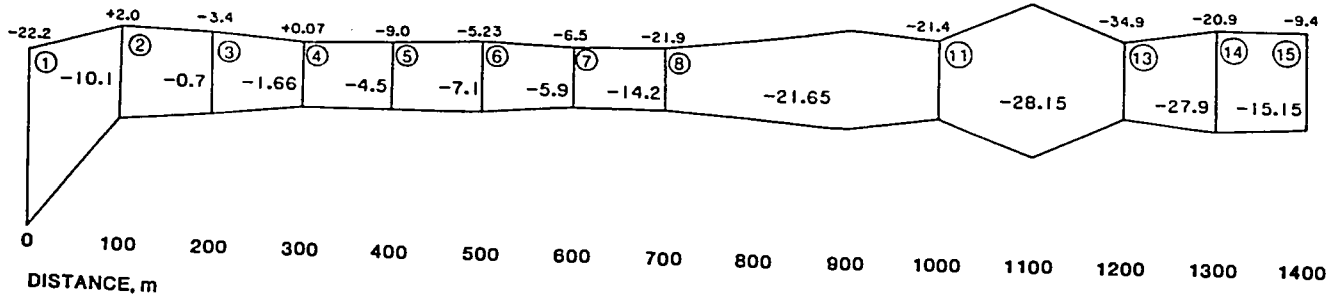


Fig. 24 : Change in river bed level, Aug 1987 to Feb 1988, Metsemotlhaba River.
Based on 12 resurveyed benchmark-based cross sections. Small numbers are aggradation(+) / degradation(-) values for reach between two sections. Section numbers are encircled.
Mean degradation over entire study reach : 14.9 cm.
Upstream section 0 - 100 is excluded.

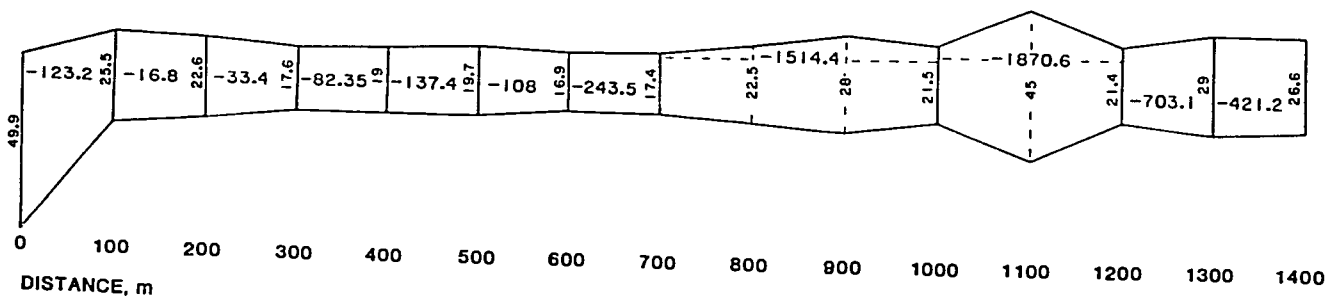


Fig. 25 : Change in volume of alluvial sediment, Aug 1987 to Feb 1988, Metsemotlhaba River.
Based as in Fig. 24. Small numbers are interbank section lengths in meters. Large numbers are volume changes, for each reach between two cross sections, in cubic meters. The total minimum volume exported from study reach (section 100 to section 1400) was 5,130 m3. Reach 0 - 100 was excluded from computation because of bend effects.

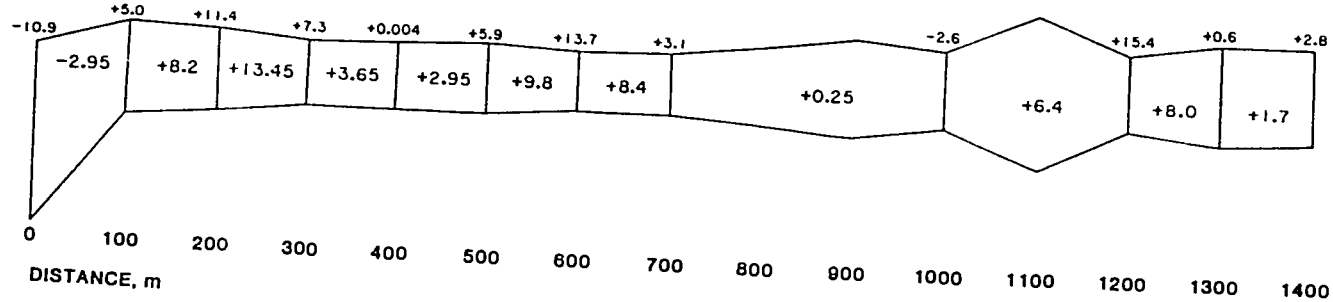


Fig. 26 : Change in river bed level, Feb 1988 to Oct 1988, Metsemotlhaba River.
Based on 12 resurveyed benchmark-based cross sections.
Small numbers are aggradation(+) / degradation(-) values for reach between two sections.
Mean aggradation over entire study reach : 5.4 cm.
Upstream section 0 - 100 is excluded.

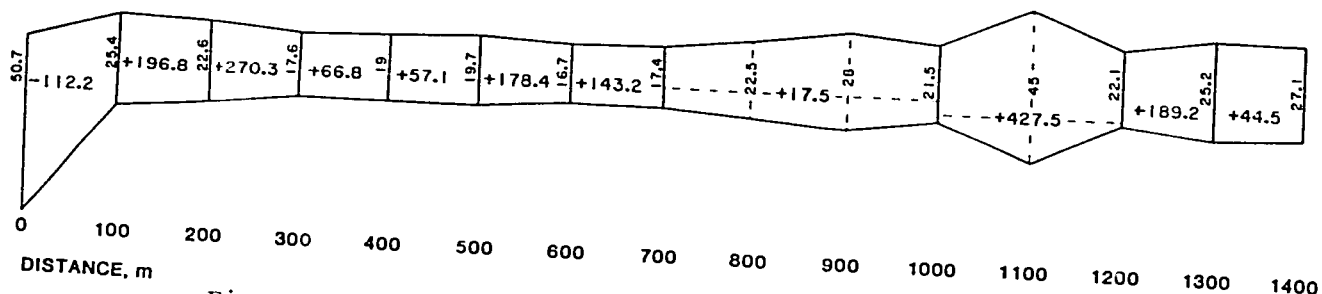


Fig. 27 : Change in volume of alluvial sediment, Feb 1988 - Oct 1988, Metsemotlhaba River.
Based as in Fig. 26. Small numbers are interbank section lengths in meters. Large numbers are volume changes, for each reach between two cross sections, in cubic meters. The total volume moved into study reach (section 100 to section 1400) was 1,590 m3. Reach 0 - 100 was excluded from computation because of bend effects.

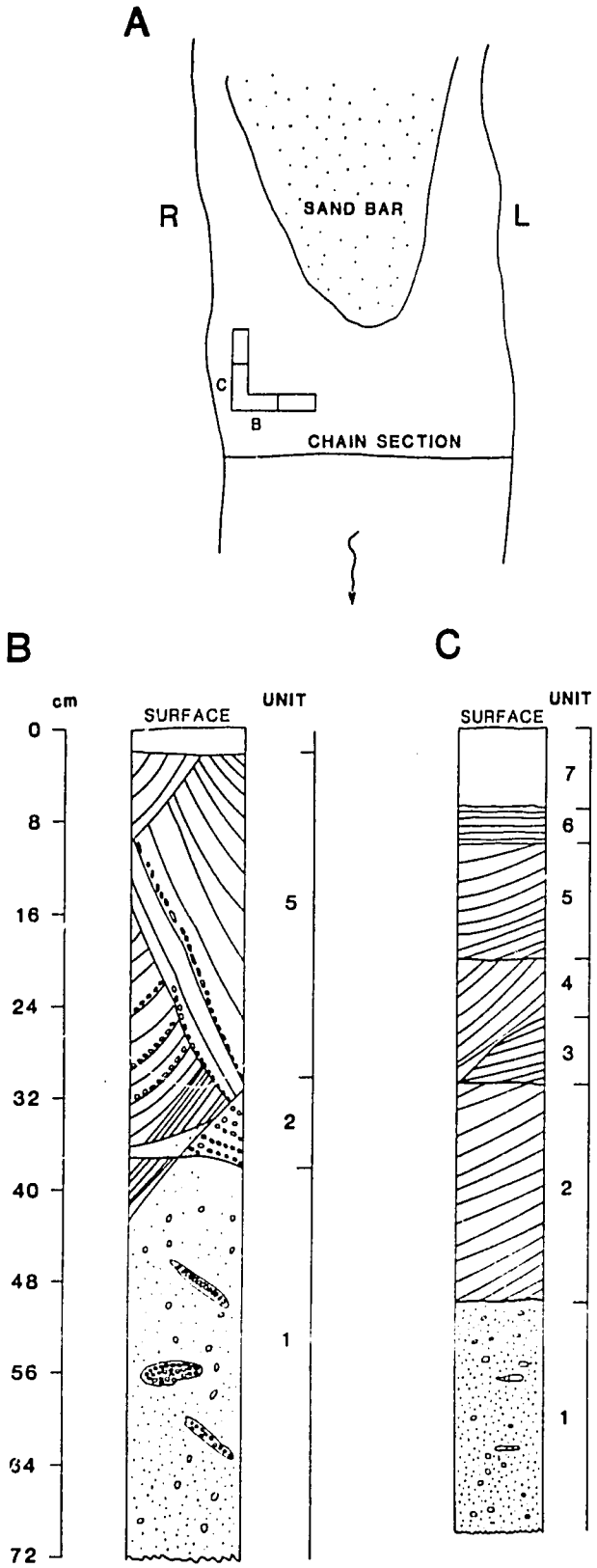
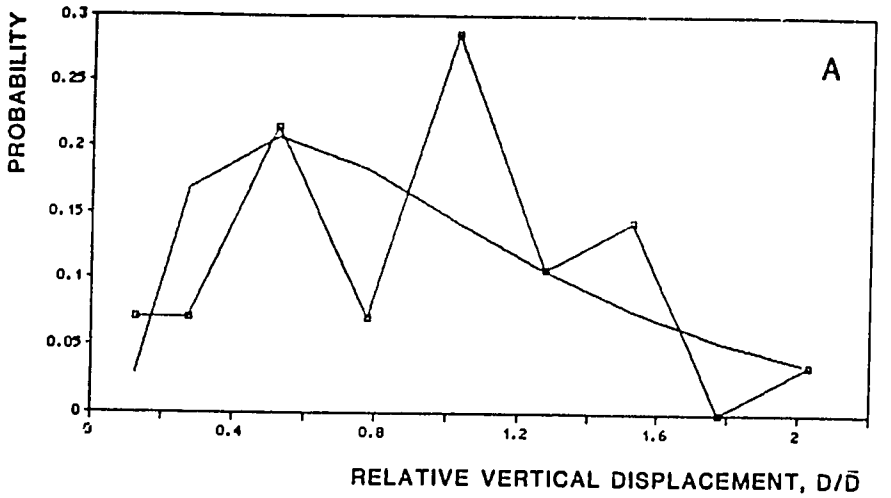
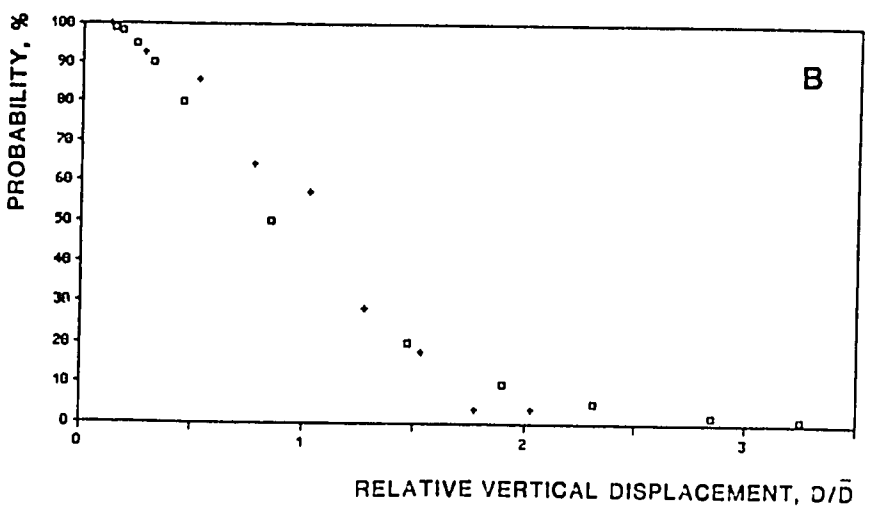


Fig. 28 : Alluvial stratigraphy, Metsemotlhaba R.
A - Location sketch ; trench 3 (at station 275 m)
B - Cross section
C - Longitudinal section

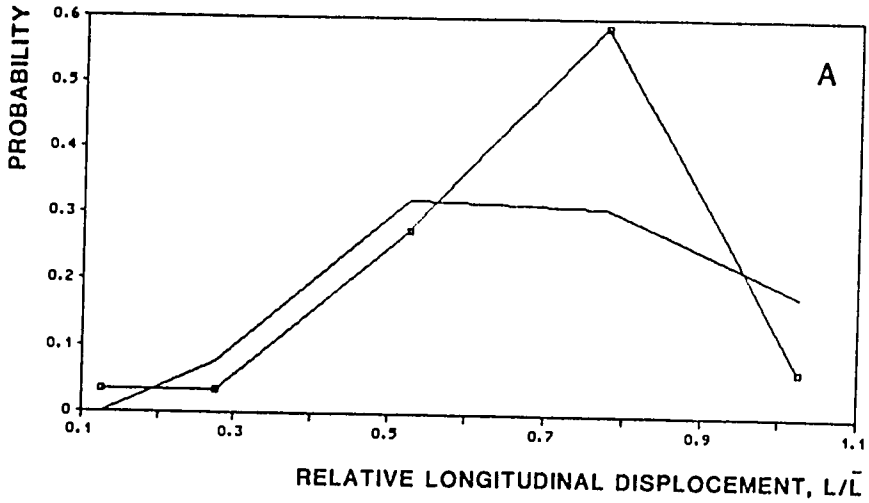


Note : 29 particles recovered. Squares are field data.
Curve is for $\gamma = 0.1$

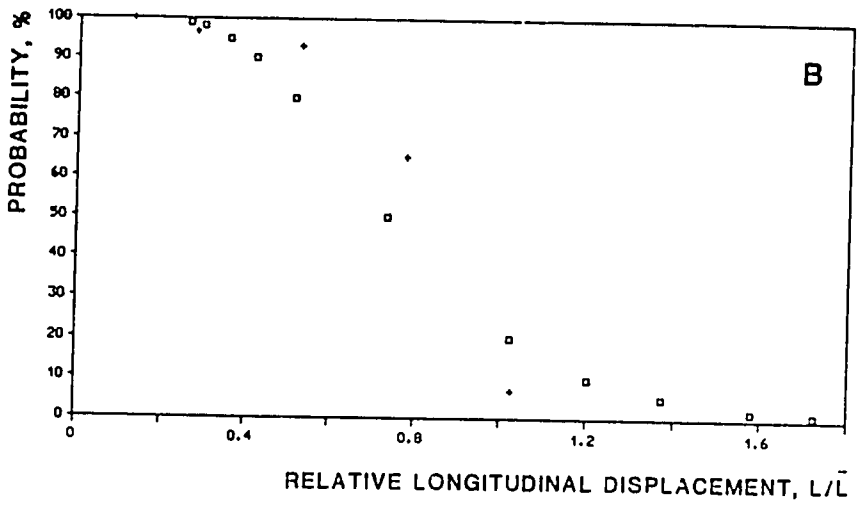


Note : Mean displacement : 28 cm. Crosses are field data.
Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 29 : Burial of tracer particles : field data and fitted gamma distribution. Bonwapitse R., Sep 1987 - Sep 1988

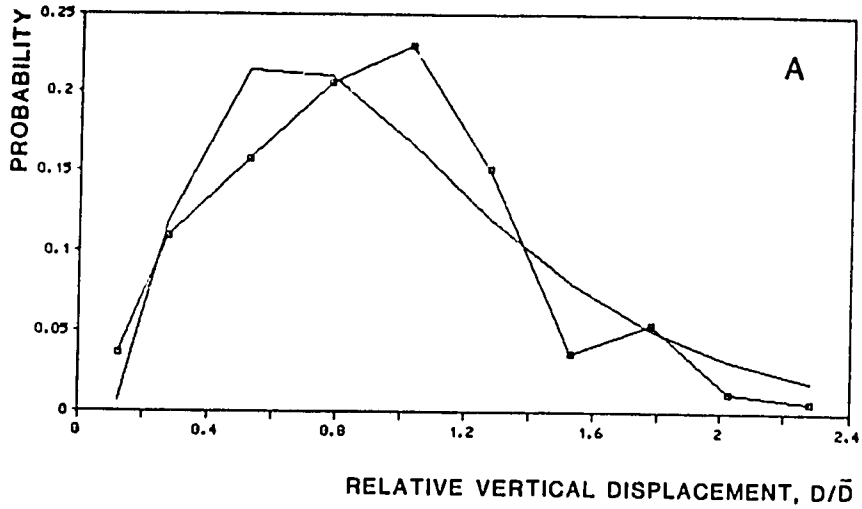


Note : Mean displacement : 924 m. Squares are field data.
Curve is for $\gamma = 0.1$

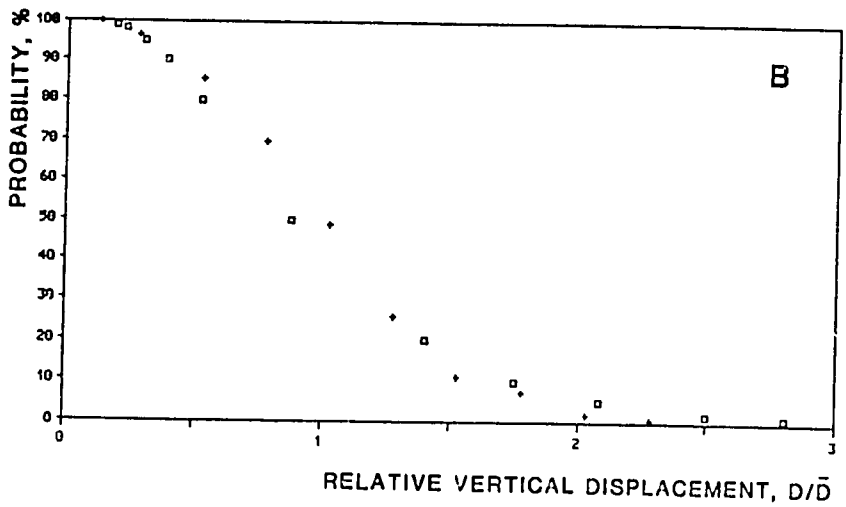


Note : Crosses are field data. Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 30 : Downstream displacement of tracer particles : field data and fitted gamma distribution. Bonwapitse R., Sep 1987 to Sep 1988

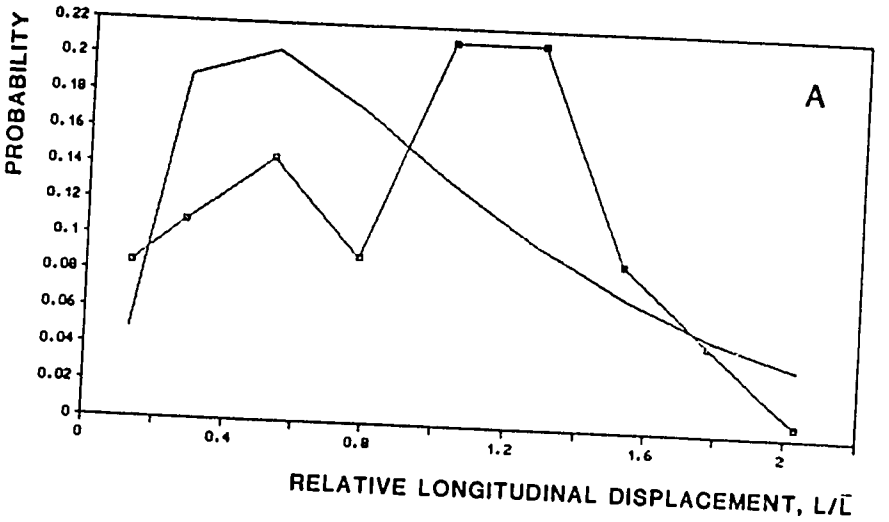


Note : 165 particles recovered. Squares are field data.
Curve is for $\gamma = 0.1$

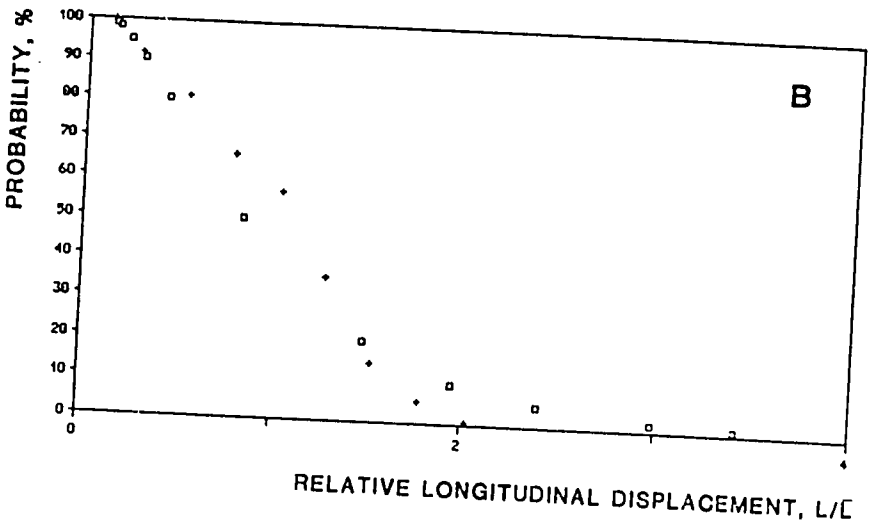


Note : Mean displacement : 44 cm. Crosses are field data.
Gamma of fitted curve (squares) set to $\gamma = 0.1$

Fig. 31 : 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. 32 : Downstream displacement of tracer particles : field data and fitted gamma distribution.
Metsemotlhaba R., Sep 1987 to Sep 1988

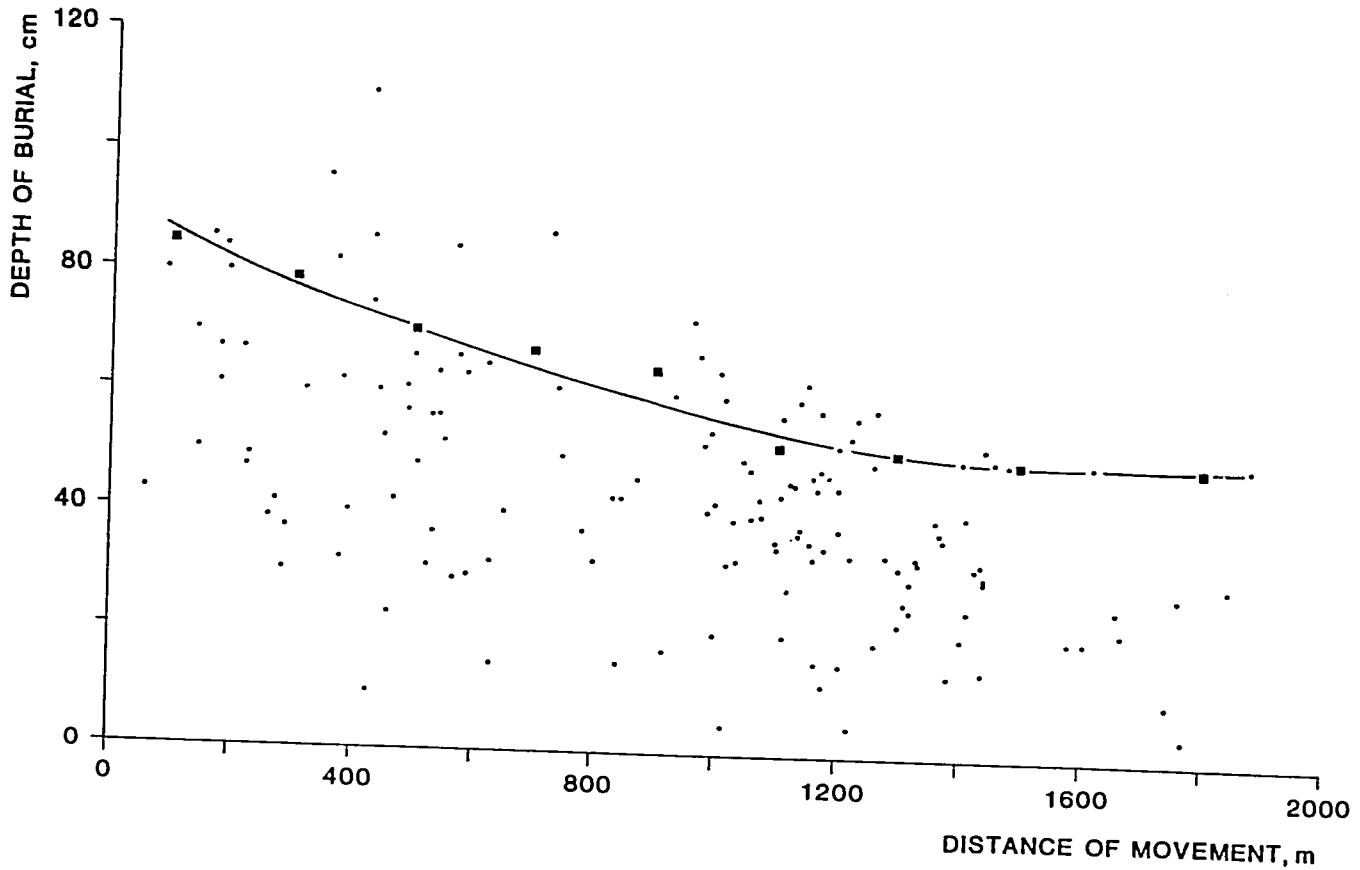


Fig. 33 : Longitudinal and vertical displacement, small particles. Metsemotlhaba R., Sep 1987 - Sep 1988
Curve, based on squares computed for 200 m long reaches, indicates depth limit of 80% of the particles

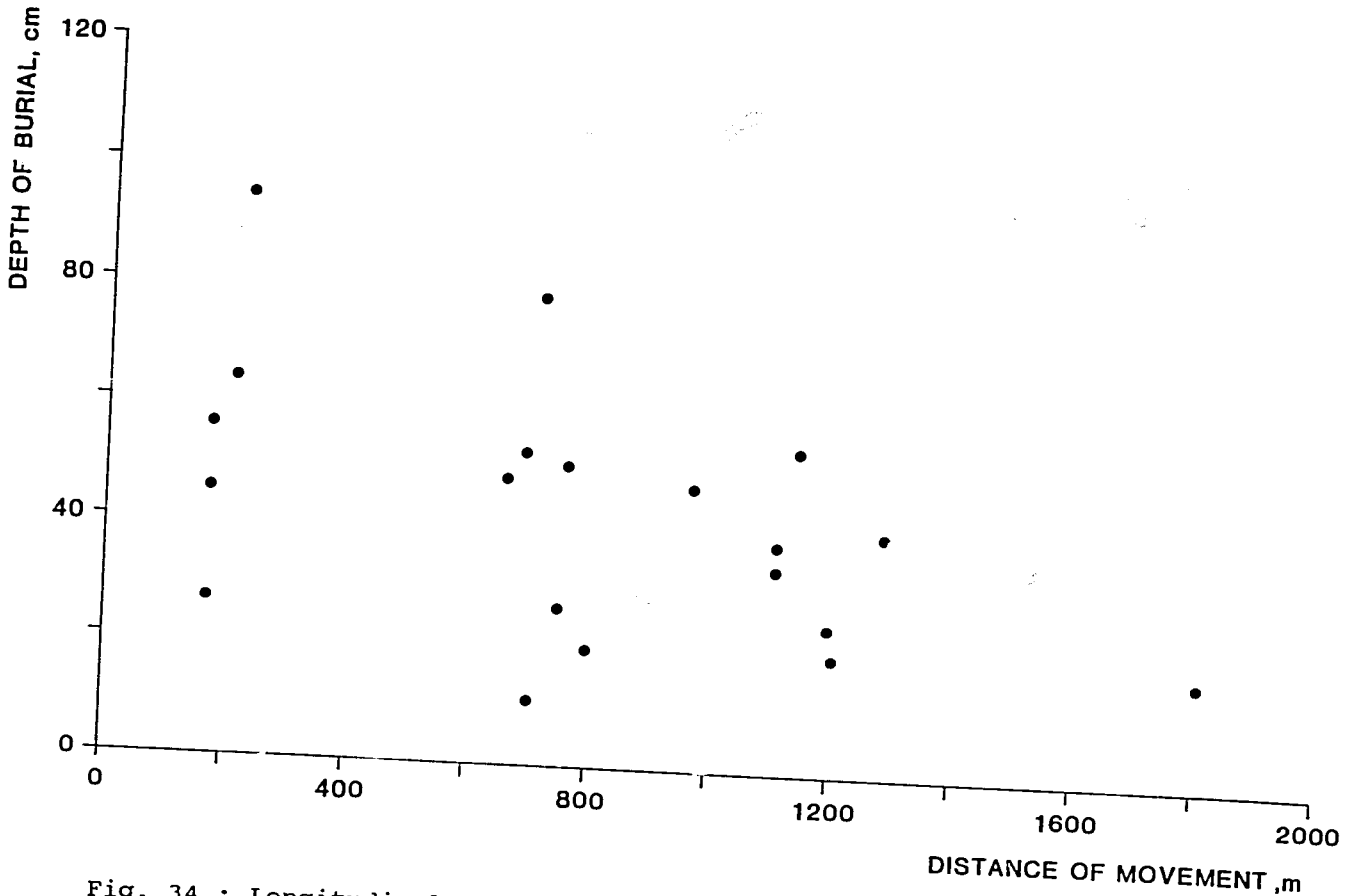


Fig. 34 : Longitudinal and vertical displacement, large particles.
Metsemotlhaba R., Sep 1987 - Sep 1988

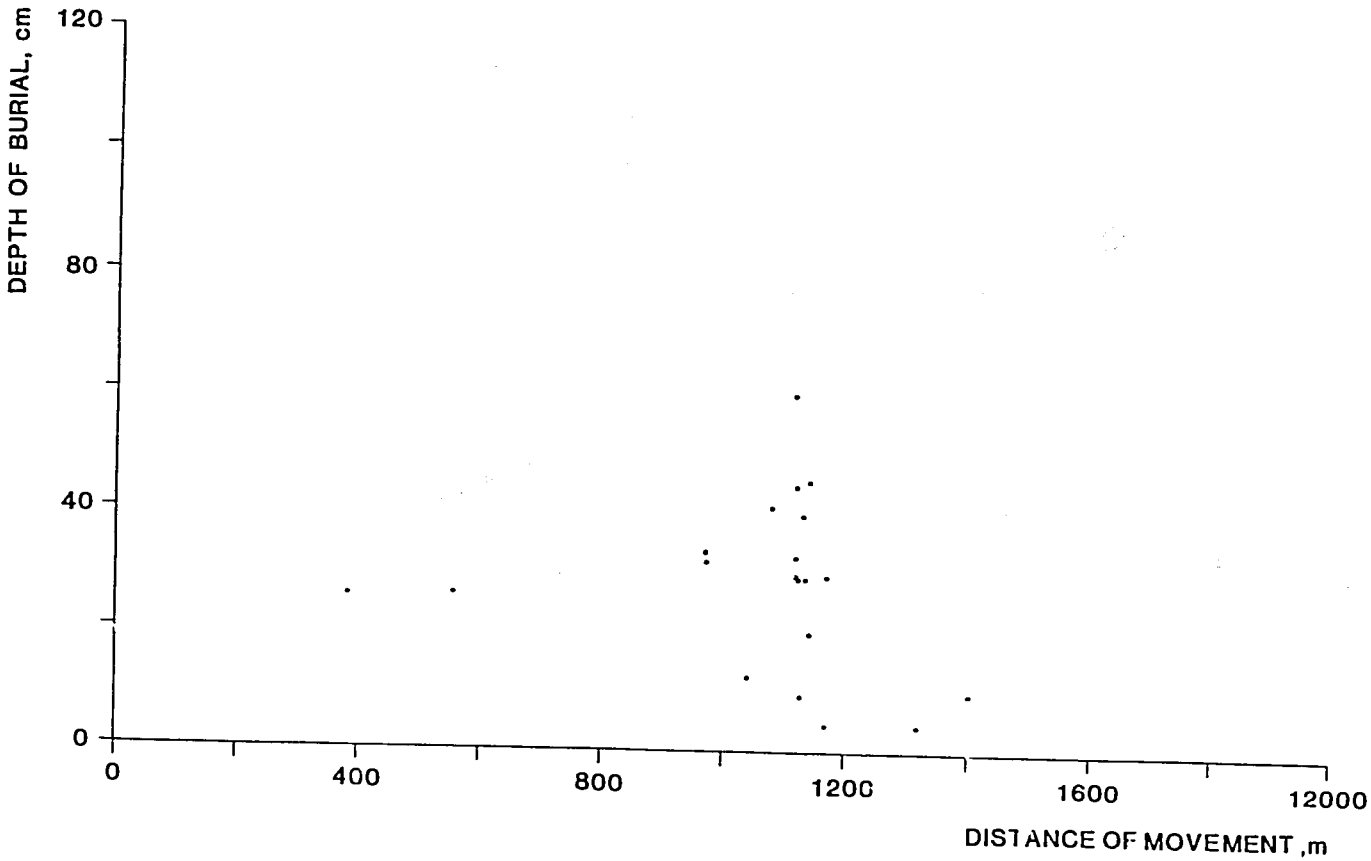


Fig. 35 : Longitudinal and vertical displacement, small particles.
Bonwapitse R., Sep 1987 - Sep 1988

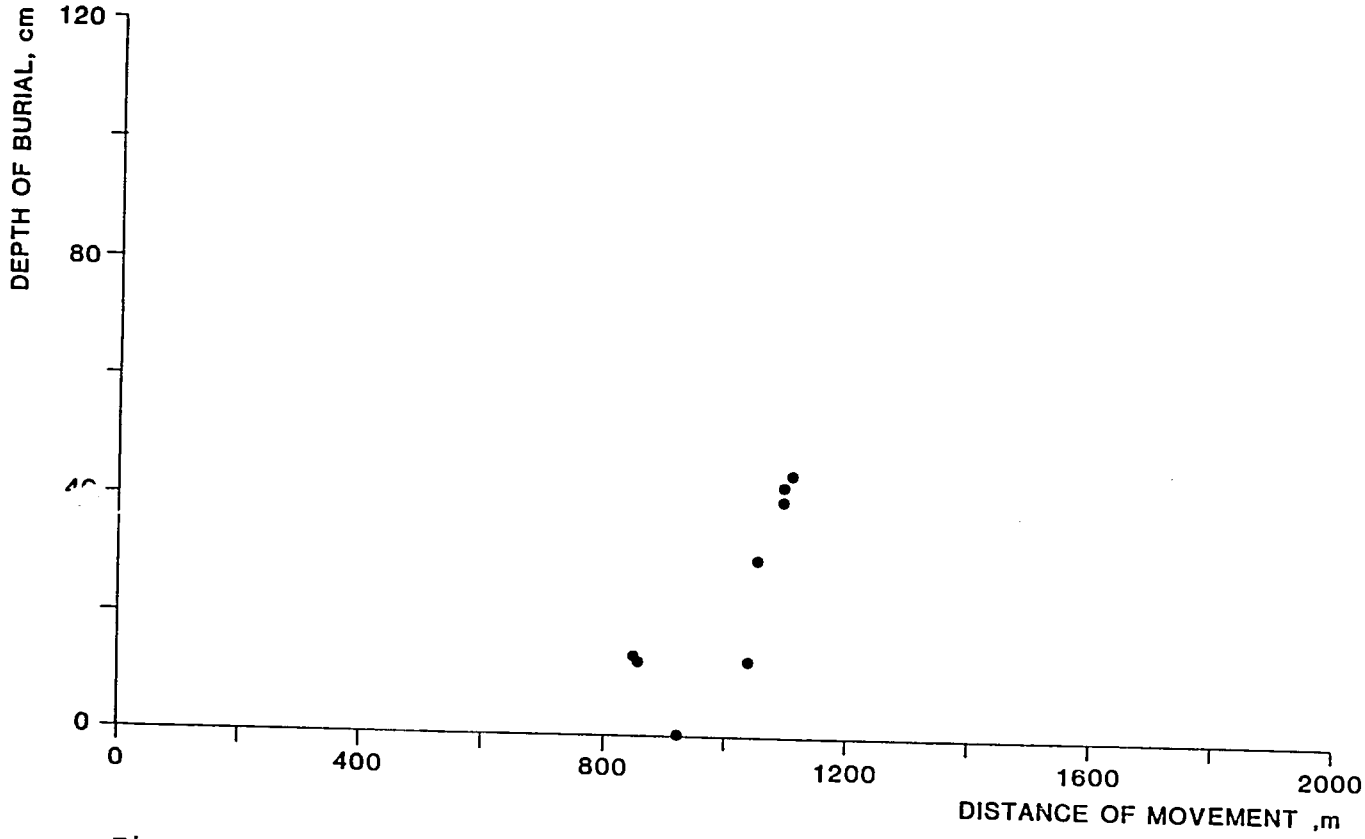


Fig. 36 : Longitudinal and vertical displacement, large particles.
Bonwapitse R., Sep 1987 - Sep 1988

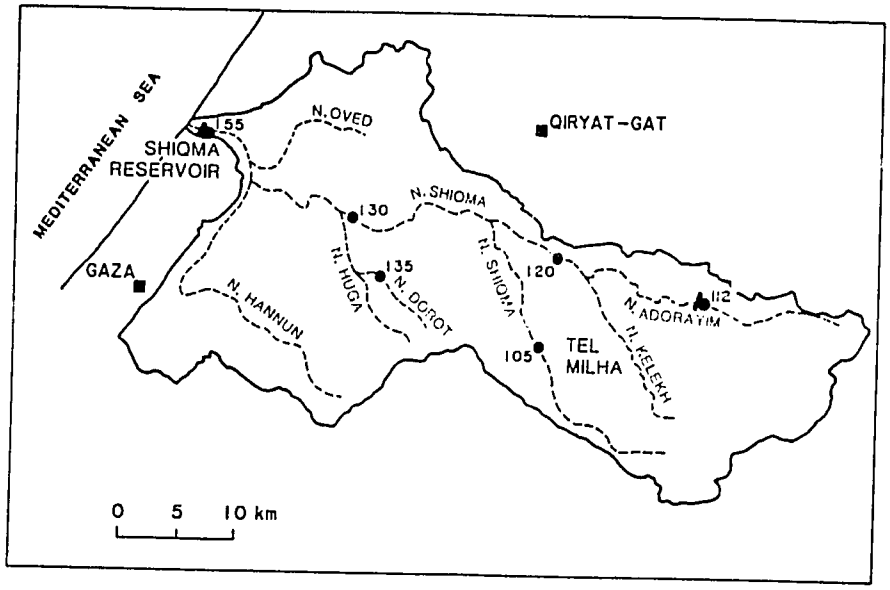


Fig. 37 : Nahal Shiqma catchment : location map

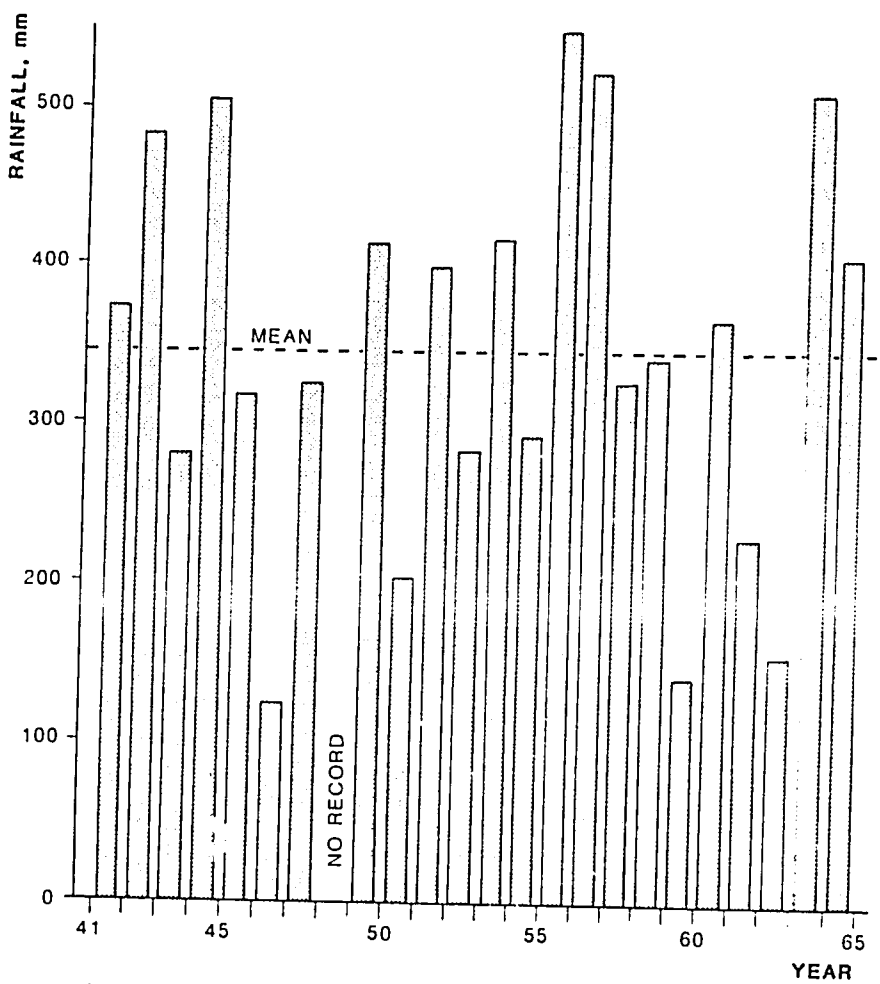


Fig. 38 : Annual rainfall, Dorot, 1941-1965

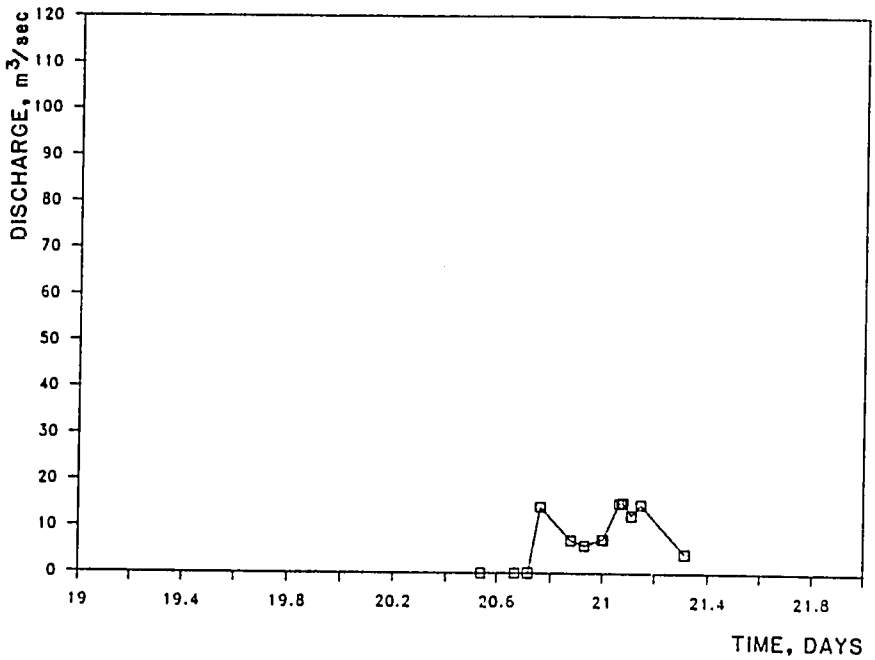


Fig. 38 : Flow of 20 Jan 1961, Nahal Shiqma at Beror Hayil

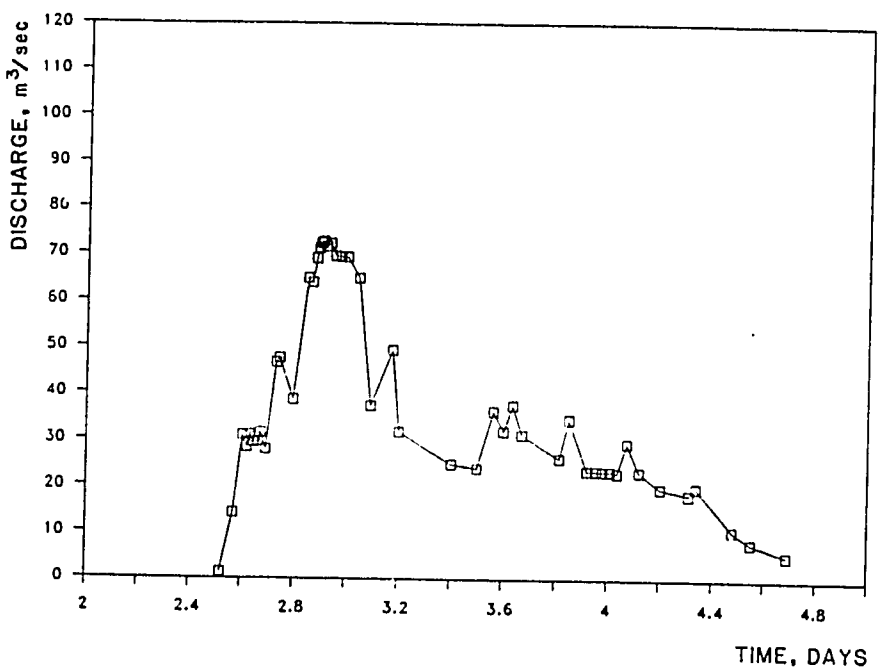


Fig. 39 : Flow of 2 Dec 1963, Nahal Shiqma at Beror Hayil

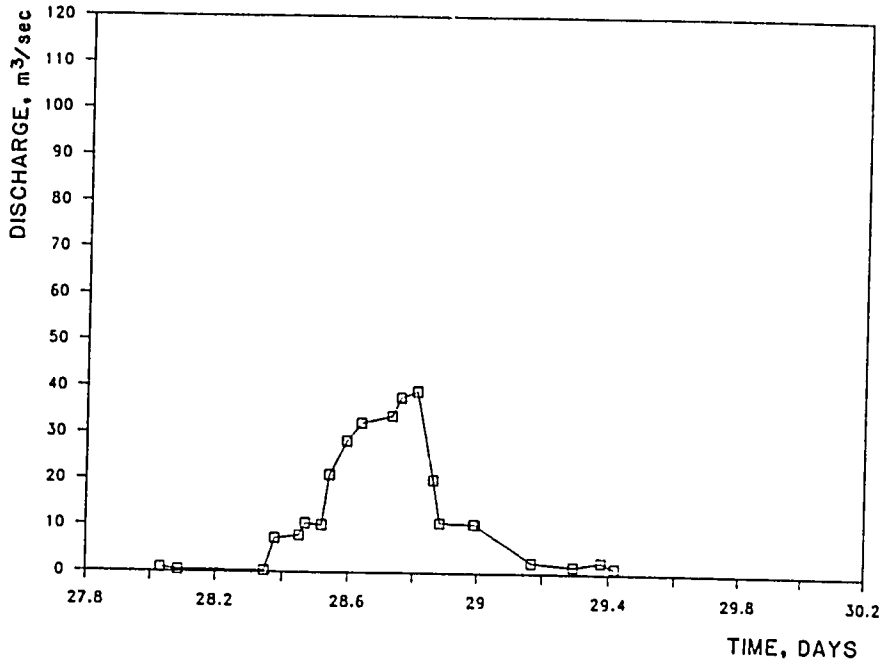


Fig. 40 : Flow of 28 Dec 1971, Nahal Shiqma at Beror Hayil

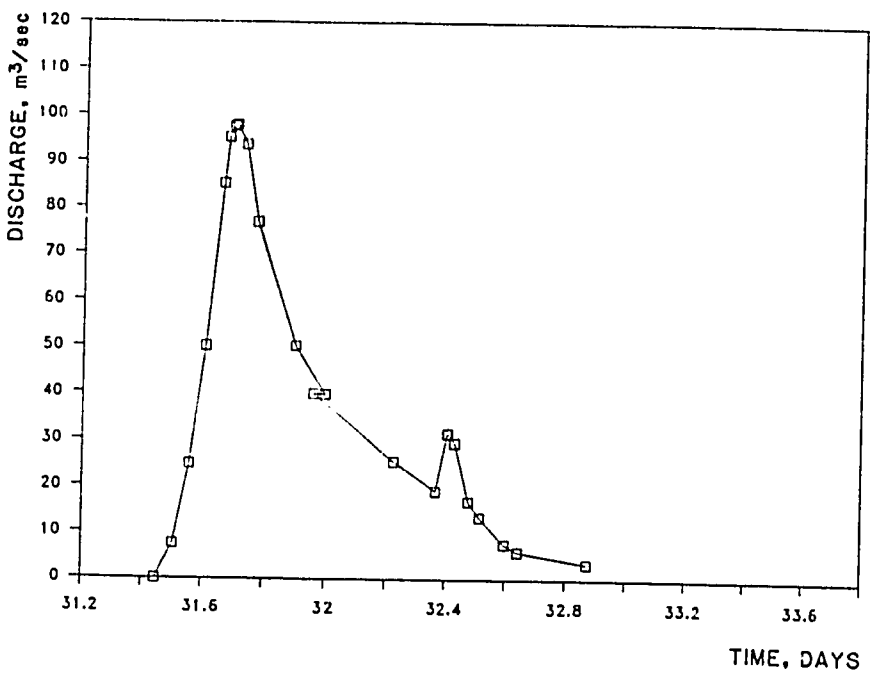


Fig. 41 : Flow of 31 Jan 1974, Nahal Shiqma at Beror Hayil

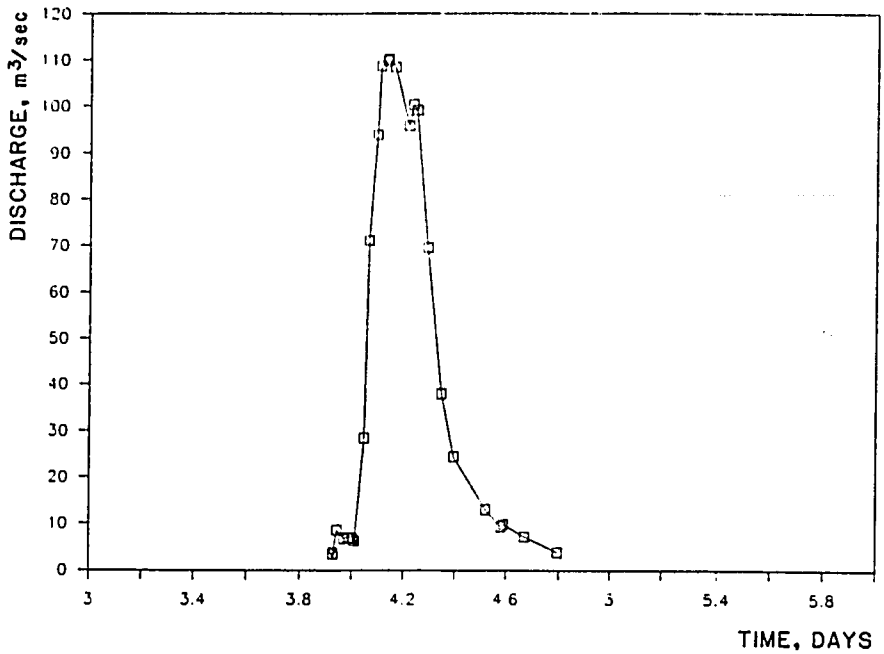


Fig. 42 : Flow of 3 Jan 1978, Nahal Shiqma at Beror Hayil

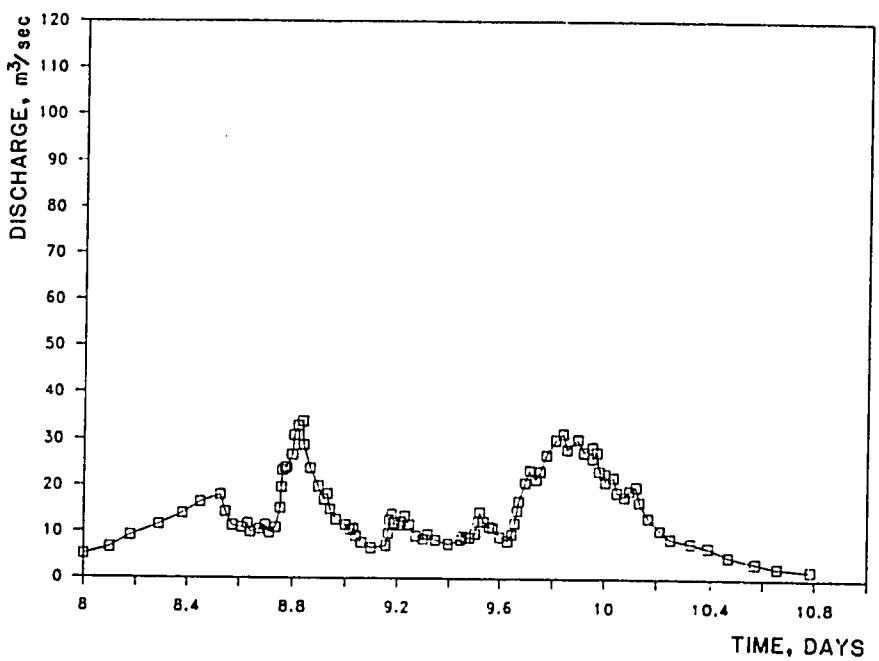


Fig. 43 : Flow of 8 Nov 1986, Nahal Shiqma at Beror Hayil

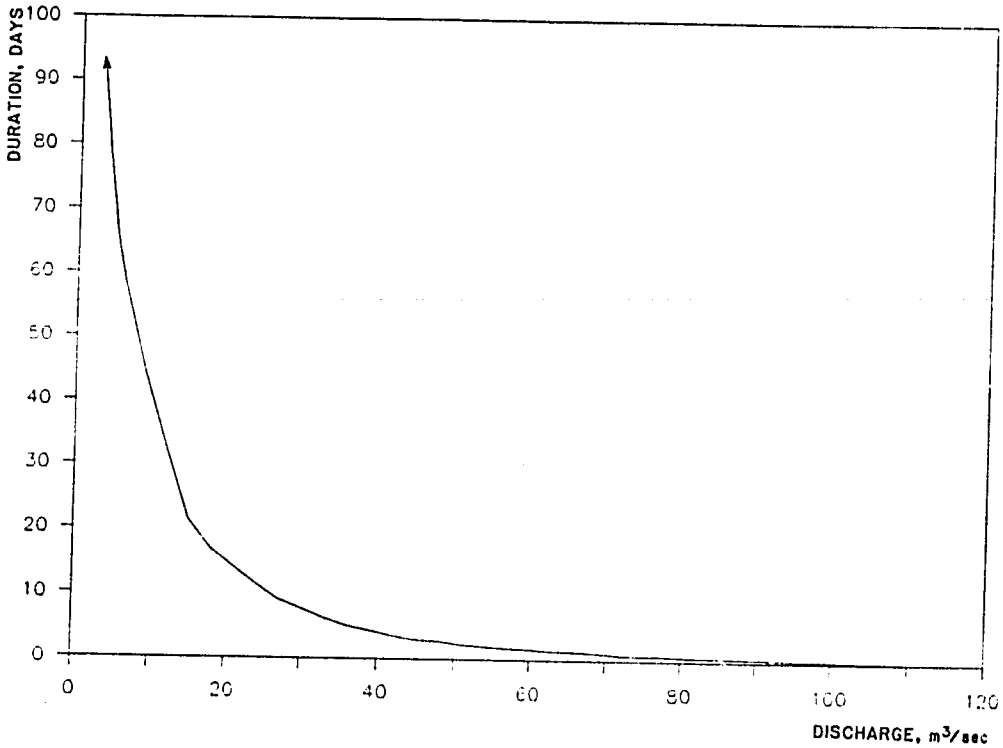


Fig. 44 : Flow frequency, Nahal Shiqma at Beror Hayil, 1960-1987

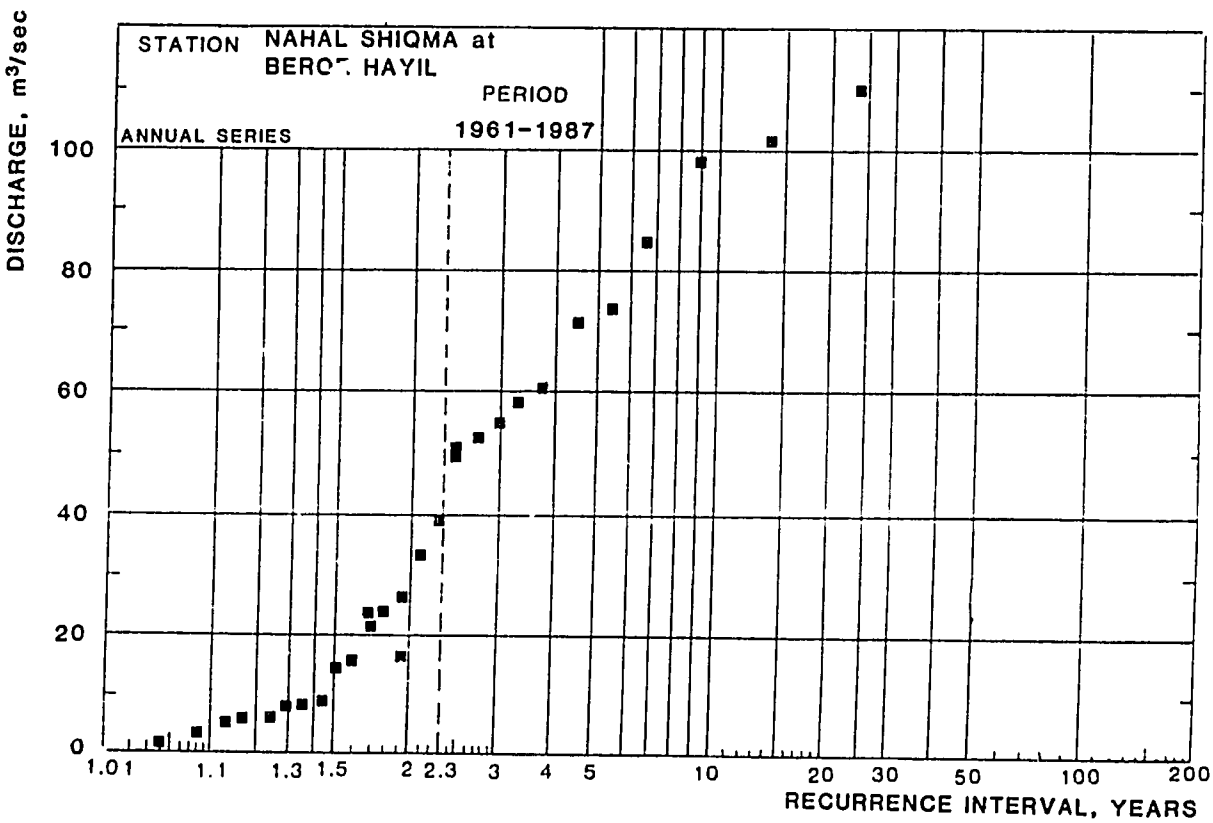


Fig. 45 : Magnitude and frequency of annual flows,
Nahal Shiqma at Beror Hayil, 1960-1987