

Stepped-bed morphology in arid gravelly channels

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ABSTRACT

The stepping phenomenon indicates systematic channel-bed variations that are not identical to the well-known pools and riffles. Channel beds in the Dead Sea area demonstrate that the main elements in a stepped bed are the regular and the rapid segments, which constitute distinct populations. The bed material of the stepped channel is heterogeneous in size, but significant uniformity prevails within the segment types.

The cyclic spacing of the segment types deviates clearly from that of pools and riffles in that it is at closer intervals. The

coarser the sediment, the more pronounced the segmentation. Stepping may produce variations in flow velocities from subcritical to supercritical and causes the overall flow regime to vary. Widening and braiding of the channels downstream does not replace the steps. Megasteps form in the canyons but are not cyclic. Conditions favoring stepping indicate a coarse fluvial environment.

INTRODUCTION

The channel steps are formed by alternating steeply and moderately sloping segments of a channel bed. Stepping comes

within the range of the macro-bed forms. The step consists of a combination of two sedimentary units (Figs. 1, 2, 3), a steeper rapid segment, and a less steep regular segment.

The rapid segment resembles the front of a transverse bar and is composed mainly of gravel and boulders. The regular segments consist of gently sloping, well-sorted gravel platforms with much smaller particle sizes than are found in the rapid segments. The thalweg is more incised and discernible in the rapids. Headward erosion of the front of the rapid forms interfingering between the two elements of some steps. The stepping pattern is not confined to the thalweg but spreads sideward across the width of some channels. Stepping is not the same as "pools and riffles," "maigres et mouillés," and other phenomena as defined by Leopold and others (1964), nor does stepping resemble the "Ostler lenses" described by Martini and Ostler (1973). A riffle is synonymous with a gravel bar, extending parallel to the flow line, and a pool is a depression in the channel bed. In the stepping pattern, pools are not divided by sills. No bed gradient was found in which the direc-

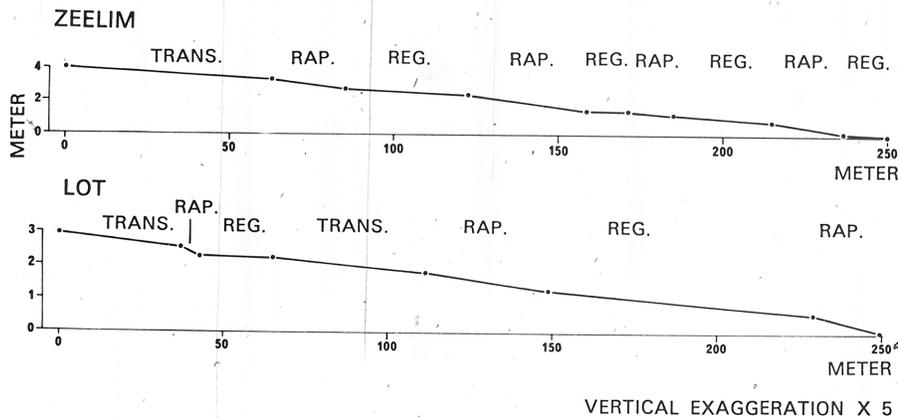


Figure 1. Stepping in longitudinal profiles of Zeelim and Lot channels. Only part of surveyed length included.

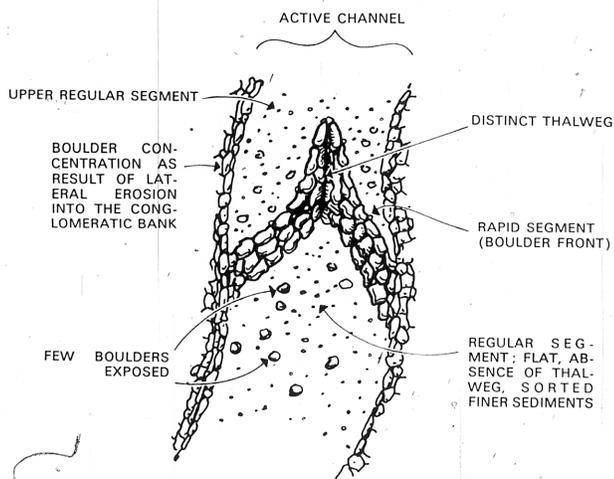


Figure 2. Schematic plan illustrating contact between regular and rapid segments.



Figure 3. Stepping near Dead Sea coast: two regular segments and rapid segment between them (Zeelim).

tion of slope was upstream, as is to be expected in depressions.

Stepping is not considered to be a primary sedimentary structure by Pettijohn and Potter (1964), Picard and High (1973), and Keller and Melhorn (1973), even though it maintains definite shape and clear spacing and is abundant under certain dynamic and sedimentary conditions. Wertz (1964, 1966) described this bed form in detail. A similar feature was described by Krumbein (1942) as a boulder jam, which is an accumulation of boulders with a steep gradient downstream and a surface that slopes moderately upstream. Scott and Gravlee (1968) described boulder fronts transverse to the channel, composed of boulders 3.5 m in diameter. The boulders were transported, as a result of dam failure, as viscous subaqueous rock flows; alterna-

tively, the boulders may have moved as bed material. Stepped micromorphology was described by Denny (1965) mainly on intergully patches on alluvial fans where stepping is spatially intermittent. It is characterized by alternating coarse and fine sediments and by coarse microrapids; the heights of the rapids do not exceed a few centimetres. This microstepping may be due to wetted silt creep, with fragments on top, dammed by coarse material. Damming by coarse material that forms longer segments on slopes was described by Washburn (1956); step lengths thus formed exceed 7 m, and their height reaches 1 to 2 m.

REGIONAL SETTING AND METHODS

Stepping is developed in ephemeral streams with a high coarse-grained bed-load discharge (Wertz, 1966) and is typical of the wadis in the Dead Sea area (Fig. 4). This area occupies a section of the rift valley, which attained its present form during late Pliocene and early Pleistocene time. The lower parts of the fault scarp, bordering it to the west, are mantled by limnic sediments, gravel, and colluvium. From the canyons toward the Dead Sea, the streams incise old fans. Mean annual precipitation is 50 mm, but near the watersheds of the Hemar and Zeelim, annual precipitation averages 500 mm. Stepping was studied

along the wadis from Jericho to Sedom. Detailed quantitative studies were made of the Zeelim, Hemar, and Lot channel beds. The drainage area of the Zeelim is 236 km², that of the Hemar is 326 km², and the catchment area of the Lot is 20 km². The channel beds are composed mainly of gravel and boulders. Except for the stepping phenomenon, no other accumulation forms were discerned. East of the western fault scarp, bed rock is exposed only along a few short segments of the bed; the exposed formation is the "Hamarmar" lacustrine clay. On the banks, conglomerate with alternating limnic lime and clay is exposed. The conglomerate of the channel banks is unsorted, uncemented, and without distinct layering, and it is richer in fine sediment than is the bed gravel.

Channel segments 500 to 1,500 m long were studied. Since the most relevant dimensions of the stepped-bed form are the height and length of the segments along the flow line, this phenomenon is treated two-dimensionally as an aspect of the longitudinal profile. Segments were defined by coarseness and by the degree of sorting, which also constitute roughness factors. A useful factor in the roughness determination is the amount of space between boulders on the bed, which generally indicates the energy gradient. Intermediate slopes that could not be related to either rapid or regular segments were defined as transitional segments (Fig. 5). The validity of the definitions was tested by slope measurements, determination of the roughness coefficient, estimates of flow velocity, and size analysis of the channel-bed sediment. In all respects mentioned, the defined segments constitute separate and distinct populations.

DIMENSIONS AND CYCLIC RELATIONS OF THE SEGMENTS

In the Lot and Zeelim channels (Fig. 6), the regular segments constitute the most common bed morphology (40 to 44 per-

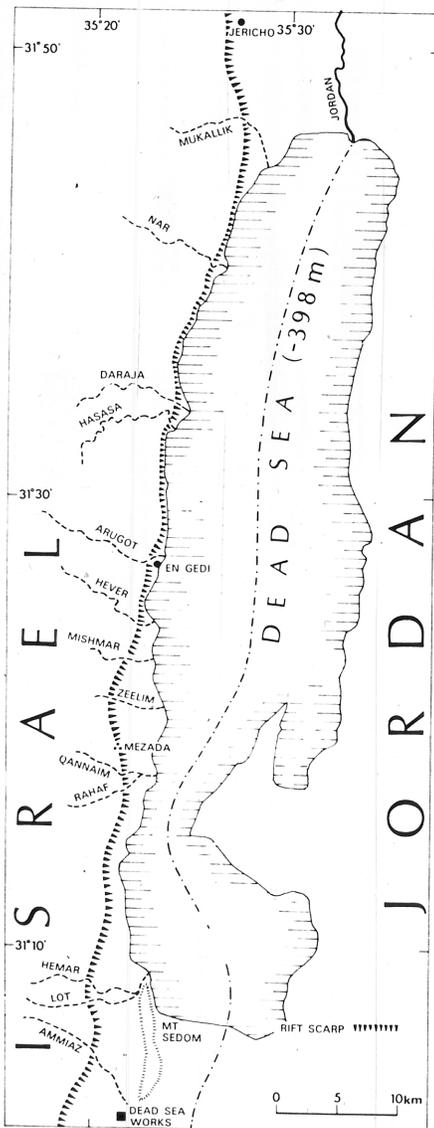


Figure 4. Location map.



Figure 5. Transitional segment (Zeelim).

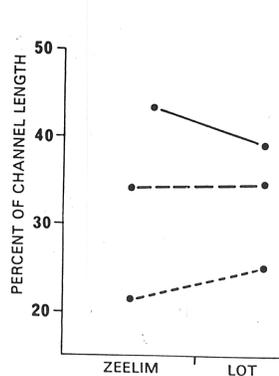


Figure 6. Frequency of segment types.

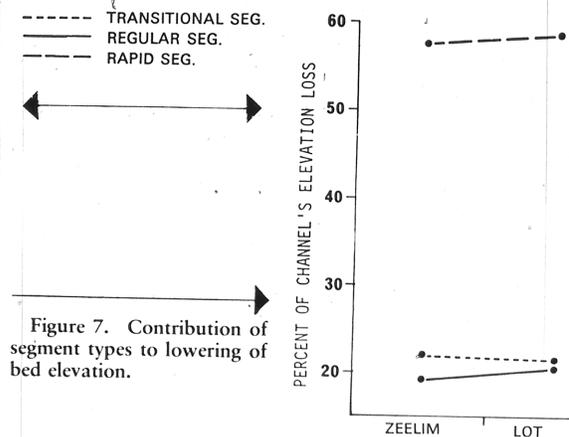


Figure 7. Contribution of segment types to lowering of bed elevation.

cent). Nevertheless, owing to the moderate slope of the regular segments, their contribution to lowering of bed elevation is usually the smallest, about 20 percent (Fig. 7). The rapids give rise to the major drop in bed elevation (58 percent). This conclusion conforms to that of Yang (1971) and Keller (1972); that is, pools are longer than riffles. For the purposes of this comparison, pools were defined as interrapid segments. Wertz (1964, 1966) indicated that toward the upper reaches the rapids were shorter and steeper and distances between them decrease, whereas downstream, where a sandy sediment predominates, the rapids lengthen, become gradually less prominent, and fade out. According to Wertz the entire stepping phenomenon is finally buried downstream. Such geometric variations downstream were not found in the Dead Sea area, reflecting the coarseness and the mountainous character of the channels studied.

The attempt to establish to what degree a sequence of three consequent channel sections is composed of the three defined units showed (Fig. 8), that only half of the channel lengths investigated constitute complete sequences; elsewhere, the cyclical occurrence of the transitional type is missing, which may indicate that the transitional segment is only a secondary type. Figure 8 illustrates that the occurrence of the main segment types — that is, the rapid and regular segments — is cyclical. Evenly distributed segments of essentially uniform length indicate a tendency toward uniform expenditure of energy. The occurrence of the different segments along the channel beds is not completely uniform, resulting in the imperfect linearity of the cumulative curves (Fig. 9). When taking into account the different lengths of the segments, their distribution along the bed does not become more uniform, indicating that the rate of energy expenditure does not become more even by the segment length.

Leopold and Wolman (1957) regarded the cyclic spacing of pools and riffles as dependent upon channel width. Leopold and others (1964) and Keller (1972) defined this average longitudinal spacing as five to seven channel widths. Keller emphasized that this average value is not identical with the mode. In his opinion the number of bed components increases with increase in channel sinuosity in order to preserve that average spacing, whose existence he viewed as an indicator of grade. Analysis of stepping suggests that the average space between regular segments is 1.4 channel widths, whereas between rapids it is 2.2 channel widths. These coefficients, which do not change along the stream, are distinctly smaller than the ratio 1:5-7, which is typical of perennial streams with episodic floods. From the data available, it is impos-

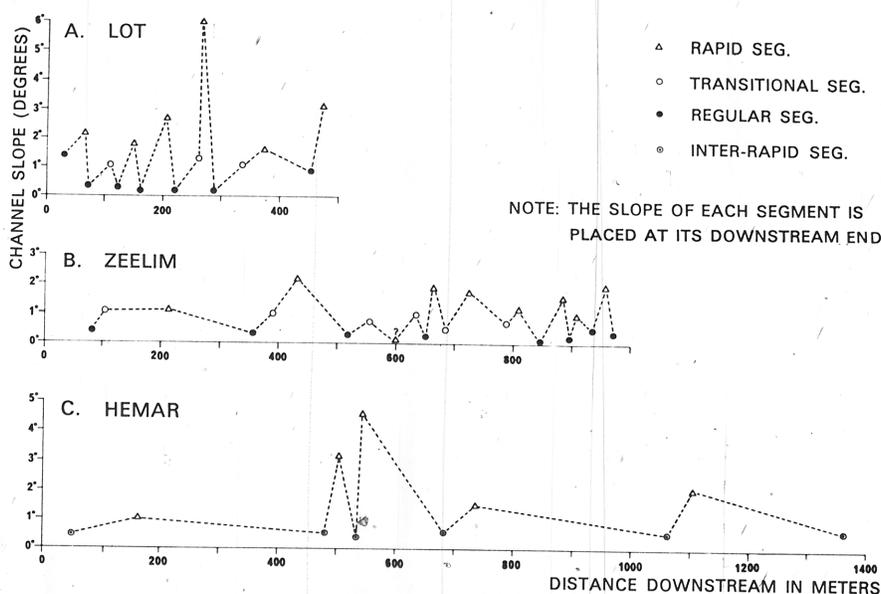


Figure 8. Segment and slope variations along channel beds.

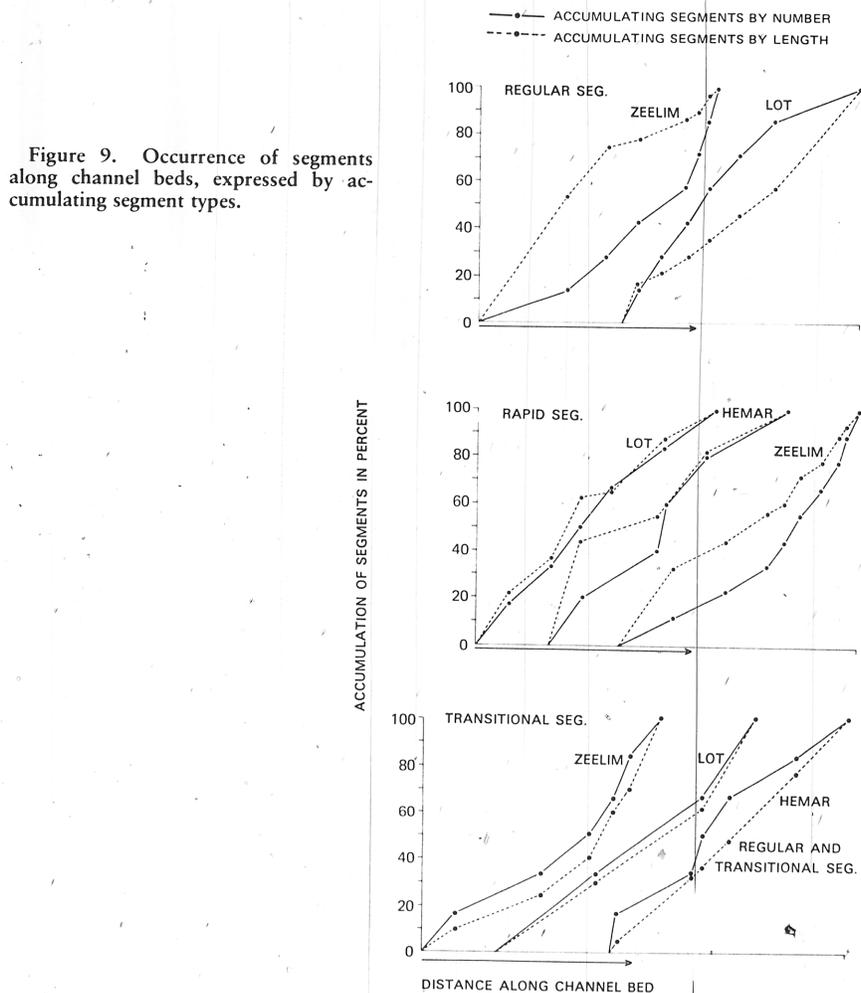


Figure 9. Occurrence of segments along channel beds, expressed by accumulating segment types.

sible to establish whether some relation exists between cyclic spacing of stepping components and berm height discharge. The Lot channel, with its relatively small basin and discharge, does not differ from the other streams in order of magnitude of cyclic spacing.

SLOPE GRADIENTS AND ROUGHNESS

Slopes are almost identical in the Zeelim and Hemar channels; 0°25'E and 0°47'E, respectively. The Lot channel shows a steeper slope, 1°25'E, which might be due to its relatively small basin. Slope variations among segments are not lithologically determined; throughout most of the channels bed rock is not exposed. Neither does step-

ping show a systematic relation to channel bends. Variation of the bed slope is not accompanied by cyclic alternation in the channel form, indicating that steps do not correspond to changes in the channel morphology.

Three different slope populations were identified: regular segments are most moderately sloped, 0°25'E (Fig. 10), slope of transitional segments is medium, 1°4'E, and the rapid segments are the steepest, 2°19'E. Thus, field delineation proved determinable from slope measurements. This division confirms that the transitional segments, defined only by roughness and sorting criteria, also constitute a slope category. Segment slope gradient varies from one stream to another, but in all three channels the range of the regular and transitional

slopes is smaller than that of the rapids. Similarly, Leopold and others (1964) and Yang (1971) indicated that the mean slope of the pools is lower than that of the stream, whereas the average slope of the riffles is steeper.

Field delineation between the various segment types was the most difficult in the Hemar. Ill-defined segments in the Hemar result in major overlap between transitional and regular segments; these types were therefore treated as one category (Fig. 8C). The rapids and the regular segments are regarded as the principal categories; the transitional segments are closer in character to regular segments and are considered a secondary type. A comparison of slope variance in each stream with the variance among streams indicates that the slope range of intrastream segments is large and that each stream does not present a distinct slope population. Even the Lot, with its relatively small dimensions, is not excluded here. Channel-slope measurements from maps along stepped beds have very limited significance, because of the asymmetrical distribution of the bed gradients (Fig. 11); the average slope measured on a map may deviate significantly from the mode. This results from the relative shortness of the rapids and from the small number of transitional segments, whereas the regular segments are long.

The roughness coefficient was determined in order to typify the segments and facilitate flow-velocity calculations. Roughness estimation was aided by Manning roughness coefficient tables and by

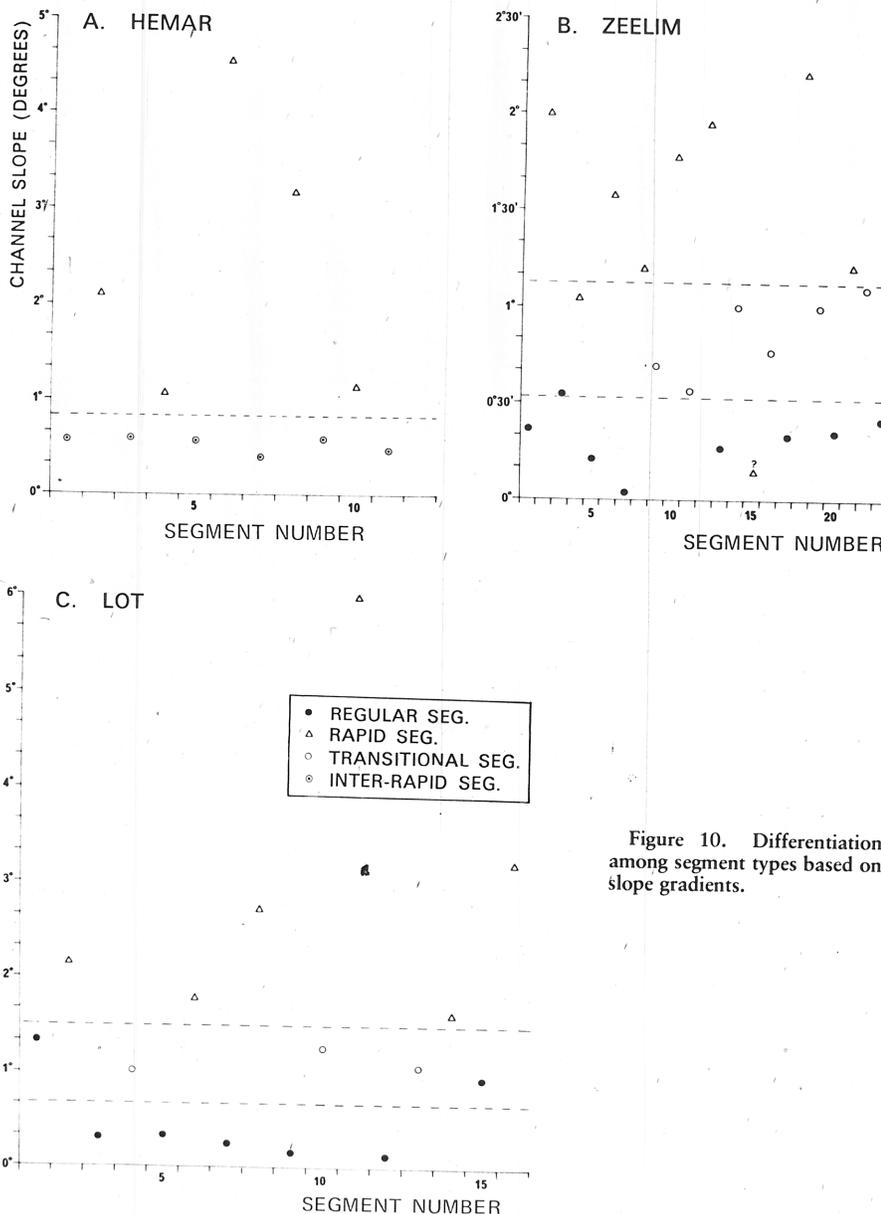


Figure 10. Differentiation among segment types based on slope gradients.

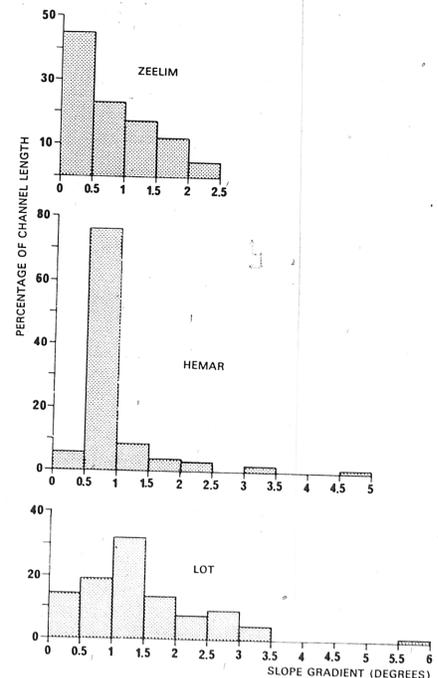


Figure 11. Frequency distribution of channel gradients.

channel photos that provide roughness data (Barnes, 1967).

The average roughness of the rapids was determined as $n = 0.055$, and the average roughness of the regular segments was determined as $n = 0.035$. In the absence of sedimentary structures in the channel, the roughness factor here relates mainly to the size of the sediment and constitutes the grain roughness. Boulders in the rapids represent the major rough constituent; vegetation contribution to roughness is negligible. Since the roughness coefficient is dependent upon and modified by flow height, it is also worthwhile to define relative roughness (R/D), where R is the hydraulic radius and an estimate of depth of flow at berm height, and D is the sediment size represented by the mean diameter of the 25 largest boulders. Relative roughness indicates the re-

tarding effect of the roughness components. Relative roughness values in the rapids are approximately 3.5, resulting in a relatively high retarding influence. In the regular segments, the values are approximately 9.6, indicating a much lower retarding effect. Where R expresses depth as a result of the transition to supercritical flow in rapids, the retarding effect will be even higher.

SEDIMENT SIZE

Studies of the granulometric expression of the steps was made along the Lot and the Zeelim channels, where stepping is of significance to the slope. The sediments consist of dolomite, limestone, and flint. Fourteen samples were taken in each stream, seven in the rapids and seven in regular segments successively, by digging a hole $50 \times 50 \times$

15 cm in the segment center. Each sample was reduced by quartering to 9 kg and hand sieved in the field, with an interval of 1ϕ and a range of 2 to 128 mm. To find the maximum sediment size variation, the B axis of the 25 coarsest fragments was measured along two traverses in the form of a cross in all the segments sampled. Leopold's criticism (1970) of the bias in the non-spot-sampling method is not relevant in this case because the objective was to determine the maximum grain size only.

Stepping causes a cyclic variation of grain size, within the overall gradual decrease in size downstream. Both the Zeelim and the Lot channels have identical trends despite the pronounced difference in basin dimensions. Sand and finer sediments (≤ 2 mm) constitute only 16 to 18 percent of the bed sediment (Fig. 12). Nowhere does it consti-

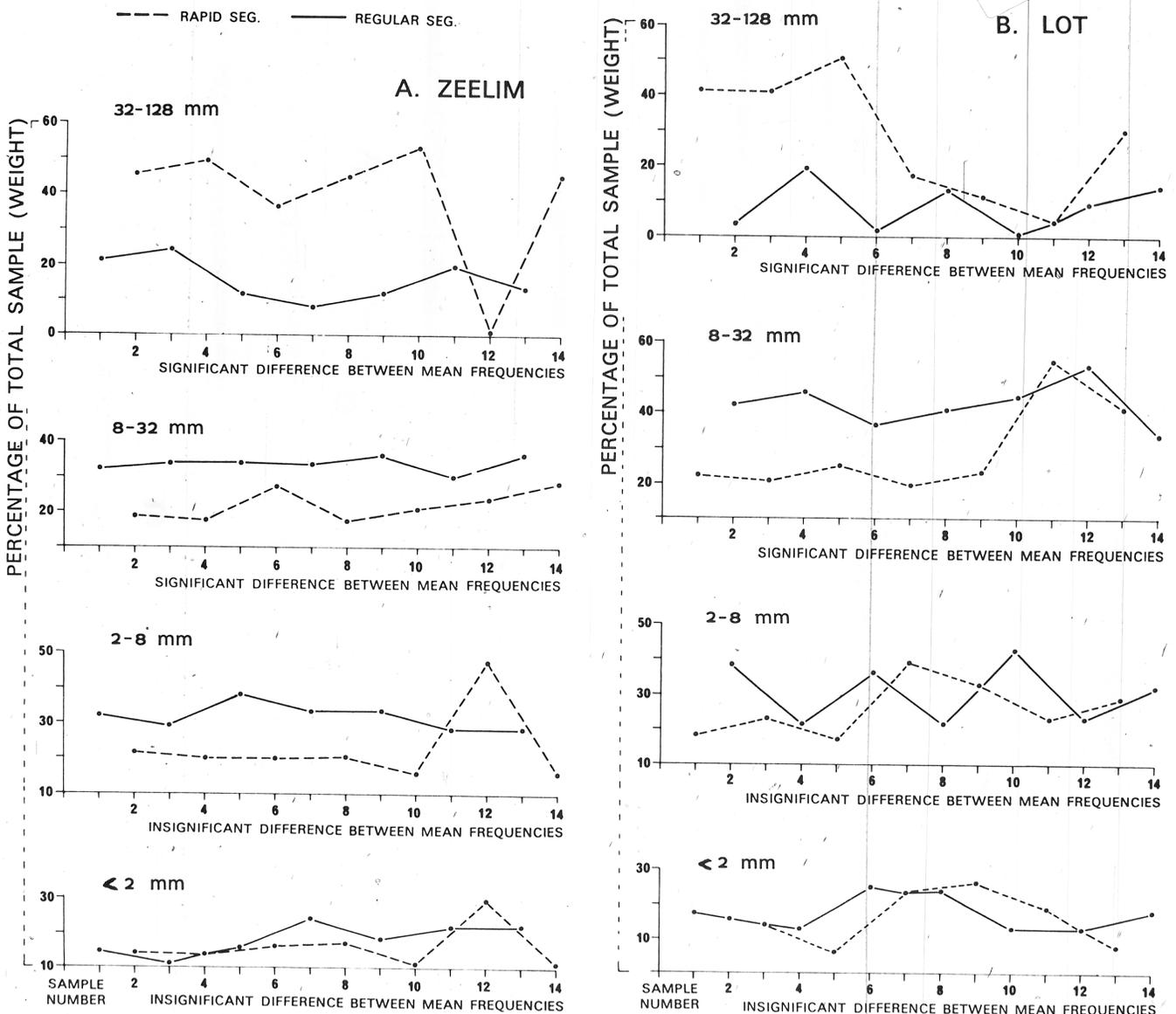


Figure 12. Frequencies of grain-size fractions in rapid and regular segments in Lot and Zeelim channels.

tute the second mode. Thus, stepping differs from pools and riffles in scarcity of the sand fraction. Furthermore, the amount of sand is not significantly different between rapids and regular segments. Stepping differs from pools and riffles by the lack of cyclic occurrence of sand compared to the periodicity of the channel segments. Thus, winnowing of fine sediment from the rapids to the regular segments did not take place. Differences between the segment types are apparent only from medium (8 to 32 mm) and coarser pebbles. The size range of 32 to 128 mm is significantly more prevalent in the rapids and expresses their coarseness. This is also expressed by the positively skewed size distribution of the rapids (Fig. 13). The rapids are about equally composed of boulders and cobbles, whereas only 5 percent of the regular segments is boulders. Thus, sediment size differences between regular and rapid segments become more pronounced toward the coarser fraction. Sediment size similarity between corresponding segment types in different channels is much greater than that between adjacent segments of different types in the same channel.

The velocity required to move particles up to boulder size is, according to Sternberg's formula (Leliavsky, 1966), 2.1 m/sec when flow reaches berm stage — that is, still within the range of the estimate of flow velocities on the regular segments, calculated according to the Manning equation. Only the coarse sedimentary tail of the rapids (>51 cm), which composes 6 percent, requires a velocity of 2.9 m/sec or more; this is beyond the flow velocity on regular segments yet within the range of velocities over rapids at berm stage. This indicates that when flow reaches berm stage the channels are capable of carrying almost all the sediment in their beds.

Yang (1971) maintained, in contrast to Wertz (1964, 1966) and in agreement with Leopold and others (1964), that boulders exposed in the rapids constitute the top of a sedimentary column that becomes finer with depth. No confirmation could be found from channel beds and bank exposure. Digging shows that bed sediment becomes coarser with depth. Regular segments may thus constitute depressions, filled with fine sediment during the last phase of a flood (Wertz, 1966). There was no way of establishing whether the boulders are continuous under the fill.

NATURE OF FLOW

The length of the channel segments is dozens of metres — sufficiently long to be considered as having regular flow. Accordingly, the Manning equation was used for calculating discharge and flow velocity at berm stage, although parameters constituting the hydraulic geometry do not express

the extreme variations of the hydrograph during flood episodes. Following that, critical velocity (V_c) and critical depth (D_c) were computed for an average regular segment. Calculations (Table 1) indicate that $V_c > V$ Manning on an average regular segment, indicating that flow is subcritical up to berm stage, although close to the threshold. Considering the rapid as a short segment, one could conclude that up to berm stage a critical cross section will develop over it. Water will pass the rapid with supercritical velocity, causing a hydraulic jump at its base. This conclusion is based on slope variations between segment types, on the great affinity between R and D_c , and on the tendency of the flow to reach critical depth at the top of rapids. Table 1 shows that on the average rapid, $V_c < V$ Manning, except for the Zeelim.

Owing to the increased slope gradient and in spite of the pronounced roughness, mean flow velocity over the rapids is 25 percent faster than that on regular segments. As slope variations are not balanced by roughness, flow velocity varies from one segment to another. Thus, the overall mean flow regime along the consecutive segment types, up to berm stage, is a varied flow. Similar conclusions were arrived at by Yang (1971). Dolling (1968), who studied a

stream with a regular flow, suggested that a high velocity/depth coefficient signifies riffles, whereas a low one typifies pools.

In spite of the uncertainties in estimating Manning's n and using mean slope in computations, the findings confirm the theory of least time rate of energy expenditure (Yang, 1971), according to which the stream will strive to accommodate a longitudinal profile in which the time of travel of a water mass along a reach is minimum when the potential energy expenditure is maximum. Duration of potential energy expenditure will not tend to approach zero; thus, the rapid segments will not strive toward verticality. The significance of this aspect is that along the rapids, which constitute the shorter segments, there exists, up to berm stage, an energy gradient that is greater than the average, and only through this conspicuous drop of bed elevation are the low gradients of the regular segments facilitated.

LOCATION AND DEGREE OF DEVELOPMENT

Channel steps exist in several stages of development. "Megasteps" form in the canyons (Mukallik, Daraja, Mishmar, Zeelim), where the Cenomanian dolomite is

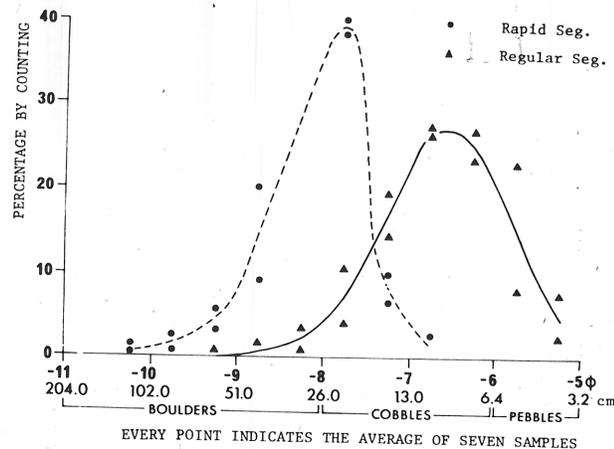


Figure 13. Mean frequency of coarsest sediments in rapid and regular segments of Lot and Zeelim channels.

TABLE 1. MEAN HYDRAULIC COEFFICIENTS AT BERM STAGE

| Froude no.* | V_c (m/sec) | D_c (m) | R (m) | Q (m ³) | V Manning (m/sec) | Roughness (n) | Segment type | Location |
|---------------|------------------|--------------|------------|--------------------------|------------------------|----------------------|---------------------------|----------|
| $Fr_2 = 0.81$ | 2.5 | 0.66 | 0.76 | 44.2 | 2.2 | 0.035 | Regular | Lot |
| $Fr_1 = 1.2$ | | | | | 3.1 ($R = D_c$) | 0.055 | Rapid | |
| $Fr_2 = 0.68$ | 2.8 | 0.79 | 1.07 | 169.5 | 2.3 | 0.035 | Regular | Zeelim |
| $Fr_1 = 0.93$ | | | | | 2.6 ($R = D_c$) | 0.055 | Rapid | |
| $Fr_2 = 0.86$ | 3.0 | 0.90 | 0.93 | 80.3 | 2.6 | 0.035 | Regular + transitional | Hemar |
| $Fr_1 = 1.1$ | | | | | 3.4 ($R = D_c$) | 0.055 | Rapid | |

* Fr_1 , rapids; Fr_2 , regular segments.

actively incised and huge boulders, 1 to 5 m in diameter, are supplied to the channel. The rapid segment here is short and very steep and composes a waterfall with a pool at its base (Fig. 14). It constitutes a local base level. The regular segment here is also short, and its components are coarser and less sorted when compared to regular segments outside the canyons. Megasteps are not cyclic and, apart from their dimensions, they differ causally from steps outside the canyons. While outside stepping is the re-



Figure 14. View looking upstream along the Zeelim channel: megastep; upper regular segment is hidden.



Figure 15. Deposit of fines capping channel berm; note terrace above (Zeelim).

sult of fluvial dynamics, megasteps are the product of slope processes. In the canyons, boulders are detached from the cliffs, but channel flow does not have the power to set them in motion or to determine their distribution along the channel. Removal of these huge boulders is made possible only through basal undercutting followed by rolling.

Without boulders no stepping can develop, though small low bars do exist. When the supply of coarse sediment from the banks increases, patches of sorted medium-sized pebbles begin to form, alternated with coarser sediment. Downstream, regular segments increase in number and most of the coarse sediment is concentrated in bars. Rapid segments are present as well, but the contrast between the segment types becomes vague. Widening of the channels and increase in number of bars toward the Dead Sea do not prevent the development of steps in the interbar channels. Stepping and braiding do not replace one another but coexist.

Since parts of the components in rapid and regular segments are identical in size, identification of stepping in banks of recent channels by sediment-size differences is difficult. In conglomeratic banks, sharp transitions from coarse to fine components are seen, yet no stratigraphy clearly shows stepping, expressed as depressions filled with medium-sized cobbles, bordered by accumulations of boulders and cobbles. Stepping was not observed on berms and on terrace treads, which are usually more regular than active channel beds. Similar evidence is found in Wertz (1966) and Miller (1958). The concept of stepping as an expression of definite sedimentary and dynamic conditions allows explanation of its absence by differences between the conditions that prevailed on the terraces, compared with those prevailing in the active channels.

Stepping on the terraces may not have been preserved, because deposition of fine sediments on the berm (Fig. 15) may have buried the former micromorphology. Eo-

lian deposition and washing down of fine material from bars into the interbar channels might also have buried stepped morphology on terraces. Partial confirmation of this process is the fine fill in the interbar channels on the terraces; the bar surface, composed of pebbles, lacks this fine fill (Fig. 16).

SIGNIFICANCE OF CONDITIONS FAVORING STEPPING

Fully developed stepping marks the transitional channel reach between the upstream region, with its coarse unsorted sediment, and the lower region, where finer sediment predominates. Stepping indicates steep channel gradients and at least some degree of heterogeneity in material size — that is, sorting only at an initial stage. Obstacles may initiate development of a step (Krumbein, 1942), yet they cannot cause cyclic stepping. Similarly, cyclic stepping cannot form in channels with flow velocities incapable of removing the coarse bed material. Because the contacts between the segments cease to exert a hydraulic influence above berm stage, they cannot be regarded as knickpoints. Stepping constitutes minor obstructions in the longitudinal profile but does not indicate cycles of channel development. The sedimentary coarseness, degree of sorting, and relatively steep slope gradients make stepping an indicator of environment. The rapid segment indicates a kinematic wave (Langbein and Leopold, 1968) whose characteristics are the cyclic distribution of boulder accumulations and their sparse occurrence among the concentrations on the regular segments. The transition to supercritical velocities over the rapids, seems to constitute a self-regulating mechanism, which controls the amount of particles concentrated and prevents blockage of the channel.

SUMMARY

Stepping is not identical with pools and riffles. Like most ephemeral channels, step-

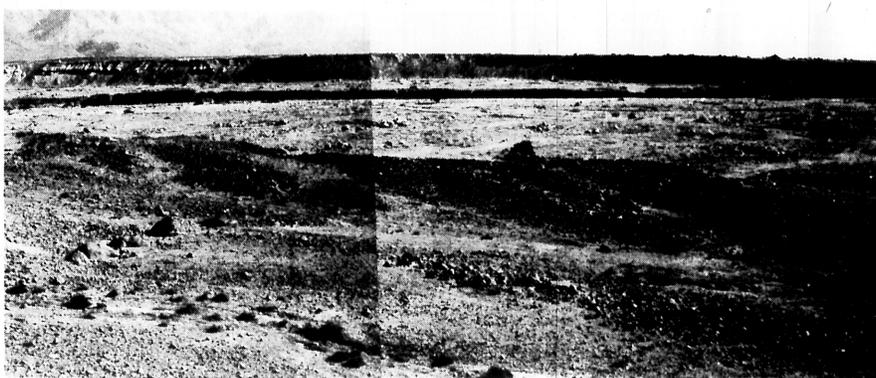


Figure 16. Bars and channels on a terrace (Zeelim).

ping lacks depressions, and its sandy fraction is only meager. Geometrically, its cyclic spacing differs from that of pools and riffles, and its environment is of steeper bed gradients.

Regular, rapid, and transitional segments constitute distinct slope populations. A stepped channel is not a homogeneous slope unit. Reliable field definitions of bed segments are based on sediment coarseness, degree of sorting, and channel-bed gradients.

Rapids, in spite of their relatively short length, are the main contributors to drop in bed elevation. Regular segments compose most of the bed. The consistency of stepping down to the Dead Sea coast indicates the prevalence of similar fan conditions in both upper and lower channel reaches.

Differences among the segment types become distinct only in the coarse fractions. The rapids are composed of coarse sediment. Overall coarse-sediment distribution along the channels indicates a kinematic wave.

Megasteps bear no relation to the stepping phenomenon, but rather, they are products of slope processes. They lack cyclicity and may constitute local base levels.

Calculation of mean flow velocities suggests that stepped-bed morphology has hydrological significance up to berm stage. Flow on regular segments may often be subcritical, whereas on rapids it becomes supercritical. The asymmetrical distribution of bed gradients in stepped channels demonstrates the limited significance of measuring on maps bed gradients of stepped reaches.

No systematic relation between stepping and channel bends was observed. Neither is stepping related to any cyclic variations in the channel morphology. The lack of stepping in the stratigraphic columns, exposed in terrace risers, suggests that stepping is quickly destroyed and may not serve as a

bed structure of paleogeologic importance. Stepping indicates a steep, coarse, and poorly sorted fluvial environment.

ACKNOWLEDGMENTS

I gratefully acknowledge the constructive criticism and suggestions by W. W. Emmett and R. Gerson. J. Hartshorn read the manuscript and made valuable suggestions.

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MANUSCRIPT RECEIVED BY THE SOCIETY DECEMBER 18, 1974

REVISED MANUSCRIPT RECEIVED MARCH 8, 1976

MANUSCRIPT ACCEPTED JUNE 2, 1976