Fig. 1. Typical dam constructed nearly 2,000 years ago by the Nabatean people of the Negev Desert, Israel. The dams are typically about 1 m high, 50 m long, of rock blocks without mortar. View looking upstream across the deposited sediment. Photo by the author.

channel. In the case of a discontinuous gully, the width is confined and probably less than in the original condition. But in neither case is it obvious what happens to hydraulic roughness, to velocity, or even to depth. Quantitative data are simply not available.

We do not understand the adjustment process to the extent necessary to predict or compute the gradient finally assumed in the quasi-equilibirum condition.

In the case of the check dam, the unanswered question, simply put, is how the small gradient developed can permit the incoming sediment to be transported over the depositional wedge. Why should the final gradient be so small, about 50% of the slope of the channel upstream of the base level effect?

First it is necessary to settle the problem of time. I remember being lectured by an experienced engineer under whom I worked in 1934 that the gradient of deposition would gradually increase until the final slope approximated that of the channel before the barrier raised the local base level.

NEGEV DESERT, CA. 2000 YEARS AGO

To settle this question, I investigated the barriers constructed by ancient man, with the help of Dr. Asher P. Schick in Israel. Nabatean culture in the period 300 B.C. to 100 A.D. developed highly sophisticated hydrological knowledge, as proven by Shanan et al. (1950). Of particular import in the present discussion is the construction of many barriers or check dams in the vicinity of Avdat where these investigators have reproduced the agricultural methods and productivity of the Nabatean culture. The age of the dams we studied is not definitely known, but one stone mound in the general area is known to be of the Byzantine period, though similar agricultural practices are of much greater antiquity.

The dams we surveyed were built in alluvial valleys in the Negev Desert of Israel where the sporadic rainfall averages about 100 mm annually. The dams were part of a complicated floodwater farming system in which the drainage area was treated by clearing the surface of stones, which were placed in long rows of stone mounds. Conduits were constructed to lead runoff water directly to a field formed on the wedge of deposition upstream of a dam. "These conduits artificially increase the catchment area for a particular field. They cover tens of thousands of dunams (100 m^2 area) and drain every square meter of the Abde (Avdat) region" (Shanan et al., 1950, p 113).

The typical dam is about 1 m high, consisting of rock blocks laid without mortar, stretching across the alluvial valley with dam length varying from 29 to 46 m. Figure 1 shows the downstream face of a typical dam. The sediment wedge behind each dam feathers out at the base of the next dam upstream, so those ancient people knew from experience the grade of deposition above a barrier.

The stone-free nature of the deposit above a dam was good for growing crops, especially because it received runoff water from the hillslopes. The deposits behind the dams in Havat Yehuda can be seen in Fig. 2. Some of the dams had complicated stone structures to lead the runoff water over the crest. In Fig. 3 there are carefully squared stones on the top of the dam spaced in a way that suggests they divide the runoff and keep it from concentrating in one place. So also in Fig. 4, a carefully constructed shallow channel lined with rocks can be seen just upstream of the dam, seeming to direct runoff into a chosen zone in contrast with the apparent spreading action of rocks in Fig. 3.

The valley of Havat Yehuda has 17 dams along its length served by a drainage area of 0.79 km^2. The

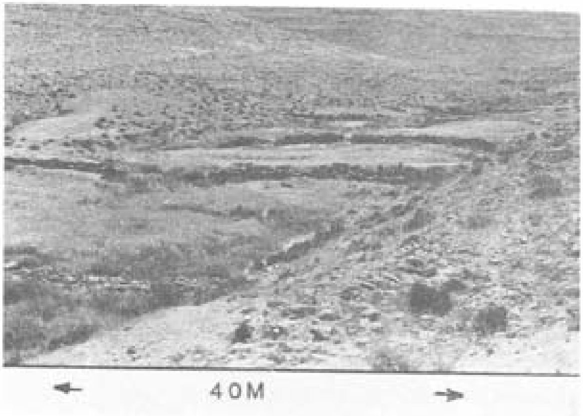

Fig. 2. View upstream showing ancient Nabatean dams in Havat Yehuda, Negev Desert, Israel. This valley has 17 dams, of which 4 are seen in this photograph. The sediment deposit upstream of each dam was cultivated by the ancients and is still used today. Photo by the author.

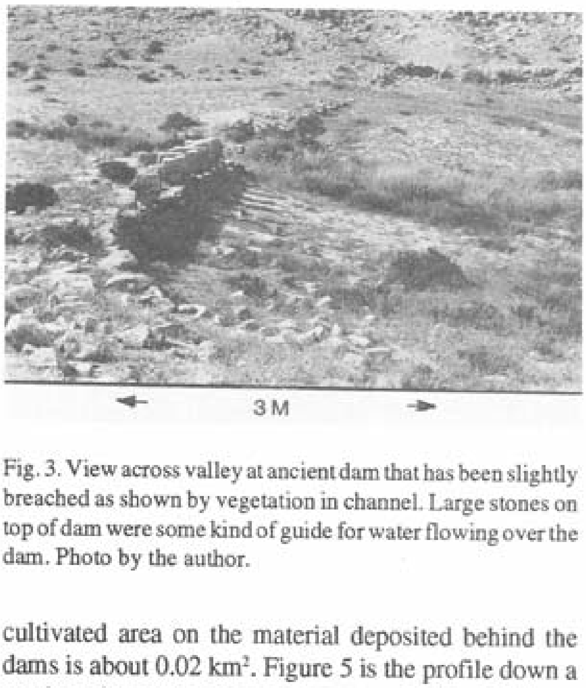

Fig. 3. View across valley at ancient dam that has been slightly breached as shown by vegetation in channel. Large stones on top of dam were some kind of guide for water flowing over the dam. Photo by the author.

cultivated area on the material deposited behind the dams is about 0.02 km^2. Figure 5 is the profile down a portion of the valley that encompasses 7 of the 17 dams. The surface of the deposit behind a dam is presently less smooth than it once was because local Bedouin farmers are growing wheat on the same area cultivated by the ancients but with no modern attempt to provide maintenance to the system. The slope of the valley floor in the zone where dams were constructed is 0.042 and the average slope of deposited sediment is 0.016, a ratio of 38%.

Another farm surveyed was Havat Baruch, consisting of 7 dams at the edge of a valley watercourse and

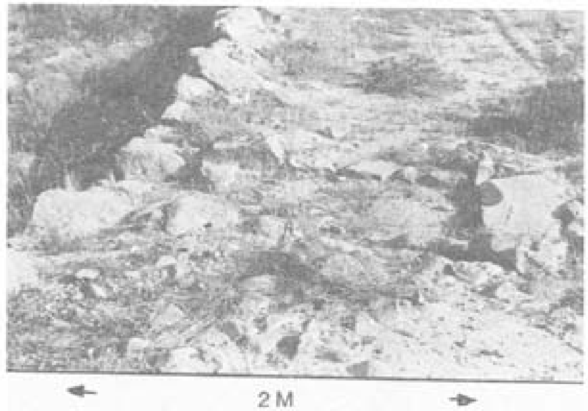

Fig. 4. Sediment deposit upstream of ancient dam built of rock blocks seen at left. In foreground is a built discharge or overflow channel, with parallel low rock margins and paved surface between. Photo by the author.

irrigated by two small gullies and adjacent slopes, not by the adjacent wadi. The drainage area utilized is 0.13 km^2 and the cultivated area 0.009 km^2. The original slope was 0.029 and that of the deposited sediment 0.015, a ratio of 52% (Fig. 6).

It is very clear in the field, wherever check dams exist, that the width of the deposited sediment behind the dam is greater than that of the natural channel upstream. The effect of this change in width is likely to affect each or some of the hydraulic factors, velocity, depth, roughness, as well as slope. Width change appears also to be an observable fact in the early stages of development of a discontinuous gully.

That width change is one of the major effects of a check dam is also implied by another of the Nabatean structures, two impressive dams near Kurnab. In a somewhat confined valley just upstream of a bedrock gorge, two dams of uncemented rock blocks were constructed by Nabateans circa 100 B.C., one 6 m high and just upstream, another 2.8 m high. The sediment wedge upstream of the lower dam has a slope of 0.0075, and it reaches the toe of the upper dam. Upstream of the upper dam the sediment wedge has a slope of 0.0076 and it grades upstream into an unaffected channel of slope 0.0079. These two dams (see Fig. 7) may be the only examples of such high structures still intact after nearly 2,000 years.

These dams differ from the farm check dams discussed earlier in that they are in a confined valley so that the length of the dam is about equal to the width of the channel it interrupts. The gradient of deposition is only slightly smaller than the slope of the natural channel, a

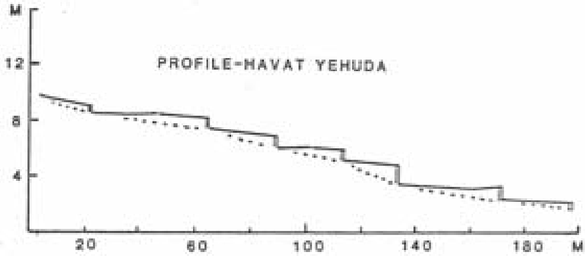

Fig. 5. Longitudinal profile down a segment of the valley of Havat Yehuda, near Avdat, Israel. Seven of the 17 dams are shown, with the surveyed wedges of deposited sediment behind each dam. The dotted line is the profile of the original valley floor.

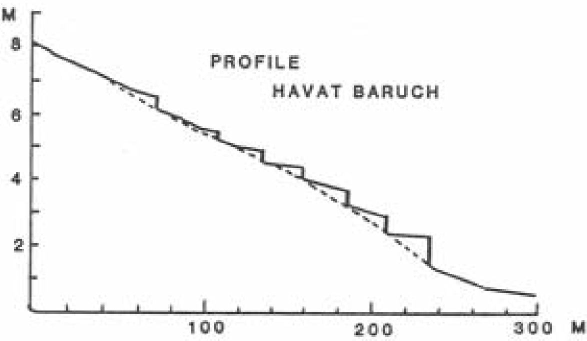

Fig. 6. Longitudinal profile of the farming area that was surrounded by a rock wall within which 7 dams were built at Havat Baruch, near Avdat, Israel. Crops were grown on the sediment deposited behind the dams.

difference that may not be significant. Observing these structures and their location suggests that in some manner the slope of the affected reach is related to the width. If width is not changed, the slope of deposition is comparable to that of the unaffected channel.

In most of these ancient dams the ratio of the gradient of deposition to that of the valley floor is of the same order as in more recent check dams studied in the United States (Leopold and Bull, 1979). It can thus be stated unequivocally that, as concluded by Leopold, Wolman, and Miller (1964), the gradient of deposition becomes stable in a short period of time and does not change with time thereafter, even over a period of 1000 or more years.

This is of great theoretical importance in geomorphology. It is one example of the fact that the effect of base level extends upstream only a very short distance. Self-regulating feedback mechanisms must operate to balance the contribution of each of the adjustable hydraulic factors. We now know that such adjustment governs the hydraulic geometry tending toward a condition of minimum variance among those factors. But how such adjustment requires such a large change in channel slope over the depositional wedge is not known.

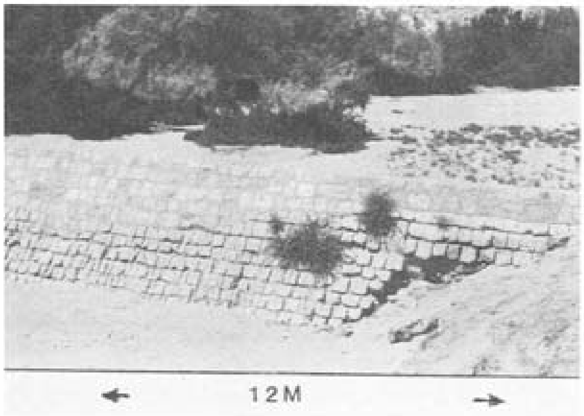

Fig. 7. Well-preserved dam of uncemented rock blocks built by the Nabateans about 2000 years ago. It is one of 2 dams that are 130 m apart in the wadi of Kurnab, Negev desert, Israel. Few ancient dams have survived for such a period of time. Photo by the author.

U.S.A., CA. 1950

The problem from the standpoint of hydraulics and geomorphology is to understand how the sediment produced upstream can be carried over the flat gradient of the deposited wedge. No procedure has been developed that can predict quantitatively the gradient assumed by a channel even when values of the apparently requisite parameters are known. In fact, few authors have attempted to do this. Hack (1957, p 60) derived an empirical relation for streams in Virginia expressing slope as a function of drainage area (a surrogate for discharge) and bed particle size. If drainage area is equated to 1 cfs per mi^2, the mean annual discharge for eastern U.S., his diagram is surprisingly good. But in the mountains of New Mexico, Miller (1958) found no such relation. Though the gradient assumed by a channel may be dependent primarily on discharge and bed material size, this is too general to be a quantifiable tool for prediction. Even where those parameters are controlling, it is not clear what discharge or what particle size are the determinants.

It is highly desirable to obtain quantitative values of hydraulic parameters in actual conditions behind dams. This is not easy because many field sites where check