Sediment management and flood protection of desert towns: effects of small catchments

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Abstract Dealing with the sediment problems associated with floods poses difficult challenges to planners and managers of desert towns. Infrequent but powerful floods from even small catchments generally contain 5-10% of sediment by weight, most of it bed material. As shown by several case studies, corroborated by a simulated flash flood experiment, this sediment is capable of disrupting drainage regulators such as check dams and diversions. Based on the experience of Eilat in southern Israel, and its hyperarid surroundings, several options for dealing with the flooding/sediment hazard are evaluated. Minimal intervention with the dimensions and pathways of the natural drainage system, coupled with effective zoning regulations, should be the preferred choice in protecting desert towns.

INTRODUCTION

Floods, however infrequent, are common to all arid areas and often exact a heavy price in loss of life and property (French, 1987). Especially vulnerable are towns and linear structures, such as roads, located at the foot of desert mountain ranges, often in association with alluvial fans which are a common feature of arid landscapes (Schick, 1974; Rhoads, 1986). The flooding processes involved are markedly different from those operating in humid environments: time to peak tends to be very short; specific peak discharge of the high magnitude events is very high; and the supercritical flow provides high values of stream power that manifest themselves in pulsating flows, movement of sediment in slugs, and substantial reworking of the channel geometry throughout the event (Graf, 1988). The barren slopes typical of arid environments, especially those characterized by minimal infiltration capacity (Greenbaum, 1986), provide little protection from areal erosion, and the general lack of a continuous cover of riparian vegetation presents the opportunity for very large amounts of bed material to be transported by all large floods (Schick *et al.*, 1987).

While flooding at the foot of arid mountains has been recognized as an environmental hazard throughout most of this century, many aspects of the processes leading to this flooding and controlling its attributes remain uncertain or, at least, less than adequately documented. The reasons for this lack of scientific understanding stems, *inter alia*, from the usually very short-lived nature of a typical desert flood. Also, the probability of an adequately equipped scientific team being able to document a complete desert flood on-site is very small, given the complex logistics typical of the world's deserts.

A much improved knowledge of the sediment attributes of desert floods is needed for effective management of problems associated with arid watersheds. Upstream dams constructed to protect downstream towns and structures are occasionally subject to surprisingly high rates of sedimentation, often by a single high magnitude–

low frequency event. Their loss of storage increases the probability of a subsequent breach by overflow, initiating a human-induced flash flood. As most of these structures are earth dams, the possibility of a breach by seepage is not a rare occurrence and must be considered. Further downstream, much use is made of flow diversion by drainage ditches which often cause the floodwater to be deflected at an angle beyond its natural tolerance. The result is the on-site deposition of nearly all the bed load (generally amounting to between one half and three quarters of the total sediment load), complete clogging of the ditch, and a subsequent "jumpout" of the floodwaters. Much of the overflow, even if successfully controlled further downstream, finds its way onto the artificially flattened urban areas (parking lots, airfields, recreation areas) where large amounts of fine material provided by the suspended sediment load are deposited.

As a sequel to our intensive study of the rainfall-runoff-flooding-erosion-sedimentation relationships undertaken over the last 30 years in the small hyperarid catchment of Nahal Yael in the southern Negev Desert, Israel (Schick *et al.*, 1997), we have conducted an artificially controlled flash flood experiment in a similar small ephemeral stream channel upstream of the town of Eilat. In this simulation experiment, many aspects of the desert flood phenomenon were measured or systematically observed, including rates and depths of infiltration into the channel bed, floodfront velocity, peak discharge flattening during routing, flow surges, and post-flood exfiltration, and data for a dry and a wet channel bed were compared (Schick *et al.*, 1996). The techniques of fluorescent tracing used in this experiment are discussed in another paper presented to this Scientific Assembly (Lange *et al.*, 1997). In this paper we focus on the sediment aspects of this experiment and its implications for a more scientifically-based and effective management of the sediment problem associated with flooding in arid environments. While large fluvial systems usually call for major control and protection works, it is the small and less dramatic local *wadi*, or even a mere assemblage of rocky slopes, which is a more universal, even if less dramatic, source of erosion and sedimentation problems. It is this type of problem which concerns us in this presentation.

SEVERAL CASE STUDIES

The following text describes four case studies related to the erosion and sedimentation management problems outlined above. The first evaluates the effects of a medium-frequency flood on a low lying part of an urban area with industrial and other non-residential land use. The next two studies evaluate the drainage and flood protection measures planned for a new expansion of the town of Eilat and for its entire urban area, as a typical example of a desert city. Finally, a controlled flash flood experiment created by a dam breach in a small catchment draining towards the town is evaluated in terms of flooding and associated erosion and sedimentation effects.

The November 1994 flow in Nahal Roded

A minor flow resulting from a highly localized storm of >40 mm of rain over some with an estimated peak discharge of 40 $m^3 s^{-1}$. The event flow volume of *ca.* 50 000 m^3 was relatively small due to substantial infiltration into the wide alluvial channel bed of Nahal Roded upstream of the fan, as well as to the abstraction of much of the water by extensive quarrying holes. While most of the bed material was trapped in those deep holes, substantial amounts of fine sediment exited as wash load onto the alluvial fan. The northern half of the fan is used mainly for agriculture; the southern half — which adjoins the urban area of Eilat to the south — has a major salt production plant with evaporation pans, a birdwatching pond, and a plant producing beta-carotene from algae. Both were "protected" by a small diversion ditch designed to carry excess floodwaters southwards towards the Gulf of Aqaba. However, a waste and gravel ramp, which was under construction as part of an ongoing landscaping effort, caused the blockage of the flow in the ditch and the diversion of the flow onto the dirt road leading to the algae plant. The result was a near total inundation of the plant with many of the production ponds being filled with sediment, causing direct damage and loss of production.

Shahmon Quarter, Eilat

A part of the new Shahmon development southwest of the town of Eilat adjoins the toeslope of a small granite hill, without any appreciable intervening strip which might promote runoff transmission losses and thus inhibit flooding risks. A series of small interconnected reservoirs was constructed to divert flows to adjoining stream channels and prevent any flow into the development even during low probability storms. However, due to the interference of a nearby highway, flow from a neighbouring upstream catchment was in fact inadvertently diverted into the protective system, increasing its contributing area fourfold. Overflow from the string of reservoirs thereby becomes a possibility to be reckoned with, leading to sediment free runoff entering the development. This in turn has the potential for substantial erosion and disruption of the internal drainage facilities geared to handle only locally generated runoff. Thus, for some storms, the quarter might be better protected from flooding and associated erosion and sedimentation effects without the measures described.

Circular diversions

For a number of years, proposals were made to fully protect the entire town of Eilat from runoff from the mountains by constructing a major circular floodway along the town outskirts. Such a canal would convey intercepted floodwater around the town into natural drainageways to the north and to the south. Many of the stream channels must necessarily join the floodway at a perpendicular angle, causing on-site deposition of nearly all the bed load. Unless constructed with enormous proportions, flow in the floodway will be severely obstructed and, in the higher magnitude events, even fully clogged, resulting in "jumpouts" and erosive, sediment-free water entering the town. The risk progressively increases along the floodway, as it is joined by additional natural channels from the mountains.

The Nahal Shahmon flash flood simulation

The Nahal Shahmon flash flood experiment simulated a 5-10 year flood in a 0.7 km^2 catchment which originated at a point *ca.* 2 km upstream of the urban fringe of Eilat (Schick *et al.*, 1996). The first run was performed on a dry channel bed — a situation common in arid areas where rainfall is often highly localized; the second was released 24 h later, on a wet channel bed. The only major difference between a natural flood and the simulated one was the fact that the dambreak did not originate from rainfall excess over the catchment and therefore its floodwaters included only very little of the fine sediment which would normally be contributed by slope and gully erosion (see Lekach & Schick, 1982).

The first flood released 550 m^3 and the second 620 m^3 of water. These amounts were reduced to about one half within the first 260 m of the channel (slope 0.08) due to infiltration. A submerged bridge at 260 m served as a local base level for the channel and trapped, during the first simulated flood, *ca.* 35 m^3 of sediment, nearly all in coarse bed material sizes up to 270 mm in diameter. For the second flood,the equivalent values were 40 m^3 and 360 mm, respectively. The resulting sediment concentration (by weight) of 5-10% is typical of medium and large desert floods in small, steep catchments and closely replicates several flood events monitored in the Nahal Yael dam, for which concentrations of 9-11% were recorded for each of five events (Schick & Lekach, 1993). Larger catchments show similar concentrations: a medium frequency flood which occurred in 1972 in the catchment of Wadi Taba, just south of the Israel-Egypt boundary, completely filling a 2560 m^3 sediment trap dug immediately upstream of the Eilat to Sharm esh-Sheikh road in order to protect the road. In this case, the estimated concentration for the entire event was 5% (Schick, 1974). A high magnitude flood in Wadi Mikeimin, a 12.9 km^2 tributary of the Wadi Watir in southeastern Sinai, yielded a concentration of 9-11% (Schick & Lekach, 1987). Thus, in hyperarid, steep environments, a sediment concentration of 5-10% can serve as a rule of thumb for the design of diversion ditches whose dimensions must be able to accommodate volumes of deposition associated with such levels of concentration.

The peak discharge of the second flood (6.8 m^3 s^{-1}) was about double that of the first and its effective duration (2 min) was about one half. Contrary to expectation, most of the effects of both the floods were quite similar. The first flood terminated at a point 1.2 km downstream of the breach and the second reached only 150 m further downstream, despite the pre-wetting. The most conspicuous difference between the two floods was in flow velocity, which was 60% higher for the second flow, caused no doubt by both the smoother, pre-wetted channel as well as the much higher peakedness. This difference was, however, reflected to only a minor extent in the sediment transport, which was only 25% higher for the second flood. Flood duration is, therefore, no doubt also of major importance in the sediment transport and yield associated with such desert floods.

Further downstream, after substantial loss by channel infiltration, the dwindling flow still carried (or "pushed") significant amounts of bed material which included some granules and even small pebbles. The breach was made at a point which drains only one quarter of the total drainage basin involved. Modelling the remaining three quarters with a similar flow, appropriately synchronized and routed, yields a flood event which reaches deep into the urban area and transports substantial amounts of sediment.

IMPLICATIONS FOR PLANNING AND MANAGEMENT

Flows from natural into urban areas

The movement of sediment laden flows into the urban area is accompanied by a decrease in the conveyance capacity of the drainage system and by the development of unplanned flowpaths. Two approaches are available for handling the problems: firstly, total prevention of the entry of floodwater into the urban area, and secondly, controlled flow of floodwater through the urban area.

Total prevention This approach tends to work well for small and medium floods. However, in high magnitude events the possibility of breakdown of the entire system exists, with the resulting damage exceeding that which would have occurred without any protective works.

A floodway which encircles the protected urban area usually carries the water-sediment mixture considerable distances, sometimes with inadequate gradients. Localized deposition, coupled with lateral or vertical erosion of the floodway, will occur and is difficult to predict in advance. From a general environmental standpoint, a floodway in close proximity to urban dwellings is an aesthetic blemish as well as a magnet for trash. Provided for events whose recurrence period is a number of years, such floodways are often inadequately maintained and may be considerably below their functional capacity on the day of the flood. The same holds for a system incorporating checkdams and reservoirs. In both, sediment is the main problem.

Controlled transit This approach requires a high level of planning and zoning enforcement, in order to ensure that appropriate areas, many of which may have a dual function (e.g. roads and parks), are left open. The control system is based on a widely distributed network of relatively small culverts, street floodways, and occasional sedimentation basins. For flood events of medium size, up to a frequency of a few years, these systems generally operate reasonably well, although a few problems will occur for most floods, mostly caused by preferred loci of sedimentation associated with abrupt changes of flow direction or slope. For events with a long recurrence interval some damage must be expected, even if all planning and maintenance measures are assiduously undertaken. Areas undergoing construction are especially vulnerable to intense erosion and sedimentation processes.

Flows generated within the urban area

In many aspects, the erosion and sedimentation problems associated with the management of excess rainfall generated in urban areas are not unique to arid areas. However, the lack of protective vegetation in those open spaces which are not irrigated is more likely to cause localized and sometimes intense erosion and associated sedimentation. The problem may be compounded by inputs of runoff from adjoining uplands characterized by a low infiltration capacity, such as the granite mountains just upslope of the expanding town of Eilat (Schick, 1995).

Three general approaches to the management of urban drainage are available:
(a) drainage by subsurface storm sewers;
(b) drainage towards drainage ditches and streets that also serve as floodways;
(c) on-site infiltration over the entire urban area.

Drainage by an underground sewer system may be problematic in desert areas, due to an inadequate level of maintenance associated with the low frequency of its use. The steep slopes typical of many urban developments in deserts may result in low efficiency of the inlets designed to accommodate the flow. Also, such inlets are liable to clogging by sediment transported by the floodwaters, even with relatively low sediment concentrations.

Using streets as floodwater conveyors is a popular means of handling the flooding problem. However, full attention must be paid to the design of the gradient and to the role of pavement curbstones in limiting the lateral component of the flow. This component is emphasized by the deposition of laterally alternating sand and gravel bars formed by the flow, which not only cause a decrease in the conveyance capacity but also markedly increase the probability of a "jumpout", especially where the street runs at an oblique angle to the contours of the terrain (Schick, 1995).

The option to leave widespread open areas within the urban zone of desert towns has much to commend it. If properly planned, runoff generation is reduced, and, accordingly, the sediment problem also becomes less important and more manageable. However, the procedure is costly in terms of land economics and requires a zoning ordnance which is so strict that it borders on the unrealistic. This is especially so in desert towns with an older nucleus or even with more modern parts in which this consideration had been disregarded during construction. Although it will provide added recharge to the groundwater beneath the town, the infiltrating water will contain pollutants from the streets and roofs which will have been accumulating for many months, and may pose a health hazard. This applies also to the possible use of the street runoff downstream of the town.

CONCLUSIONS

This paper deals with runoff generated in small catchments upstream of desert towns with particular emphasis on the associated erosion and sedimentation processes and the ensuing problems. Based on a recent flash flood experiment and on our experience in the hyperarid southern Negev Desert and the problems faced by the town of Eilat, we propose the following generalizations:

(a) Rainstorms of even a few mm have the potential, in small catchments as well as within urban areas, to create runoff producing significant erosion and sedimentation effects.
(b) Although a precise evaluation of these effects is, to some extent, site specific, any control measures such as settling basins, channel diversions, and street floodways must be designed to cope with sediment loads of up to 10% concentration or more, most of which is bed material, often with pebble and cobble sizes.

(c) Elaborate protection systems, such as major diversions and settling reservoirs, are likely to break down more often than anticipated by the designer. The reasons for this include inadequate maintenance caused by the low frequency of flooding, violation of planning ordnances triggered by financial pressure on the land resources, and an unrealistic evaluation of the high magnitude–low frequency event.

Any coupling of a flood-generated water mass with an inadequate slope is bound to create substantial and damaging sedimentation. In cases where the water mass has been relieved of its sediment load, as in a dambreak, the result will be massive erosion, with subsequent redeposition. The degree of indeterminacy in predicting the exact scenario is such that full protection is not achievable. The best solution is to imitate nature and its floodways — the stream channels which have been formed over millennia of geomorphic equilibrium — rather than resort to massive engineering intervention. In managing erosion and sedimentation problems associated with desert floods, small (and simple) is beautiful.

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