

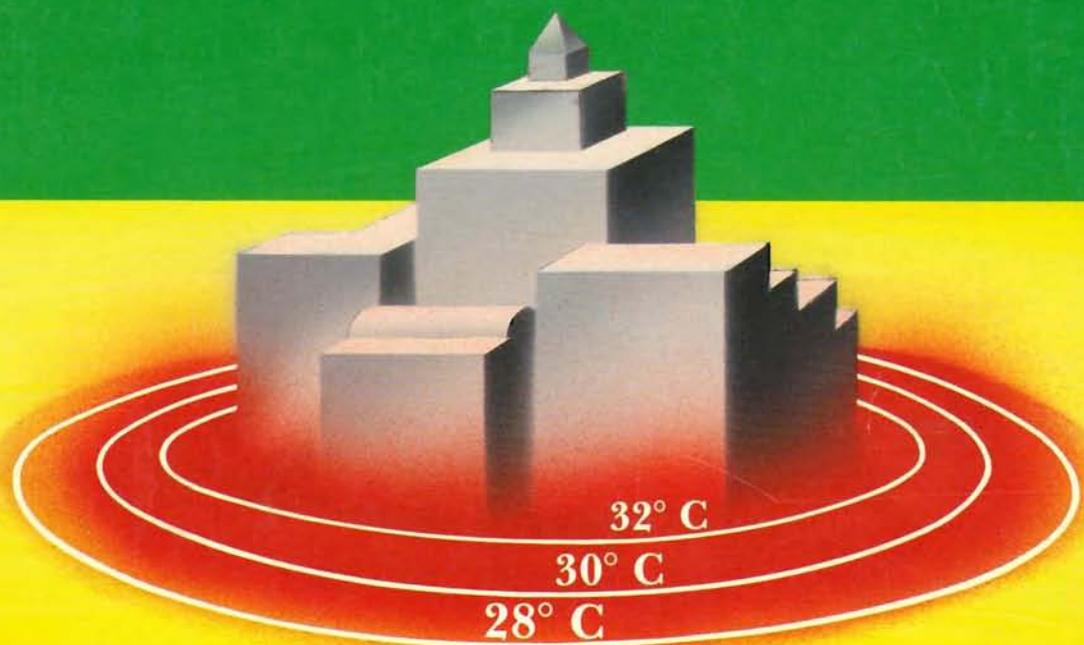
World Climate Programme

URBAN CLIMATOLOGY
AND ITS APPLICATIONS
WITH SPECIAL REGARD TO
TROPICAL AREAS

PROCEEDINGS OF THE TECHNICAL CONFERENCE

organized by the World Meteorological Organization and
co-sponsored by the World Health Organization

(Mexico D. F., 26-30 November 1984)



WMO — No. 652

**URBAN HYDROLOGY IN THE TROPICS : PROBLEMS, SOLUTIONS,
DATA COLLECTION AND ANALYSIS**

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1. STATEMENT OF PROBLEMS

Modifications of the land surface during urbanization change the type or magnitude of runoff processes. The major change in runoff processes results from covering parts of the catchment with impervious roofs, sidewalks, roads, and parking lots, and from drastically lowering the infiltration capacity of soils exposed and packed down on construction sites and unpaved roads and tracks. As a result, the volume and rate of overland flow are increased, or overland flow is introduced into areas which formerly contributed only low volumes of relatively slow subsurface flow.

Paved and packed surfaces are smoothed, so that the speed of overland flow is increased. Drainage density is increased and overland flow paths are shortened as gutters, drains, and storm sewers are laid in the urbanized area to convey runoff rapidly to stream channels. Natural stream channels are often straightened, deepened, or lined with concrete to make them hydraulically smoother to increase the speed with which the flood wave is transmitted downstream, so that even without an increase in runoff volume, the peak discharge rate would be increased. The land-surface modifications are summarized in Figure 1, and their effects on the stream hydrograph are illustrated in Figure 2.

Temporary storage of floodwaters in large artificial channels, in detention ponds, artificial lakes, or behind obstructions such as highway embankments and under-sized culverts, may decrease flood peaks in some

urbanized basins. Diversion of stormflow out of the basin may accomplish the same result. However, in most cities, flood peaks are increased by urbanization, and the effects are greatest, relative to the undisturbed condition, in small basins and in smaller flood-producing storms. In the largest storms, most of the landscape generates runoff whether it is urbanized or not, whereas in smaller rainstorms, the contributing area may constitute only a small fraction (<10%) of the undisturbed drainage basin, and may be increased severalfold by the introduction of artificial impervious areas. The effects are also greatest relative to natural conditions, in small basins, because they may be entirely urbanized and lack storage areas such as broad floodplains where water may pond to modulate flood peaks



Figure 1. Schematic representation of the problems to be managed in the control of urban storm runoff. (Source: Dunne and Leopold, *Water in Environmental Planning*, Copyright W.H. Freeman Co., 1978).

The increased peak flows cause overbank flooding, stream channel erosion, undermining of bridges and other structures, or overtaxing of sewer systems. Traffic is disrupted, homes and businesses damaged, and in severe cases, such as the recent floods in Mexico City, lives are lost. The problem is often exacerbated by deposition within natural and artificial channels and reservoirs of sediment eroded from construction sites and roadways. Much of the storm runoff is contaminated with sediment, feces, oil, and other chemicals, which pollute surface water sources and spread disease.

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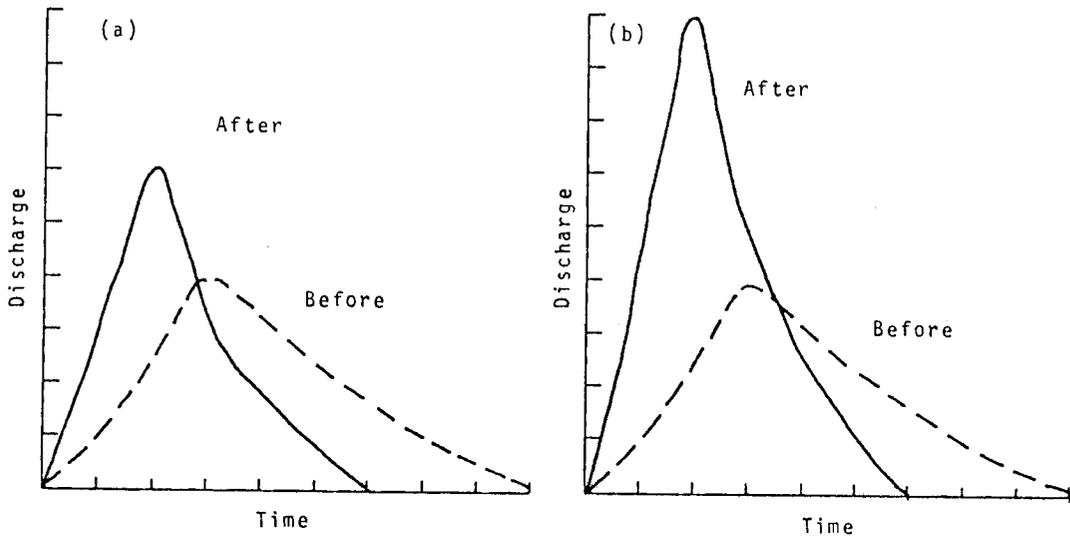


Figure 2. (a) Effect on the flood hydrograph of increasing the speed of runoff without increasing its volume; (b) Effect on the flood hydrograph of increasing both the speed and volume of runoff.

The increase in storm runoff is accompanied by a decrease in the amount of water entering the soil in urban areas. Some of the soil water would have evaporated back to the atmosphere under natural conditions, and a portion of the infiltrated water still does so in the city. However, the amount of evaporation from urban landscapes is being studied in a rigorous and systematic way in only a few places, such as Moscow (L'vovich and Chernogayeva, 1977) and Vancouver (Kalanda *et al.*, 1980; Grimmond, 1983), and it is impossible to generalize yet about its importance in tropical cities. The unevaporated surplus contributes either to subsurface storm runoff from shallow, perched saturated layers in soils with an impeding horizon, or to slower, dry-weather flow through deeper bodies of groundwater. In most cities it is difficult to predict the effects of urbanization on each of these flow paths, because of the great spatial heterogeneity of the urbanized landscape and the possibility that intense recharge of the groundwater can occur locally where water is ponded or sewer pipes break. However, the net effect of urbanization on the water balance of the phreatic zone beneath most cities is to lower the water table and decrease dry-weather flow. Pluhowski (1969) documented an example of decreased baseflow after urbanization on Long Island. In cities such as Nairobi, Mexico City, and Los Angeles, which cover useful aquifers,

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these trends are dramatically aggravated by the pumping of groundwater for municipal and industrial use.

In many tropical cities, storm drainage problems are extreme for a variety of reasons. First, rainstorms are often intense. Second, urban growth is frequently rapid and uncontrolled, so that neither time nor resources are available for planning to mitigate the storm runoff problem. The problem becomes particularly acute when a city spreads from a lowland into the surrounding hills. Uncontrolled storm runoff overtakes the (originally adequate) storm-sewer system of the flatter downtown area, which is frequently inundated. Examples of such developments can be seen in Barcelona, Spain, and in Rio de Janeiro and Teresopolis, Brazil. Third, the impact of sediment deposited in drains and natural channels can be particularly severe because of the highly erosive rainstorms of some tropical regions and the widespread unpaved, heavily-used roads and poorly-designed construction sites.

Important difficulties face the hydrologist in predicting the effect of urbanization or in designing measures to alleviate the urban runoff problem in tropical cities. Records of rainfall intensity and of runoff from rural or urban basins are usually sparse and short. Because uncontrolled urbanization is spreading rapidly, it is difficult to predict, or even to obtain up-to-date information on, its extent and nature. However, the hydrologic processes that are disrupted by urbanization are quite well-understood, and are similar in the tropics and in temperate regions, where they have been studied in detail. Many of the materials and designs used in urbanization are common to both regions. Thus, to an extent that is unusual in rural hydrology, it is possible to transfer concepts and measured parameters from temperate urban areas to tropical cities.

In this paper I will review the types of strategies that have been developed for reducing peak discharge rates from small, urban drainage basins. Then, I will summarize the kinds of data collection and analysis that are necessary for providing the numerical values on which to base both the generalized predictions, needed at the planning stage of urban development for anticipating storm-drainage problems and for comparing the effects of various control strategies, and the detailed computations

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needed at the design stage. My emphasis will be on simple measurements and analytical techniques in the belief that these are the only ones which can be used as quickly as is necessary and with the limited resources available for urban hydrology in most tropical cities. Although the techniques are simple, their results for small areas and open-channel flow problems are no less precise than those of the current generation of complex, expensive methods. However, the latter do have a role to play in the design or improvement of large networks of channels, sewer pipes, and control structures, serving large, heterogeneous urban landscapes. These networks are usually designed and constructed by specialized engineering firms. Examples of the methods used with a heavy bias toward engineering practice in the United States, are reviewed in the publication edited by Yen (1982).

A primary message of this paper is the need for hydrologists and engineers from tropical cities to make some simple field measurements which can guide, check, and be used to alter the application of methods developed in other regions where climate, building design, and urban layout may be different. These measurements must be made with cheap, simple, and vandal-proof instrumentation.

The paper will deal with hydrological problems generated within the urban area, and not with those originating upstream. Thus, I will not discuss another common hydrological hazard in cities: that of the encroachment of buildings into flood-prone areas of the landscape. This problem and the nature of hydrological analyses required for its amelioration are described by Dunne and Leopold (1978, Chaps. 10 and 11). Nor will the paper deal, except in passing, with the effects of urbanization on groundwater or with issues of water chemistry and microbiology which are the focus of much modern research on urban runoff. An introduction to this topic is given by Roesner (1982).

2. FLOOD CONTROL IN SMALL URBAN CATCHMENTS

The range of solutions available for reducing flood peaks in urban catchments involves either reversing the hydrologic changes described above or compensating for them by temporarily holding water on or below the land

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surface and releasing it slowly to a stream channel or to the groundwater. The technology of urban storm drainage is evolving rapidly, and new techniques are continually being developed. Engineers and hydrologists concerned with the problem need to update their knowledge of the subject frequently, through reading journals or reviews such as those by Wright-McLoughlin (1969), Hittman Associates (1974), and Kibler (1982a). The following will give only a brief indication of the types of storm runoff control now being used. At all stages of planning and design, however, it is important to exercise anticipation and common sense, rather than simply installing structures because they appear in a handbook. For example, if holding urban runoff in a detention basin near the outlet of a basin (Figure 3) will cause the maximum contributions from upstream and downstream to coincide, it is better to handle the runoff from the lower part of the basin by some other means (perhaps by not detaining it at all). This is not a general rule, but only an illustration of how a problem can be aggravated with the best of intentions, unless a thorough hydrologic analysis is conducted. One way of addressing this problem would be to measure or compute flood hydrographs from the larger undisturbed area and from the smaller urban area with various forms of storm runoff control, and to compare their timing at the basin outlet.

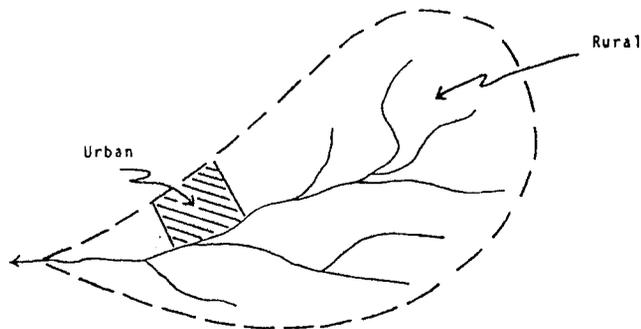


Figure 3. Detention of storm runoff from an urban area in the lower part of the drainage basin may cause that runoff to enter the main channel at the same time as runoff from the upstream, rural part of the basin.

Strategies for reducing the impact of urbanization on flood runoff deal with one or both of the effects illustrated in Figure 2. The amount of storm runoff may be reduced, or the runoff may be delayed and flows from various sources may be rendered asynchronous.

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2.1 Methods of Reducing Storm Runoff Volumes

The most obvious method of reducing runoff is to maintain the original infiltration capacity on the largest possible area within the urban landscape. This involves retaining as much of the natural vegetation and permeable topsoil as possible, which requires careful clearing and grading of land. Often, all vegetation and topsoil are removed from a site simply for convenience, and at the end of construction costly attempts are made to re-establish or import topsoil and vegetation cover. Careful survey of the site and a rational construction plan can reduce some of these costs as well as runoff and sedimentation problems. After construction, it is necessary to protect the vegetation of the urban areas from woodfuel harvest, and to promote the planting of covers that are effective in maintaining high infiltration capacities and in protecting against soil erosion. It is less useful to plant species that are not resistant to trampling damage, uncontrolled pruning, or which (like many eucalypts) are allelopathic and render soil on the forest floor bare and erodible. There lies in this problem fruitful ground for more cooperation between foresters and drainage-control engineers than one sees in most countries.



Figure 4. Porous pavement (Source: Dunne and Leopold, *Water in Environmental Planning*, Copyright W.H. Freeman Co., 1978).

Large portions of the urban landscape are either surfaced with artificial materials or are subject to such heavy pedestrian or vehicular traffic that they will not sustain a vegetation cover. Portions of heavily-used pedestrian areas can be surfaced with porous pavement (Figure 4), which consists of open-grated concrete pavers. Soil is laid and seeded with grass in the spaces within the pavement to promote infiltration. The installation is successful, of course, only where the climate and traffic allow the grass cover to survive, and where the subsoil is permeable enough to allow drainage of a significant portion of the rain infiltrated during each wet season. Unfortunately, in many tropical cities neither of these conditions is met, and the cost of installing porous pavement does not always justify the benefits. Some clay-rich tropical soils also swell or weaken dramatically when they absorb water and this effect may disrupt the surface or building foundations. Furthermore, some artificial building materials and materials for surfacing roads and parking lots weaken and deteriorate when they absorb water. Any plan to increase the infiltration of rainwater should include a review of the suitability of local soils and building materials.

2.2 Methods of Delaying Storm Runoff

Some methods of delaying storm runoff involve keeping the storm runoff at or near the land surface and simply increasing the time over which it drains into stream channels. Others involve diverting a portion of the storm runoff to slower groundwater during the storage period.

Because most of the storm runoff originates on impervious surfaces, one obvious method of runoff control is to retain water on rooftops, parking lots, and similar areas, although not on roadways where it becomes a hazard to traffic. Many new commercial, industrial, and administrative buildings are designed to hold several centimetres of water on their roofs. The roof drains are equipped with collars and flow constrictors designed to release the water slowly (at rates of 5-10 mm h⁻¹) to some ground installation for further detention or to a stream channel. Rooftop storage is not suitable for most of the lightly constructed, smaller buildings in tropical cities; it requires careful design, stout construction, and some safe means of draining rainfalls larger than the design depth.

Parking lots and pedestrian areas can also be designed to store several centimetres of water by means of curbs and berms, if the surfacing materials are sufficiently impermeable or resistant to deterioration when wet.

Since the ponding is rare and temporary, this is a cheap means of providing large volumes of storage on easily-controlled land without unduly disrupting its primary use. On sloping land, terraces and berms can also be used to detain water and to spread it onto adjacent, more permeable areas.

Runoff from rooftops, parking lots, and streets can be diverted to various kinds of trenches, pits, ponds, and underground tanks for temporary storage. For example, the runoff can be intercepted by gravel-filled trenches aligned along contours (Figure 5a). If the surrounding soil is adequately permeable, these trenches will regain their storage capacity between storms; if not, they can be equipped with a perforated drain tile set at the base of the gravel (Figure 5b). However, such trenches cannot long maintain their capacity if large amounts of fine sediment are washed into them.

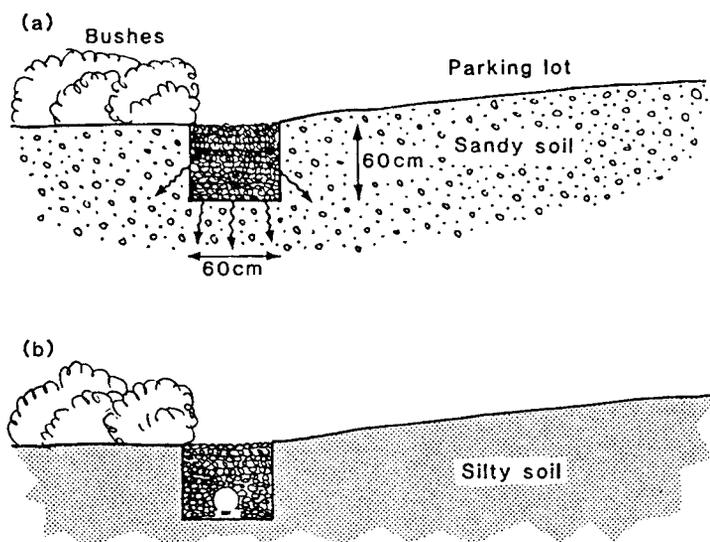


Figure 5. Trenches for intercepting, storing, and infiltrating surface runoff.

Runoff can be diverted to metal or concrete tanks installed below ground (Figure 6). At low rainfall intensities, the runoff is directed into drains and flows directly to the stream channel. At higher runoff rates, flow out of the drain is restricted to a chosen maximum value, and

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the excess runoff is backed-up and stored in a large tank under the developed site. After the rainstorm, water continues to drain slowly from the tank through its permeable base and through the drain. The capacity of the flow constrictor and the volume of the tank can be adjusted to keep peak runoff rates after development to a level smaller than or equal to those before urbanization for storms of a chosen frequency. As with rooftop and trench storage, installation of these underground tanks can be made the responsibility of the land developer as a condition of receiving the building permit. The difficulties of using such small-scale solutions are in ensuring that they are adequately designed, properly installed and maintained, and that they do not aggravate the problem of runoff timing portrayed in Figure 3. There is no simple solution to this last problem other than relying on the individual design engineer to make a reasonable estimate or measurement of the timing of flows from the upstream area and to design the local system accordingly.

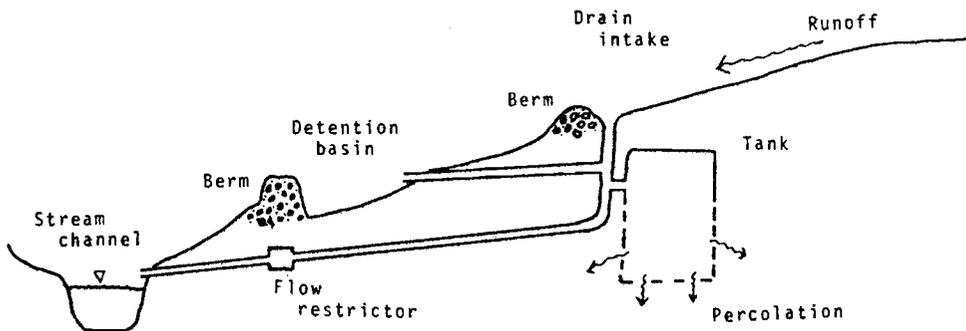


Figure 6. A typical underground storage system installed below a small urban development.

If land pressure allows, it is also possible to divert storm runoff to surface pits, which occupy natural depressions or excavations. Typical examples of such basins vary in area from 0.1 to 10 hectares and have storage capacities of 5000–50,000m³. If the substance is a deep, permeable, unsaturated sand or gravel, most of this storage capacity may lie below a pipe outlet and the water will drain to the groundwater within a few days. However, if as in much of the tropics, the city is built upon clay-rich soils or on bedrock, there is no significant infiltration, and the pipe outlet must be placed low enough to drain all of the required volume in order to restore the capacity of the pit. Maps of the surface geology

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of urban areas, and discussion with geologists, geomorphologists, or soil scientists would assist the drainage-control engineer in locating permeable zones, such as sandy river terraces or other permeable geological formations where seepage from pits would reduce storm runoff without contaminating useful groundwater.

If the surface layers are not adequately permeable, an infiltration well with a diameter of 1 to 3m and a radial pattern of distributary pipes could recharge water from the storage basin to a deeper, permeable formation. Peterson and Hargis (1973) described an example of injection from 4 wells in a detention basin serving a 162-ha residential neighbourhood on permeable volcanic rocks in Hawaii. The surrounding detention basin had a volume of 76,000m³ and was designed to control the 10-year flood. The polluted urban runoff was isolated from a shallow aquifer by casing the upper 40m of the wells. However, the high cost of such a strategy and the favourable geological conditions which it requires limit its usefulness to special situations. More commonly useful in the tropics is temporary storage in depressions which later drain through a pipe. Health considerations may even require the prompt drainage of such facilities in tropical cities.

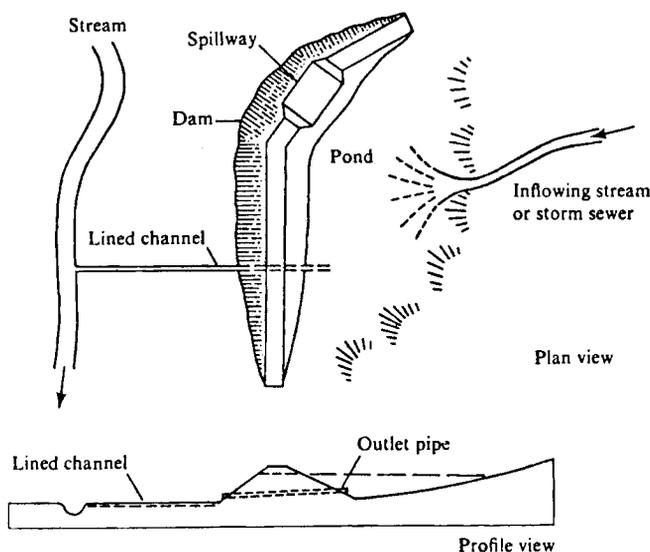


Figure 7. A small detention dam with a pipe outlet for the slow release of stormwater and a spillway for passing extreme flood peaks safely. (Source: Durne and Leopold, *Water in Environmental Planning*, Copyright W.H. Freeman Co., 1978).

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Where topography is suitable and dyking is possible, small dams can be built to provide floodwater detention basins (Figure 7) larger than those described above. The dam must be equipped with a narrow outlet pipe or weir, which allow water to drain out slowly after the storm, and a spillway to convey water safely over the dam if the capacity of the basin is over-taxed. The purpose of such a detention structure is to store a sufficient volume of water to reduce the peak discharge from short, intense rainstorms to pre-urbanization levels (Figure 8). This aim can be achieved by proper choice of the height of the dam (which determines the maximum potential volume of storage for the particular topography of the site) and the geometry of the outlet (which determines the discharge rate for a given water elevation). The effect of these detention basins on peak flows diminishes rapidly downstream of the dam as the contributing area increases and the volume of runoff stored constitutes a decreasing proportion of the total runoff. Although they are effective, if properly designed, such detention basins are costly to install, and they occupy valuable urban land. However, this land lies in the flood-prone valley floor and is not permanently inundated. It may be used for grazing and recreation between storms. In some cities, the design of detention basins takes advantage of natural lakes, but the resulting impact on water quality is usually bad as sediment and other pollutants tend to fill and eutrophy the lake. The design aspects of detention basins are reviewed by Whipple *et al.*, (1983).

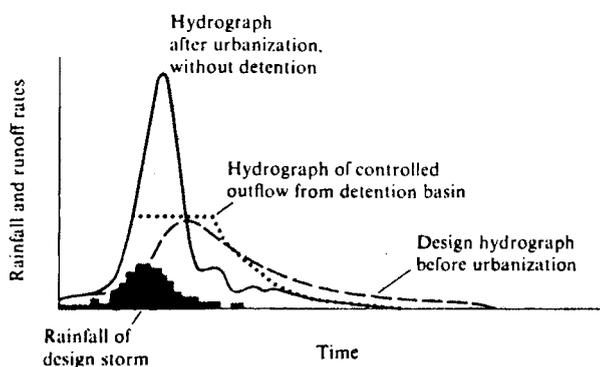


Figure 8. Storage requirement for a detention basin designed to keep flood peaks from an urban basin down to rural levels. The shaded area represents the volume of storage required. (Source: Dunne and Leopold, *Water in Water Environmental Planning*, Copyright W.H. Freeman Co., 1978).

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3. METHODS OF RUNOFF PREDICTION

In the planning and design of storm runoff control systems, it is necessary to predict the volume, peak discharge, and timing of urban runoff under a range of circumstances. This is required in order to evaluate the consequences of installing various control measures and of doing nothing. Most techniques of runoff prediction are extensions of those developed earlier for rural areas and some require first that runoff be predicted for the basin in its original rural state. The techniques are described extensively in various textbooks and manuals, such as those of the American Society of Civil Engineers (1972), Dunne and Leopold (1978), and Kibler (1982a). In this paper I will refer only to the most commonly used and simplest techniques. More complex methods, which portray the hydraulics and spatial patterns of runoff processes, require too much data for routine application in tropical cities. Such methods are reviewed by Dendrou (1982), Torno (1982) and Yen (1982).

3.1 Rational Runoff Formula

The rational method predicts peak discharge rates from data on basin area, rainfall intensity, and land surface characteristics, using the formula:

$$Q_p = 0.28CIA$$

where Q_p is the peak discharge in $m^3 s^{-1}$, I is the rainfall intensity in $mm hr^{-1}$ (usually chosen from some design consideration), A is the basin area in km^2 , and C is a coefficient chosen to reflect the proportion of rainfall that is converted to storm runoff. Although the method is widely criticized, it is also widely and successfully used, even by its critics. It is often hidden in complex computer models. The formula is useful for basins smaller than about 100 hectares, which can reasonably be expected to approach equilibrium between rainfall and runoff in a short, intense storm. The basis of the formula and considerations necessary for its application in rural and urban areas are described with worked examples by Jens and McPherson (1964), Dunne and Leopold (1978, pp. 298-305), and Kibler (1982b). It is useful for the design of culverts and channels draining small urban areas, where peak flows are needed. With the addition of some easily developed assumptions about the average shapes of hydrographs in the region,

the method can also be used to define hydrographs for the design of small detention dams. Extension of the method to tropical cities requires only that drainage areas be measured (which is not necessarily straightforward in cities, where surface channels or subsurface pipes may transfer runoff across basin boundaries); that short-period rainfall intensities be measured; and that values of C obtained from other regions and urban styles be checked and modified for tropical conditions through the simultaneous measurement of rainfall intensities and peak runoff rates in small basins.

3.2 Probability Analysis of Floods

If flows have been recorded in a basin with a more-or-less constant degree of urbanization, it is possible to analyze the probabilities of a certain discharge being equalled or exceeded within a year or longer period. Such information is the basis of much engineering design of channels, bridges, and other structures. The concepts, methods, and limitations of probability analysis are reviewed in any textbook on hydrology. It is also common to combine data from all gauging stations in a region by some means of multivariate analysis to provide a method of estimating the probabilities of flood peaks at ungauged sites in the region (e.g. Benson, 1962, 1964; Rantz, 1971; Wong, 1963).

The flow records from most urban basins are neither long enough nor stationary enough for probability analysis. The most common method of applying probability analysis to urban runoff is first to define flood frequencies for the rural condition and then to increase the peak flow of a given frequency by an amount that is related to the amount of impervious area or the proportion of the area drained by artificial channels (e.g. Figure 9). Early examples from the work of Carter (1961), Leopold (1968), Anderson (1970), and Rantz (1971) are summarized by Dunne and Leopold (1978, pp. 324-329). These early, simple methods provide models of what might be accomplished in tropical cities after a few years of measurement. Less useful as models for the tropics are multivariate analyses of flow records of uneven quality from large areas (e.g. Sauer *et al.*, 1983). Such analyses depend upon the slow, expensive accumulation of massive amounts of data, requiring much subjective judgment for their interpretation. The nature of the flow data and of some of the controlling variables preclude

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the use of very rigorous statistical methods, and the prediction errors are as high as those from simpler methods.

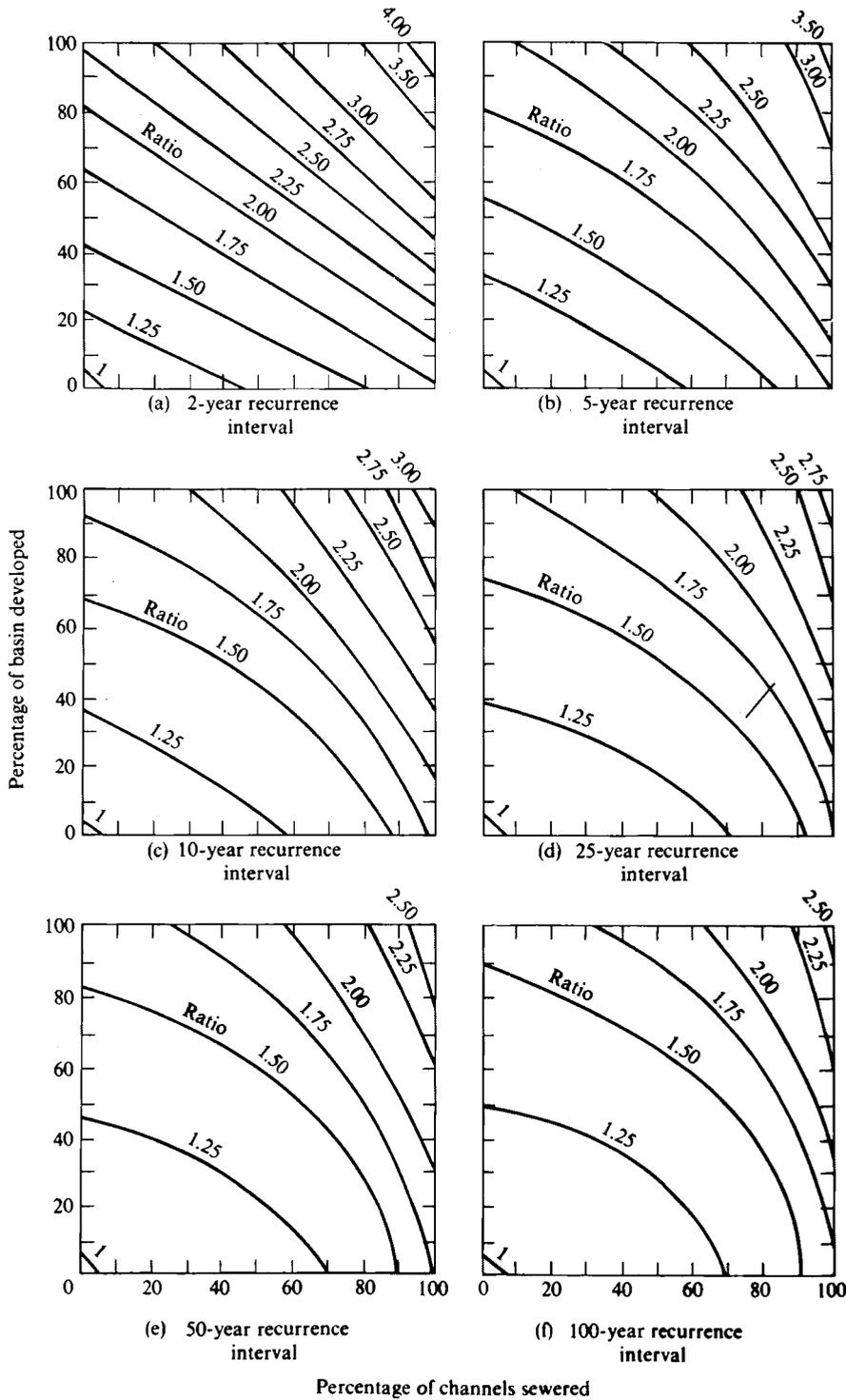


Figure 9. Ratios of peak discharges for urban basins to those for rural basins for floods of various recurrence intervals. Development of 100% of the basin is roughly equivalent to 50% of the area being impervious (Source: Rantz, 1971).

3.3 Unit Hydrograph

The unit hydrograph for a drainage basin defines the time distribution of a unit depth of runoff (e.g. lmm or lcm) generated by a rainstorm of fairly uniform intensity occurring within a period of time, which depends upon the area of the basin and is found by trial and error. The concept, though approximate, is useful because many of the basin characteristics, such as size, shape, and channel gradient, which affect the timing of runoff (i.e. the shape of the flood hydrograph) are constant from storm to storm. This is particularly true in urban basins. Use of a unit hydrograph for runoff prediction is based on the assumption that the shape of the hydrograph thus remains constant from storm to storm, so that there exists a linear relationship between the volume of storm runoff generated and the discharge at any time. This approximation allows the ordinates of the unit hydrograph to be multiplied by the ratio between the depth of runoff generated in the predicted storm and the unit depth of runoff under the unit hydrograph (Figure 10).

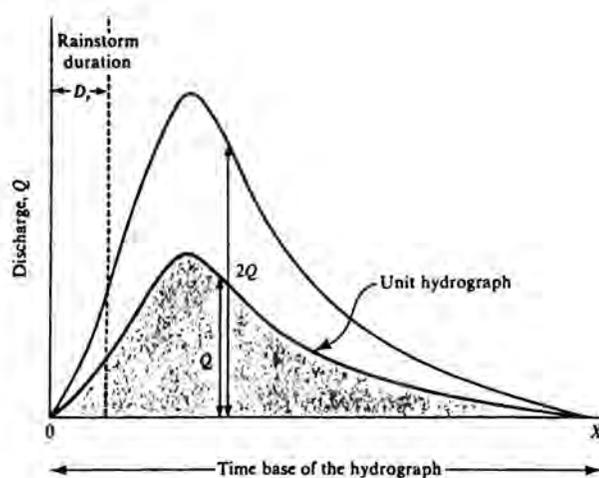


Figure 10. A one-centimetre unit hydrograph (shaded) and a hydrograph consisting of 2 cm of runoff, obtained by doubling the ordinates of the unit hydrograph. (Source: Dunne and Leopold, *Water in Environmental Planning*, Copyright W.H. Freeman Co., 1978).

There are many important, but simple, methodological issues to be addressed in constructing unit hydrographs from field measurements of

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rainfall intensity and runoff, but they are beyond the scope of this paper. They are discussed by Wang and Wu (1972), and by Reid and Dunne (1984). Once unit hydrographs have been established for a sample of basins, parameters of the shape (e.g. peak discharge, time to peak discharge, duration of storm runoff) can be correlated with physical characteristics of the basin. The resulting regression equations can be used to generate synthetic unit hydrographs for ungauged basins in which the necessary physical characteristics have been measured. Snyder (1938) introduced the concept of a synthetic unit hydrograph for rural basins, and it was developed into a widely used tool for small basins by the U.S. Soil Conservation Service (1972). Espey et al. (1966), Rantz (1971), and Hall (1977) have developed unit hydrographs and their synthetic counterparts for urban basins. The procedures, methods of checking them by simple field measurements, and worked examples are provided by Dunne and Leopold (1978, pp. 329-350) and by Kibler (1982b).

3.4 Prediction of Storm Runoff Volume and Timing

In the design of flood detention structures or in preliminary identification of those portions of a drainage basin which are likely to produce most of the storm runoff after urbanization, it is commonly useful to predict volumes of storm runoff in chosen design storms. This can be accomplished through local correlations, if measurements of rainfall and runoff are available.

Another technique for estimating runoff volumes involves subtracting from rainfall an index of the total amount of water abstracted from the storm runoff process by interception, evaporation, and infiltration (Aron, 1982). The conceptual analyses of these abstractions are usually too detailed to represent our knowledge of the physics and spatial complexity of the processes. Most of the analyses are based on data from rural landscapes with poorly conceived extensions to urban areas where they create an illusion of understanding. For example, the use of infiltration equations in heterogeneous urban areas constitutes little more than a technique for providing two or three free parameters which can be adjusted during calibration of runoff models against rainfall and runoff data. It is simpler and clearer to obtain a few local measurements of rainfall

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and runoff volumes and to develop from these a summary "lumped" index of abstractions, such as the Φ -index, which is defined as the average rate of abstraction during a storm (Aron, 1982; Kibler, 1982b, p. 122). Rantz (1971) extended the method to urban basins.

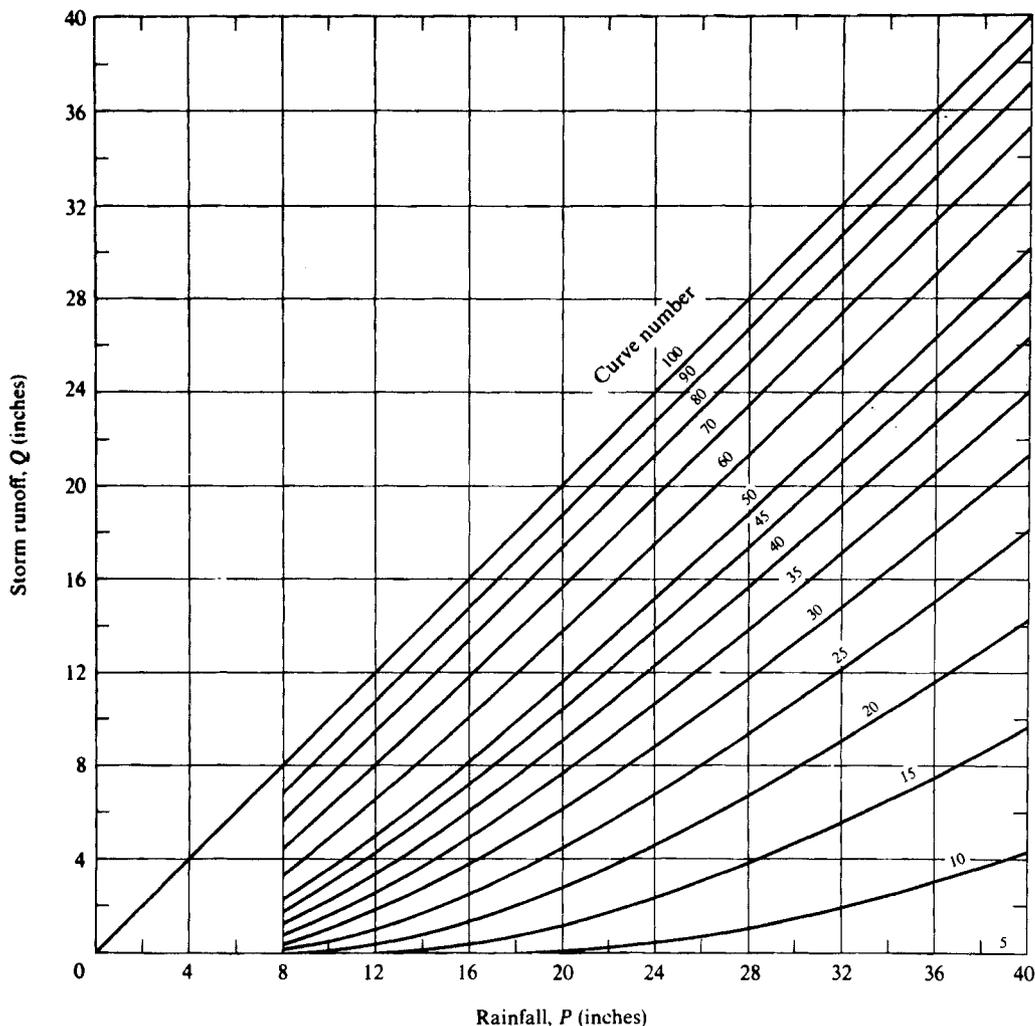


Figure 11. Chart for estimating the volume of storm runoff from total rainfall for various soil-cover complexes indicated by curve numbers. (Source: U.S. Soil Conservation Service, 1972).

A third useful method of predicting runoff volumes as well as the entire hydrograph is the U.S. Soil Conservation (1972) method of using curve numbers, (Figure 11), which are empirical indices of the hydrologic response of soil and vegetation covers, developed from runoff records in small basins in the United States. As such, the values may need to be

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modified on the basis of tropical measurements, but they represent a good starting point on which to base preliminary calculations as well as analyses of runoff records. The method has been extended recently to urban areas, where the curve number, and hence the volume of runoff per unit of rainfall increase with the extent of impervious cover (Figure 12). If the entire hydrograph is needed, the hydrologist may use a dimensionless unit hydrograph such as the one shown in Figure 13 to distribute runoff during the storm. The maximum value on the mass curve is the computed runoff volume and the slope of the mass curve at any time indicates the discharge. Kibler (1982a) and the original publications (U.S. Soil Conservation Service, 1972; 1975), present more details, and Dunne and Leopold (1978, pp. 339-340) emphasize the need for, and simplicity of making, a few field measurements to check and modify local application of these methods.

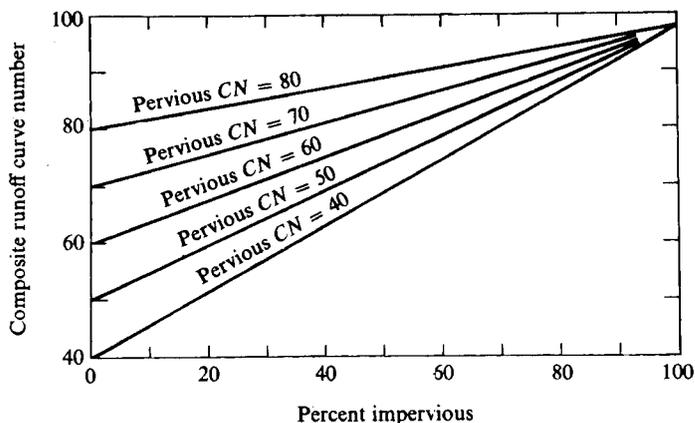


Figure 12. Composite runoff curve numbers for combinations of impervious area and curve number for the remaining unpaved area. (Source: U.S. Soil Conservation Service, 1975).

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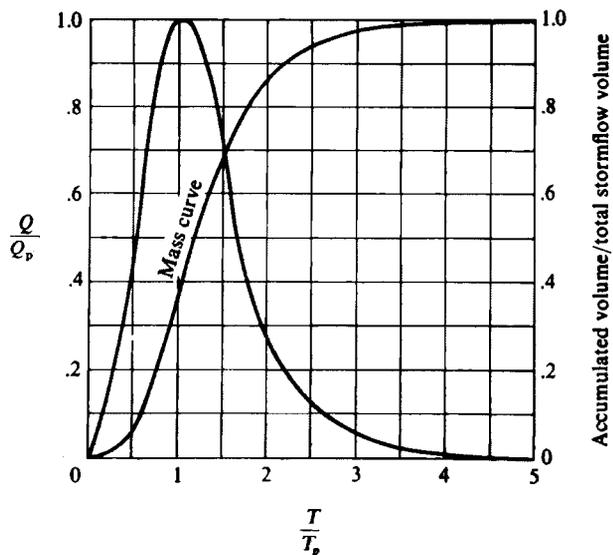


Figure 13. Dimensionless unit hydrograph and mass curve of storm runoff, based on averaged hydrographs from representative small drainage basins, Q_p and T_p are discharge and time of peak flow, respectively. (Source: U.S. Soil Conservation Service, 1972).

3.5 Flood Routing

A frequent task in urban hydrology involves assessment of the value of delaying storm runoff by diverting it through natural lakes, ponds, or bogs or by constructing small dams, as described above. It may also be necessary to examine the effect of some alteration of the land surface or of storage on the flood hydrograph downstream. These tasks require the consideration of how storage in a lake, channel, or floodplain affect the timing and shape of the flood wave. The procedures developed for this purpose are known collectively as flood routing, and there are two types of procedures: hydraulic routing and hydrologic routing. The former is required for complex or expensive projects, including networks of storm sewers, when one wishes to define the water elevation, pressure, velocity or area inundated at many places in a network of flows. The methods require large quantities of data and of computation, and are beyond the scope of this paper.

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Hydrologic routing is simpler and can be computed quickly by hand on the basis of a few specifications or a few field measurements. It provides discharge hydrographs at a few chosen points, and therefore water elevation and open-channel flow velocities can be determined also in a straightforward manner. The principles underlying hydrologic routing are: the continuity of mass (i.e. inflow to a reservoir or channel reach minus outflow equals the change in storage in some time interval), and that there is a relationship between storage volume and outflow (in the reservoir case) or between storage and both inflow and outflow (in the channel case). This latter relationship must be defined on the basis of engineering design of some structure of known hydraulic characteristics and by field measurements of water elevation and discharge. The details of computation are described by Dunne and Leopold (1978, pp. 350-363), Viessman *et al.* (1977), and other hydrological textbooks. A typical result is shown in Figure 14, which emphasizes how the designer's choice of an outlet geometry for a detention basin influences the degree to which a flood hydrograph is diminished during storage. Other worked examples are given in hydrological texts.

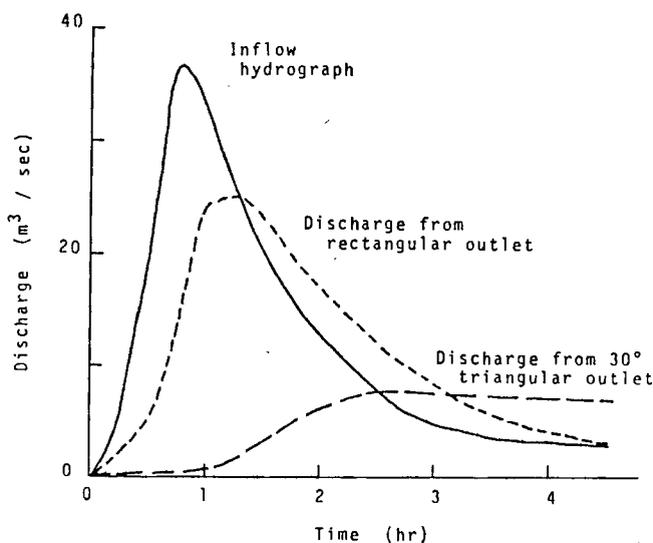


Figure 14. Hydrograph of storm runoff from a small drainage basin entering a detention basin with vertical sides and a water-surface area of 4 hectares, and the resulting outflow hydrograph from (a) a rectangular, sharp-crested weir, 10 m wide and (b) a 30° triangular weir.

4. FIELD MEASUREMENTS

One frequently hears two complaints about the conduct of hydrology in the tropics: that there are no or few local measurements, and that prediction methods developed for temperate regions are applied to tropical conditions in an inappropriate manner or with the use of empirical coefficients that have been evaluated only in the temperate zone. The solution to both of these problems is to conduct an intelligently-designed, simple, and cheap program of field measurements, and to analyze and use the resulting data. This proposition is particularly tractable in a tropical urban environment.

In developing countries several excuses are often given for the lack of fieldwork. There is no petrol for travel. There is no money for per diem expenses. There is no equipment. However, many useful field measurements can be made for urban hydrology near home or office, or at sites accessible by public transportation. Most of the necessary field measurements can be made with equipment that can be purchased from the petty cash in any office budget. Useful measurements of the hydrologically important characteristics of urban land use (types of urban areas, percent of area that is impervious, density and gradient of natural and artificial channels, etc.) can be made on aerial photographs that are available in any country, using the large numbers of underemployed technicians who populate many agency offices. The major stumbling block in such a programme is the dearth of scientific and technical leadership at an active level in the relevant agencies. There is a need for hydrologists who can decide on what should be measured, can take personnel into the field and show them how to make simple hydrological measurements, and can explain to them what to do with the results. All of the computations described above, which are the basis of most planning and design for stormwater control, can be made by hand. The absence of a computer is no reason for a lack of hydrological analysis.

The hydrologic data most commonly needed in urban stormwater control are rainfall intensity measured over short time periods, storm runoff, and the hydrologically important characteristics of the urban area.

4.1 Rainfall Intensity

The rainfall-intensity régime to which an urban stormwater-control system will be subjected is poorly known because there are few automatic rain gauges in most cities. Records at these stations are usually short and discontinuous because of equipment failures or lack of servicing. Many recording instruments allow discrimination of time intervals only to 15 minutes, whereas for the analysis of runoff from small urban areas (about 1-100 hectares), 1- to 5-minute rainstorm intensities are usually needed (Wang and Wu, 1972).

The problem of measuring rainfall and of establishing networks of gauges has been reviewed in many other publications, including those of WMO. Therefore, I will not review the subject here, except to say that there is much to be gained from adding cheap, simple, manual methods to the more sophisticated and expensive technology used by most meteorological agencies for measuring rainfall intensity. For example, work crews in urban areas could be supplied with transparent plastic rain gauges and instructed to read the accumulated rainfall in them at 5-minute intervals when their work is interrupted by a storm. They could note the time, location, and the rate of rainfall accumulation. Technicians, school teachers and pupils could do the same at their offices and homes. These results would be fragmentary, of course, but they could be assembled by an urban climatologist or hydrologist to add detail to the pattern of large rainstorms defined from the relatively small number of stationary gauges in the official network. Over a period of years, large storms would be sampled, and hydrologists would have a base for establishing: isohyetal maps of important storms in which large spatial anomalies occurred in the runoff; elevation-intensity relationships; depth-area curves; ratios between maximum rainfall intensities measured in the official network and the maximum point rainfall in the urban area or the average value over 1, 10, or 100 sq. km; and typical mass curves for short storms. There is also much to be learned from surveys of rainfall collected in non-standard containers, such as buckets and troughs during major rainstorms. For this purpose, it is important to empty the office of all technical personnel during or immediately after a large storm, so that they might search the urban area for potential sources of rainfall data (as well as flood marks

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which could be surveyed later to determine peak flood discharges). Such data are only valuable if they are compiled and continually analyzed as they accumulate. Literature which may suggest various useful forms of analysis are reviewed by Gilman (1964) and by Dunne and Leopold (1978, pp. 56-72).

A strategy for increasing the availability of useful rainfall intensity data in tropical cities might include the following actions. First, the needed types of intensity data should be summarized. Second, some automatic gauges should be purchased and placed in a few strategic locations, attention being paid to the reason for placement at the particular sites, to regular checking and maintenance of the instrument, and to a plan for reducing and analyzing the resulting data. Third, a large number of simple non-recording gauges should be purchased or made, and dispensed to work crews, hydrologists and other personnel who work and live at various places in the city so that they might visually record short-period rainfall intensities. Fourth, these fragmentary data should also be compiled and analyzed soon after collection.

Over a long-period of time the data base will grow sufficiently for standard intensity-duration-frequency analysis. Longer records of 6-, 12-, and 24-hour totals, which may be available from major weather stations, can also be rendered more useful for urban hydrology when a few short-period intensities become available to indicate typical ratios between shorter and longer maximum intensities in a storm. Hershfield (1977), Hershfield and Wilson (1958) and Reich (1963) make suggestions for ways of extending the usefulness of such records. Even in the short term, the data accumulated will become directly useful for planning and design. A long rainfall record is not necessary, for example, in the evaluation of C-values for the Rational Runoff Formula or for the Unit Hydrograph procedure. Reid and Dunne (1984) used visual observations of rainfall accumulated in a plastic cylinder together with simultaneous gauging of culvert outflow using a bucket and a watch to define unit hydrographs from various types of road surfaces. It was necessary to measure the values in only a few surface storms in order to define the unit hydrograph well.

4.2 Runoff

There are also many technical manuals which outline the instruments useful for measuring and recording flow and water-surface elevation in small streams. With these instruments, it is possible to make a continuous record of stream discharge, or intermittent visual records, or to record only the peak elevation of runoff during a specified period. It is possible to collect such data at a natural cross-section of stream channel or where the shape of the cross-section is artificially controlled by a concrete weir, bridge support, or culvert. It is usually possible to make more precise measurements at controlled cross-sections, but if one is interested mainly in high flows, measurements at natural cross-sections are usually of adequate precision for the analytical and prediction techniques for which they form the basis.

Several important points should be kept in mind when it is decided to invest resources in obtaining flow records as a basis for prediction and design in urban hydrology. First, the purpose of the measurements should be clear. If, for example, a probability analysis of peak flows is required, then it is necessary only to install cheap, vandal-proof crest-stage gauges, which record peak water-surface elevation, and to calibrate each channel cross-section so that elevation values can be converted to discharge. On the other hand, if a unit hydrograph study is required, it is necessary to have continuous records or at least frequent visual observations of water-surface elevation at a staff gauge on the stream bank. Second, it is necessary to gauge appropriate representative basins, rather than basins which are conveniently located or chosen more-or-less at random. Third, a gauging site must be selected which has no backwater problems, complex geometry, or other characteristic that would cause large measurement errors. Fourth, it is necessary to promote good measurement procedures. For example, since runoff responds so quickly to rainfall in urban areas, it is necessary to record both quantities precisely by checking the synchronicity of clocks on recorders or those of observers. It is also necessary to check recorders frequently and to maintain them in good working condition. Fifth, technical personnel should visit and take care of instruments during floods. They should check that instruments are working and should fill gaps by visual observations in cases of failure. High discharges should be

measured directly with a current meter to define the upper portion of the stage-discharge rating curve. If the flood has already receded, flood marks should be surveyed and peak discharge computed by the slope-area method (Chow, 1959; Dalrymple and Benson, 1967). Finally, the flow data from large storms should be compiled promptly and analyzed together with the associated rainfall records.

When planning a measurement programme and when analyzing its results, it is important to realize that in many basins undergoing urbanization, the hydrological conditions are changing rapidly. Therefore, it is necessary to obtain quickly a few records of storms at various stages of urbanization and to document the hydrologic condition of the basin at each stage. It is not appropriate to analyze the probability of flows on the basis of a record collected during this non-stationary period.

4.3 Drainage Basin Characteristics

In most tropical cities, the best record of land-use is aerial photography, which has been repeated several times during the past 40 years. The increased future use of infra-red photography will facilitate the discrimination of vegetation on soil-covered areas and unvegetated impervious areas. With the aid of a simple stereoscope and aerial photographs, it is possible to make preliminary maps of basin perimeters, which must then be checked on the ground because artificial channels or pipes may transfer stormwater across drainage divides. Aerial photographs can also be used for producing urban land-use maps, which classify areas on the basis of their hydrologic characteristics. The map units should be based on the local range of hydrologically important characteristics, and might include some variants of the following land-surface types: commercial; industrial; bare construction sites; high-, medium-, and low-density residential areas (defined according to the number of dwellings per hectare); agriculture, forest, etc. Such maps are useful for choosing representative measurement sites and for extending results from them to the whole urban area. Aerial photographs can also be used for measuring parameters such as the proportion of the land surface that is impervious, the length and area of roads and tracks, or the extent of artificial channels.

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For most hydrological purposes, it is neither necessary nor possible to wait for the results of citywide or national mapping projects. The hydrologist can usually make the necessary measurements quickly and cheaply from available data sources. However, for forecasting the long-term hydrological consequences of city growth, it may be necessary to couple measurements of hydrologically important land-use characteristics with some model or plan which predicts the spatial pattern of urban growth and its interaction with local topographic and climatic conditions.

5. CONCLUSION

The most significant water-related issue in most tropical cities is the control and safe disposal of storm runoff. The processes by which urbanization increases storm runoff are understood under most circumstances. Various strategies for reducing or delaying storm runoff have been developed, but their usefulness varies with local conditions. The technology of runoff control is still evolving rapidly. For small urban areas, the technology is simple to design and construct. Elaborate citywide networks of storm sewers, with loops, over-pressured segments, diversions, and complex outfalls are difficult to design and construct, and are usually installed by large, specialized engineering firms, using methods reviewed in Yen (1982).

The basis of any plan for controlling urban storm runoff must be a programme for measuring and analyzing data on rainfall intensity, runoff, and the hydrologically relevant aspects of urban land use. Some suggestions for such a programme, together with simple methods of analysis and prediction, are reviewed above.

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