CHAPTER 1

DESIGN ALTERNATIVES

THE ROLE OF THE DRAINAGE ENGINEER

Urban development is spreading over more and more of the earth's surface. The problems associated with urbanization are compounded as the density and extent of development proceeds (Schneider, 1975). The effect of particular concern is the elimination of most natural processes and their replacement by man-made streamlined procedures. One such system is the water cycle. Excess rain is no longer free to flow overland and meander along unlined channels. Instead, precipitation is on roofs or concrete or bitumen pavements, and it washes off conveying pollution created by mankind. Stormwater drains replace streams. They intensify runoff and destroy nature's balance. Channels flow more strongly in times of flood. Erosion and deposition occur. Natural self-purification processes such as reoxygenation may be destroyed as the ecology is affected. Ground water is starved due to increased surface runoff. Vegetation, dust problems and the habitat may be affected. These factors demand a thorough environmental study in parallel with town planning and design of the infrastructure.

Civilization has focussed attention on the urban system. The convenience of central facilities, mass transport systems and easy trade, have encouraged a concentration at nodes we call towns or cities. The resulting disadvantages, such as pollution and elimination of natural fields and streams, follow because man's ambition exceeds his desire for a balanced life. Many of the problems are unavoidable except at extreme expense. It is no use blaming the engineer for problems which manifest. The engineer is able to solve problems at a minimum of cost, but must work within a budget. The municipal councillor or national politician is also limited in his abilities and budget. He must balance the ballot against the fulfillment of ideals.

This book is aimed at the drainage engineer. It provides ideas and technology to compromise between limited budgets and best solutions. It presents design methodology for evaluating a best design to be achieved for stormwater drainage. Stormwater design objectives have changed over the years. The engineer used to attempt to remove stormwater as rapidly

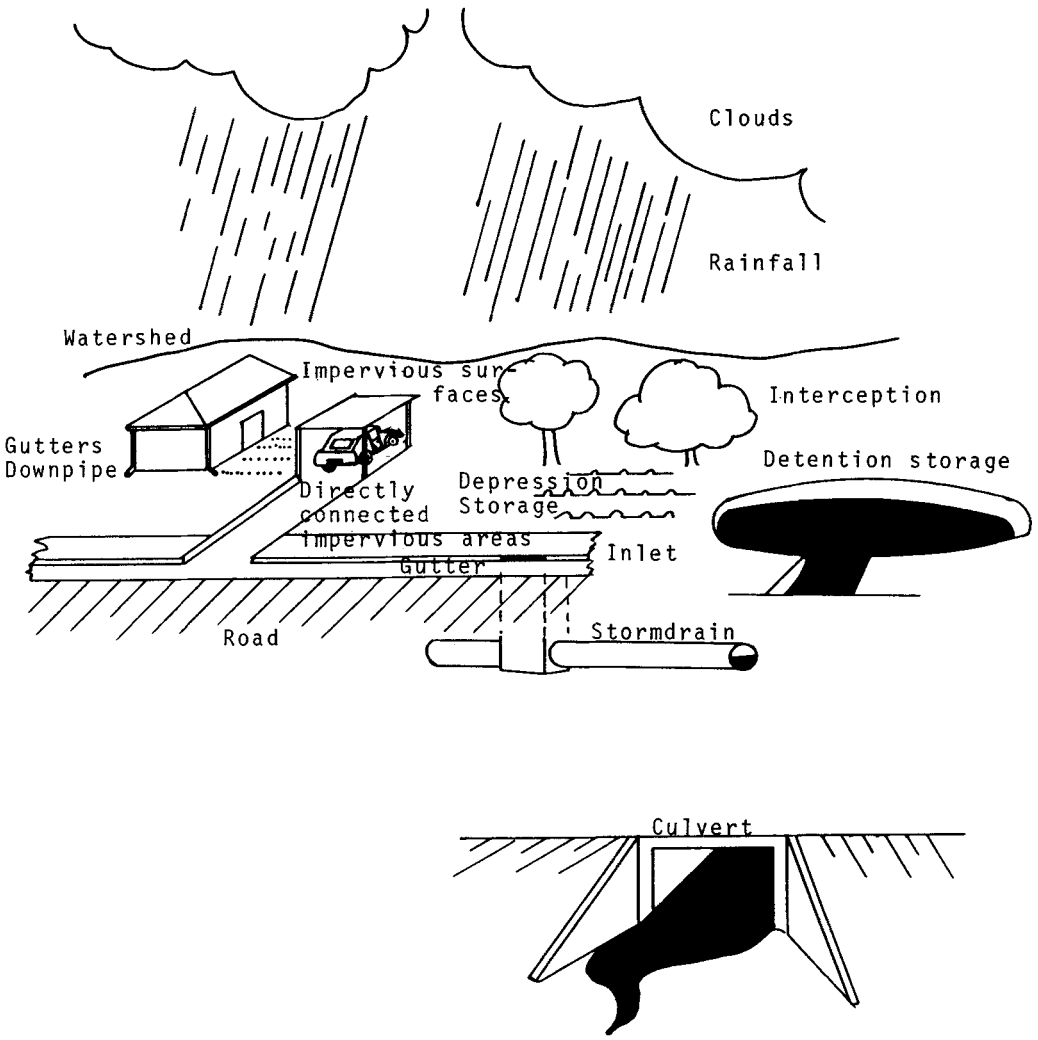

Fig. 1.1 Urban drainage processes

as possible. Nowadays the consequences of downstream flooding and alteration of the water cycle's regime are recognised.

The science of urban drainage has received considerable attention in recent years, especially in the United States. Legislation has forced engineers to think carefully about the drainage process. As a result there have developed numerous research groups and mathematical models for simulating the runoff process.

The components of stormwater systems (Fig. 1.1.) can be split into two groups: (Yen, 1978). One, the surfaces, basins, groundcover, gutters and inlets which are evident to all. The other is the major component from the engineer's point of view; namely the drains, controls, underpasses, treatment or holding works, and final discharge rates and effluent quality.

STORMWATER MANAGEMENT PRACTICES

The construction of a stormwater drainage system is not the only way to avoid flooding or pollution. The day-to-day operation or management of the catchment will have an important bearing on runoff quantity and quality. On-site detention, retention and regular cleaning could relieve the drains of a considerable load. A reasonable management policy will be assumed at the time of design. Failure to maintain this programme could result in exceedance of the capacity of the system. On the other hand improved management could alleviate the load on an underdesigned system, or enable more intensive development to take place in the catchment. Control measures may be structural (e.g. diversion, storage or channel improvements) or policy (e.g. insurance, flood warning systems or building control regulations for flood zones). Trotta et al (1977) described an automatically controlled drainage system.

Pollution control is the most obvious result of catchment management. Street sweeping, efficient refuse disposal, discharge monitoring and treatment of runoff are some of the possibilities.

Runoff control is a more difficult and more recent practice. Stormwater retention, groundwater recharge, provision of rough surfaces to retard flow and disconnection of impervious areas, are all logical practices but not explicity required until recently in the United States and Europe. The methods are still not practiced in many countries.

The accompanying Table (1.1) summarizes some practices and their accomplishment. The efficiencies and costs are discussed by Wanielista (1979).

TABLE 1.1

Stormwater Management Practices

Purpose	*Method*	*Reason*
Peak flow rate attentuation	Storm monitoring	Flood prediction
	Detention storage	Flood routing
	Channel storage	Flood routing
	Gravel surfaces	Retardation
	Rooftop storage	Routing and lag
	Parking lot storage	Routing and lag
	Disconnected impervious areas	Infiltration, attentuation
Runoff volume reduction	Retention storage	Removal of flow
	Diversion	Subtraction of flow
	Soakaways	Infiltration
	Basin recharge	Increase groundwater
	Infiltration	Flow reduction
	French drains	Seepage
	Swales	Retard flow, infiltration
	Porous pavements	Infiltration
	Contour ploughing	Infiltration
Provision for flooding	Insurance	Compensation
	Building control regulation in flood zone	Limit damage
	Flood warning	Evacuation or diversion
Catastrophy aversion	Evacuation	Structural failure
	Sandbagging	High water levels
	Emergency overflows	Water flow control
	Weir strengthening	Dangerous flood levels
	Water tanks	Polluted water supplies
Erosion Control	Berms	Settling
	Vegetation	Stabilization, retardation
	Rockfill	Flow control
	Mulching	Runoff Control
	Fertilizing	Encourages vegetation
	Settling basins	Catching sediment
	Sediment removal	Basin renewal
	Screen	Detritus
	Centrifuge	Separation
	Contour ploughing	Surface Storage
Pollution control	Street sweeping	Catching solids
	Street vacuuming	Catching fines
	Street flushing	Total removal
	Street deicing	Ice removal
	Catching first flush	Most concentrated
	Refuse removal	Avoidance of pollution
	Storage	Settling
	Aeration	Biochemical oxidation
	Chemicals	Neutralization, precipitation
	Comminuters	Grinding large solids
	Flotation	Scum, emulsion, oil
	Legislation	Enforcement of standards
	Summons or fines	Discouragement
	Waste dump isolation	Runoff detention
	Grassing street verges	Catching fines, scums

Fertilization methods	Minimization of washoff
Land disposal	Removal of recoveries

Many of the systems for flow reduction must be incorporated at design stage. These include means of retarding the concentration time (increased surface roughness and detention basins), methods of catching part of the volume of runoff (diversion systems and retention basins), and means of reducing excess runoff (percolation basins, catchment cultivation and restricted capacity drains) (Carcich, et al 1974) combined with surface channels.

The system or combination of systems to adopt for any particular catchment will depend on the catchment characteristics, such as topography, soil type and cover, climate (rainfall and evaporation pattern) desired risk and the consequences of flooding. It should be recalled that interference with the runoff process complicates the relationship between storm recurrence interval and the recurrence interval of a failure of the stormwater system to do its duty. This aspect was studied by Kamedulski and McCuen (1978).

In order to at least reduce the flood flows from developed areas to the figures before man-made development proceeded, it is useful to understand the runoff process and its assessment. Urbanization reduces the average permeability of the ground by the construction of pavements and buildings. The concentration time is reduced due to the increased runoff intensity, smoother surfaces and man-made channels. The design storm is therefore a shorter, more intense storm than that resulting in maximum development. Natural basins or depressions may be levelled, thereby increasing excess runoff even further.

SAFETY FACTORS

Any design or structure will normally be constructed with certain safety margins. This is not the same as the risk of overtopping or exceeding the capacity of the system. A storm of a certain recurrence interval will be selected from economic considerations using probability theory as outlined in a later chapter. (Walesh and Videkovich, 1978). The present consideration is the margin of safety on top of the estimated design figure.

In the case of structures such as pipes, manholes, kerbs or weirs the factor of safety with respect to strength is established routinely by designing according to a structural code of practice. Thus design stresses may be 50 percent of yield stress of steel or 30 percent of the crushing strength of concrete. Hydraulic designs usually have little

such margin. Thus freeboards may be calculated from wave height formula and not an arbitrary additional depth. In stability calculations for dams or weirs a reasonably severe loading condition with extreme uplift and minimal resistance factors, should be allowed. In view of the dire consequences of failing of such a structure by overturning, the hydraulic engineer should consider applying safety factors in addition to designing for a high recurrence interval hydrological event.

The acceptance of mathematical models for hydrological and hydraulic analysis of a drainage system may lull the design engineer into a false sense of security. Impressive sensitivity studies and verification runs by computer may indicate reasonable margins of safety, but they may remain unknowns in the input data, the programming assumptions or in the interpretation of output. The engineer who is responsible for the design drawings should therefore continue to apply normal safety factors based on judgement and the consequences of a failure.

Increasing legal action against drainage engineers in the United States of America has highlighted the need for precautions in design. Hopefully this will not result in excessive conservatism and increase in costs. The balance between economy of design and consequences of failure must not be imposed on the designer or constructor but on the responsible authority or its insurers. It is good practice to inform the affected public of design risks, flood levels and about insurance.

Where design alternatives exist which have similar costs it is sensible to select the least-risk system. Thus an open channel has usually a higher margin of safety against flooding than a closed conduit. This is because the capacity increases rapidly with increased depth in a channel.

Adjacent low-lying parking lots and parks, even if not designed detention ponds, could in an emergency serve as such. Thus the drainage system should be integrated with the town planning.

DETENTION AND RETENTION PONDS

To compensate for runoff intensification due to urbanization, stormwater could be stored in man-made basins within the catchment. The ponds can be sited in non-essential areas, e.g. parks, recreational grounds or parking lots, (Miles, 1979). In parks, the storage may be provided in depressions, which can subsequently be drained (or water permitted to percolate or evaporate in isolated situations, termed dry basins). Alternatively, the storage may be in channel freeboard on ornamental ponds or recreational lakes (referred to as wet ponds).

Drains could be led directly into the basins, in which case all initial flow would be caught before the drain overflowed and water filled the downstream drains. In this situation the end-weir arrangement may induce a routing effect by the basin. Thus in addition to retention, the upper levels of the pond would act as a detention system. Detention is the temporary storage of runoff such as in freeboards while retention involves the permanent diversion into evaporation or seepage ponds i.e. flow is not returned to the drainage system. A comparison of different methods was made by Poertner (1978). Detention ponds are often referred to as onstream, or outlet controlled, but they are not necessarily so. Offstream ponds are usually inlet controlled.

The pond could be off-channel and water could be diverted from the drainage system. Here an unrestricted inlet such as a channel with a drop into the pond, could be constructed in which case the pond would fill during the initial stage of the storm. In such a situation the pond may not affect the peak flow much in case of extreme event storms. Alternatively, the inlet could be designed to divert flow only above a certain minimum to an off-channel pond. Such a device could be a side channel weir. The rate of diversion would increase with increasing discharge in the drain. Various control devices for influencing the stage-discharge characteristics of pond outlets were described by Hall and Hockin (1980).

Retention can be at the outfall of the catchment, in which case a large-scale pond is often required such as a lake or in a park. The retention may be provided along the drains, or it may be at the head of the drains (on site). The latter may not require any single large volume; it may be sufficient to plant dense vegetation, till the land, or construct terracing.

The difference between retention and detention storage is illustrated in Figs. 1.2 to 1.4. (The reason for the difference in time to peak for high and low return periods will become clear when the section on kinematic hydrology has been studied).

The method of design of retention basins is to select a design risk and plot the corresponding design hydrograph. Select a design discharge rate and indicate this on the hydrograph. The area under the hydrograph above the design discharge is the volume of storage required. It should be borne in mind that the critical storm duration is not that associated with the most intense storm. It will be considerably longer for the maximum volume of runoff. The critical storm duration depends on the pond design and must be determined by trial. For instream detention storage, the volume required may be estimated by drawing a straight line

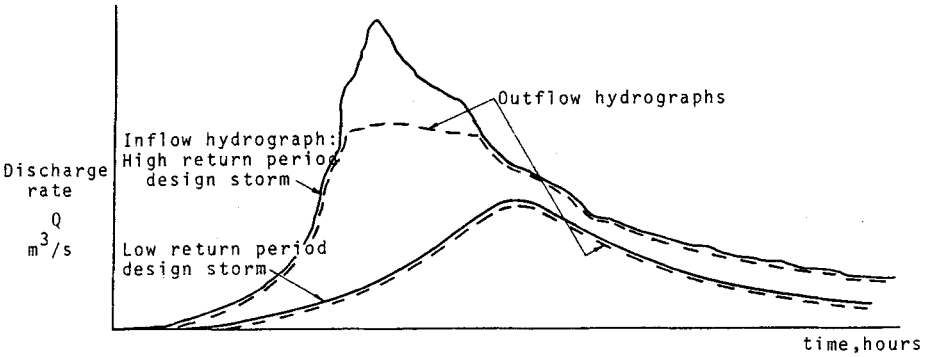

Fig. 1.2 Effect of off-channel retention storage on runoff, assuming an inlet weir to pond off drain

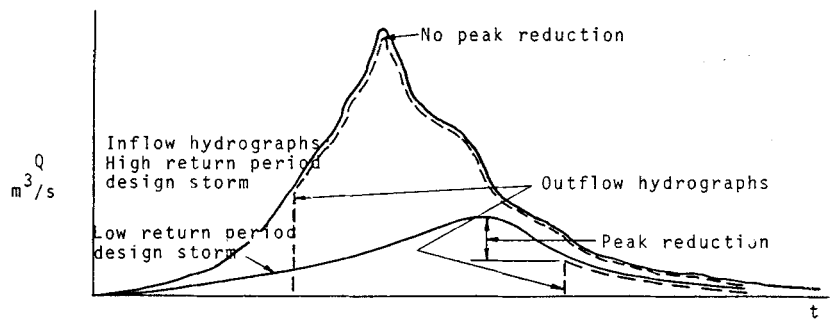

Fig. 1.3 Effect of in-line retention storage on runoff

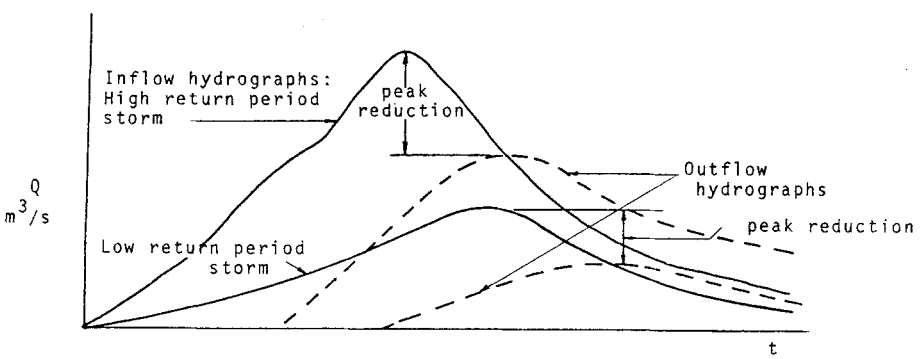

Fig. 1.4 Effect of detention storage on runoff

from the start of the inflow hydrograph to a point on the recession limb equal to the desired peak outflow rate. The area above the line below the hydrograph is an indication of the pond volume. Flood routing using numerical or graphical methods (e.g. Wilson, 1974) must be performed for the ultimate design. Approximate mathematical methods have also been proposed (Sarginson, 1973). It may be necessary to correct for the storage - discharge characteristics of the inlet to the pond, which means the cut-off line is not horizontal. In the case of in-line retention storage, the volume under the design hydrograph is stored. For detention storage, alternative storage - discharge characteristics will have to be tried until a satisfactory compromise for a range of design hydrographs is achieved. A reduction will be achieved on all recurrence interval design storms.

To determine the critical inflow duration for an instream detention pond with controlled discharge, Wright-McLaughlin (1969) proposed a graphical method. The ordinates of the intensity-duration curve are multiplied by the storm duration and runoff coefficient, C. The resulting ordinates are plotted in a mass-flow curve of volume versus time. Now for any discharge (outflow) rate which plots as a straight line on the same plot the storage required is the maximum difference between the massed inflow and outflow curves.

For an intensity-duration relationship such as

$$i = \frac{a}{(b+t)^c} \qquad (1.1)$$

an analytical solution for maximum storage is possible. Here i is storm intensity, t is storm duration, and a, b and c are constants for any locality and storm recurrence interval T. Now storage required is

$$S = \frac{CAat}{(b+t)^c} - Qt \qquad (1.2)$$

$$\text{For maximum } S,\ dS/dt=0, \qquad (1.3)$$

$$\text{Hence } Q/CA = a\{b+t-ct\}/(b+t)^{c+1} \qquad (1.4)$$

Thus one can plot S/CA versus Q/CA with t as a parameter. Fig. 1.5 is such a plot prepared by Watson (1981) for $a=1200T^{0.3}$ (mm/h), b=14.4 min and C=0.883. From this chart one is able to calculate the critical storm duration and storage S for any desired outflow rate Q, provided CA and T are known.

PERCOLATION BASINS

In theory, the ground can provide storage capacity equal to any storm which could be anticipated. The volume of storage per unit area is Dn where D is the depth to the water table and n is the soil porosity.

n is the ratio of volume of voids between soil particles to total volume, and is usually between 0.3 and 0.4, irrespective of soil particle size. Thus 1 m of soil could contain at least 300 mm of rainfall provided it could be absorbed sufficiently rapidly. Unfortunately the permeability of the soil usually limits the rate of infiltration. The rate of seepage per unit area is $\bar{v}=ki$ (1.5)
where $\bar{v}$ is the apparent seepage velocity (flow rate per unit area). k is the permeability, which may be as low as 10^{-9}m/s for impermeable clays. For granular soils it may be approximated by the equation
$k=gd^2n/800\nu$ (1.6)
where d is particle size, and ν is the kinematic viscosity of water. Thus for 1 mm particle, $k = 9.8\times10^{-6}\times0.3/800\times10^{-6}=0.004$ m/s. This is greater than any rainfall rate. The hydraulic gradient i can reach a maximum value of unity. The actual rate of penetration of water is
$v = k/n$ (1.7)
Thus the depth required to store p mm of rain is p/n and the time to infiltrate it is p/k.

Factors affecting the thoretical percolation will include the initial moisture content, which is water suspended on soil particles by surface tension, and this may be anything up to the full porosity for fine clays, although it is lower for coarse granular soils.

Air will also have to be released from the aquifer as water permeates down. The upflowing air will tend to suspend the water permeating downwards and may cause airlocks or impermeable barriers. Perched water tables may also form on the slightest lense of impermeable material. Attention should be paid to the drainage of the aquifer subsequent to saturation. The drainage rate will increase as the water table is raised and this may result in unexpected springs, marshes, soil erosion or even embankment instability.

Effect of holding on water quality

The retardation of escaping water by basins or seepage pits will reduce the rate of reoxygenation. In the case of wastewaters, or polluted runoff, this may result in obnoxious smells, or affect the ecosystem. If the water turns anaerobic this problem is severe.

Oxygenation plays an important part in natural purification processes, by reducing bio-degradable material, emulsifying solutions or oxidizing pollutants. The rate of oxygen absorption depends not only on the water surface area exposed, but also on the water depth and more particularly on the energy input Turbulence in flowing water is a natural mixing

device and considerably improves aeration. Stagnant water will lack this

On the other hand, if treatment is required before the water can be discharged into natural water bodies, the storage pond may be the place for it. (Wipple, 1979). Aerators, skimmers or sediment removal facilities may be constructed in ponds.

It must be realized that a pond will act as a natural silt trap and the ground may become unusable after a storm. The same adverse effect applies to floating pollution, such as oils, or to debris such as broken glass, tin cans, etc. The use of recreation fields for storage is therefore open to question.

On-Site Detention

Where practicable, property developers and owners should be encouraged to minimize direct runoff by directing gutters and downpipes to pervious or planted areas. The detention is thus spread over a large area and the depth of water are not at all inconvenient. Where the entire property is paved or covered, holding basins, porous layers or restricted capacity stormwater discharge pipes should be considered. In many countries legislation is sufficiently advanced to force owners to discharge at a rate not greater than the virgin land would. Economic incentive to provide even greater control may be difficult though.

Such flow attenuation also minimizes soil erosion and may reduce the concentration of pollutants such as may settle or float or even have time to react. The concept of gutterless roofs used in some countries, actually retards runoff if runoff from the roof is direct onto the garden. Although gutters detain runoff, they concentrate it with a resulting net increase in peak flow.

Parking-Lot Storage

Parking lots offer one of the most convenient areas for ponding of water in densely built, commercial or industrial areas. By careful grading or dishing of the area, the ponds can be confined to isolated areas which are rarely used except at peak shopping hours.

Porous verges (Fig. 1.6) may be constructed adjacent to the parked area to absorb or convey the surplus runoff. They will also arrest sheet flow and retard flow into drains.

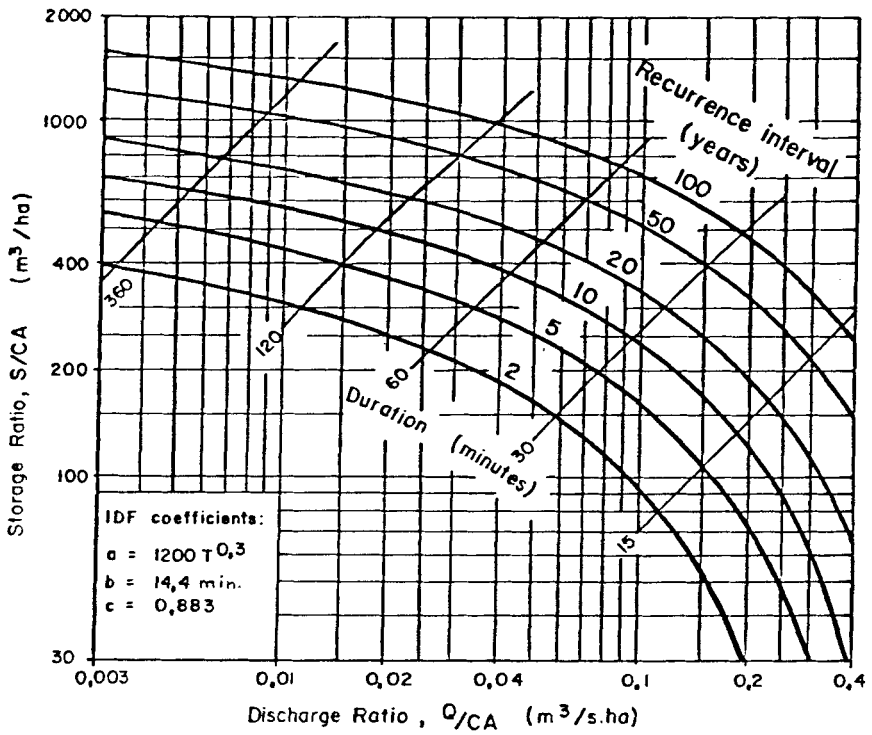

Fig. 1.5 Example curves for the preliminary design of storage ponds

Rooftop Detention

Flat roofs may be constructued with parapets to contain precipitation. Although the idea offers an otherwise unused area, it may increase the cost of construction considerably. Special attention will have to be paid to waterproofing. Additional loading must be allowed for in the structural design. Well designed control inlets to downpipes are

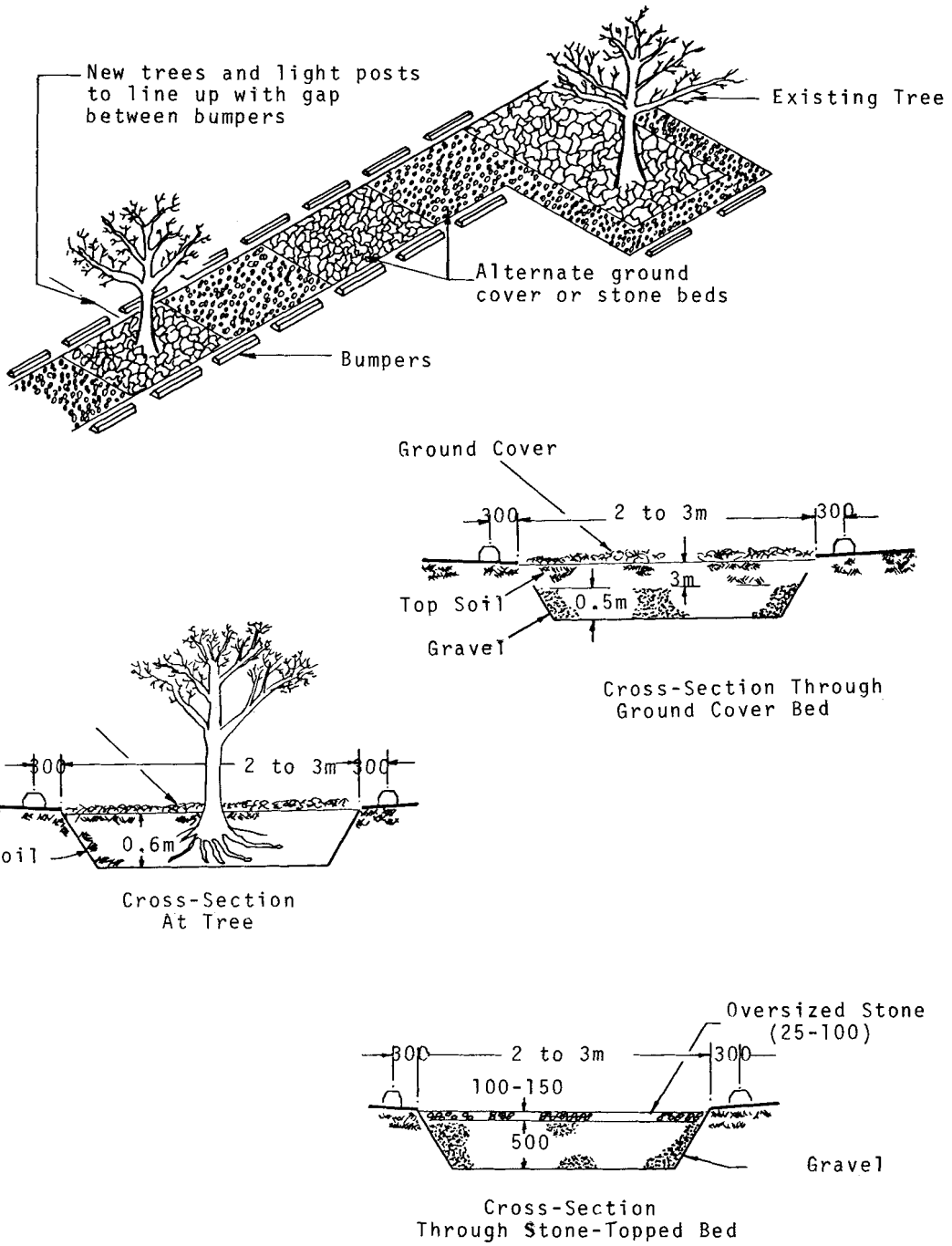

Fig. 1.6 Details of median strip for parking lot drainage

required. These must also be covered by grates to minimize blockage by debris.

OVERLAND AND CHANNEL RETARDATION

Although detention storage has been proposed as one solution to the attenuation of floods, this is in fact an artificial way, and suffers a number of disadvantages. Not least is the fact that valuable space is required to store floods. The factor of risk becomes increasingly difficult to assess. Whereas storage may be provided for a flood of a certain recurrence interval (the so-called design flood), what about greater floods? The attenuation effect is certainly not proportional to the flow rate, and in fact the reduction in the peak may be negligible in the case of larger floods than the design flood. There is also the question of storm duration to consider. The design storm duration for detention storage is invariably greater than for the channel design storm. The relationship between storage capacity and risk is therefore complex.

A better solution in many cases is to provide channel storage. This is a form of detention storage. Channel storage is effected by decreasing the flow velocity. This again has two effects. It increases the concentration time of the catchment thereby reducing the design inflow since storm intensity is known to reduce with duration for any particular recurrence interval. The channel storage also provides a way of holding back water and so reducing the peak discharge rate lower down.

One way to reduce flow velocity is to roughen the channel perimeter. The cross sectional area required for any discharge is therefore increased, but certainly not in inverse proportion to the flow velocity. This is because the discharge rates actually reduce through the collecting system if the channel system is so designed to retard flow.

The flow at any section for any storm intensity could be obtained by routing excess rain down the system, but a simpler approach would be to estimate the concentration time, or time to reach equilibrium for any storm and design the channel to convey the excess runoff corresponding to that storm. The kinematic approach could be used to estimate concentration time at any section. Flow retardation can be carefully controlled and easily designed if rockfill is used as a channel lining. The design of rockfill linings is considered in the chapter on open channels.

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