11 HYDROLOGIC DESIGN CONCEPTS

11.1 GENERAL

Those involved in the design of drainage and stormwater facilities are not the only ones who must consider the natural passage of water resulting from storm events. Anyone involved in land development and the construction of homes, as well as commercial, industrial and institutional buildings, must give consideration to new stormwater runoff management practices.

There are many types of hydrologic analyses required in building construction. When clearing land for development, it is important to provide sediment control to ensure that eroded soil does not enter into waterways and wetlands. Sediment control depends on the area of the land being cleared, the amount of rainfall that can be expected during the period where the soil will be exposed to rainfall impact and site characteristics such as the slope and soil type. In addition to hydrologic considerations during the land development stage, site development must also consider drainage patterns after development.

Site development usually results in significant increases in impervious surfaces, and subsequently surface runoff rates and volumes. In many localities, stormwater control facilities are required. In the upper reaches of a site, within a property lot for example, swales can be used to move water away from buildings and transportation facilities. Concentrated runoff from swales may enter gutters and drainage ditches along streets (Figure 11.1). Swale will also provide reduction in directly connected impervious area (DCIA) and biofiltration function to the site. At sites where land development is expected to result in large amount of imperviousness, detention basins can be used and the design of such facilities requires knowledge of the flow hydrograph of surface runoff into the basin, as well as knowledge about the flow routing through the hydraulic outlet structure.

The design must consider meteorological factors, geomorphological factors, and the economic value of the land, as well as human value such as aesthetic and public safety aspects of the design. The design should also consider the possible effects of inadequate maintenance of the stormwater facility.

11.2 OBJECTIVES

The main objectives of hydrologic analysis and design are to:

- estimate peak flow rates and/or flow hydrographs for the design of conveyance and quantity control facilities
- estimate annual runoff volumes for approximating pollutant loads in the design of water quality control facilities.

11.3 AEP AND ARI

Hydrologic events are described by stating the Annual Exceedance Probability (AEP) or the Average Recurrence Interval (ARI). The AEP is the probability that an event of specified magnitude, or volume and duration, will be exceeded in a time period. The ARI, referred to as the return period, is the average length of time between events that have the same magnitude, or volume and duration. A flood with a discharge of say 50 m^3/s may have an AEP of 0.01, meaning that on the average there is a 1% chance that a flow of 50 m^3/s will be equalled or exceeded in any year. Specifically, the ARI is given by:

$$T_r = \frac{1}{P} \cdot 100 \tag{11.1}$$

where T_r is the ARI in years and P is the AEP in percent. Hence, a 1% AEP has an ARI of 100 years.

The term ARI is used throughout this Manual, and is the recommended terminology to be used in Malaysia.

The concept of ARI is frequently misinterpreted in two ways. First, the ARI of 100 years does not imply that a given flow, say 50 m^3/s, will occur only once in 100 years. Thinking that if a particular event occurs today then it will not occur for the next T_r years is not the proper interpretation of the ARI. This misconception is a deterministic perspective, and if hydrology were so predictable, many of the world's water resource problems could be easily solved. The ARI represents the statistical average number of years between similar events given a very long period of record.

The second common misuse is the failure to recognise the exceedance probability concept. This 50 m^3/s discharge has a 1 in 100 chance of being exceeded in any given year. It is not that the exact value of 50 m^3/s has a 1% probability of occurrence. Technically, the probability of exactly 50 m^3/s occurring is zero. For a continuous random variable, the probability is the area under the probability density function between two distinct values of the variate. There is no area under the curve for just one point.

Occasionally it is necessary to determine the probability of a specific event being exceeded within a specific time. The probability P of an event having a given ARI, T_r occurring at least once in N successive years is given as,

$$P = 1 - \left(1 - \frac{1}{T_r}\right)^N \tag{11.2}$$

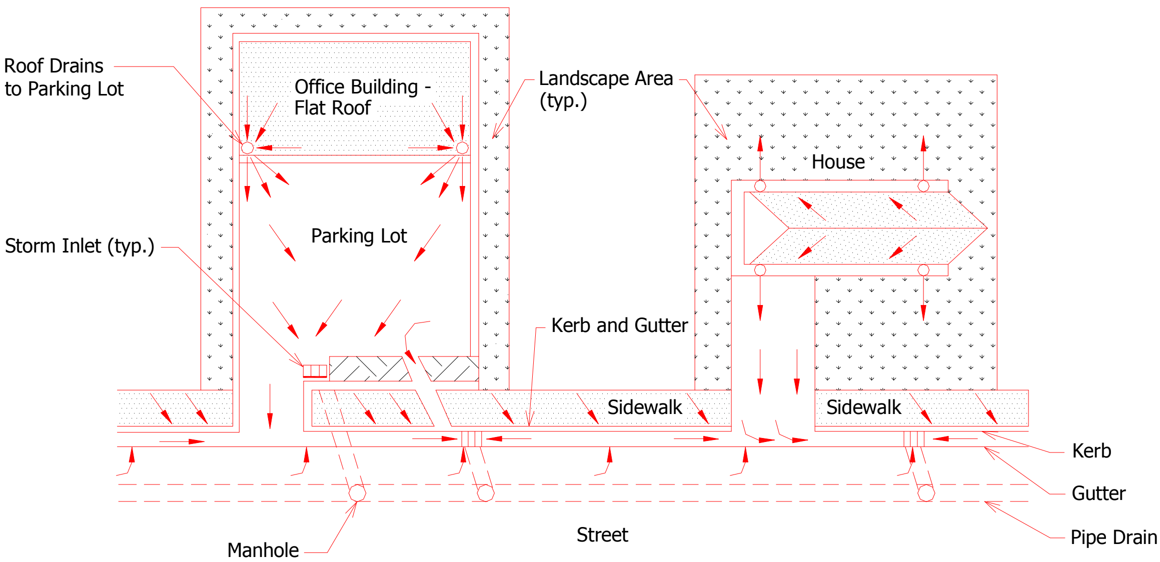
A distinction exists between the probability of an event occurring at least once and exactly once in a given time period. Another form of the risk equation (Equation 11.3) determines the probability of an event occurring a precise number of times in a given period. In this equation,

$$P = \frac{N!\left(\frac{1}{T_r}\right)^N\left(1-\frac{1}{T_r}\right)^{N-I}}{I!(N-I)!} \tag{11.3}$$

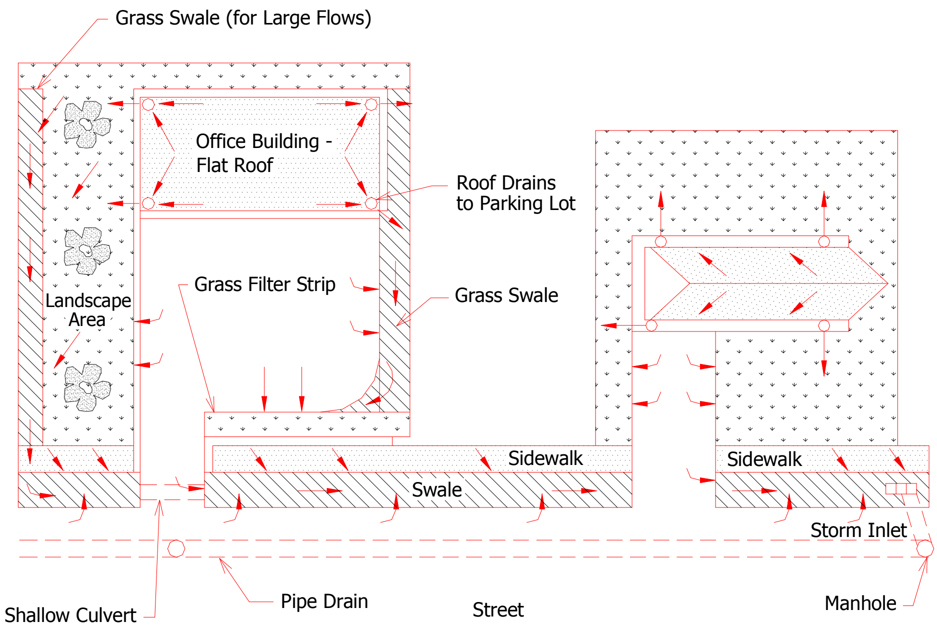
Where, I is the exact number of times the event with the ARI of T_r occurs in N successive years.

11.4 FREQUENCY ANALYSIS AND ARI

Every rainfall event is unique. Temporal and spatial distribution of rainfall varies seasonally as well as within a storm event due to the prevailing climatic conditions at the time of the storm. Just as every rainfall event is unique, the resulting runoff from a storm event is also unique. The temporal and spatial distribution of the rainfall affects the



(a) Traditional



(b) New Methods (With Swales and Reduced Directly Connected Impervious Area)

Figure 11.1 Traditional and New Drainage Methods for Site Development (UDFCD, 1992) temporal and spatial distribution of runoff. Surface conditions such as the amount of vegetation, landuse, type of soil, soil condition, topography, and other factors affect runoff volume and distribution.

The conditions of conveyance elements such as blockage by sediment or obstruction by trees and vegetation, are among other factors that also have an effect on spatial and temporal runoff distribution.

In the design of the individual smaller components of a stormwater system, the effects of the temporal and spatial distribution of runoff are relatively small. However, these effects must be considered in designing larger components such as detention basins or delineating floodplains.

Hydrologic data are historical by nature. Unlike conventional experiments where data are collected through repetition, hydrologic data are collected through observation of an event (e.g. a measured amount of rainfall for a storm or the flood water depth). The variables relating to hydrologic data such as time and space, rainfall variation, abstractions, surface conditions, and numerous others that affect runoff are considered continuous; that is, quantitatively they can assume any real value. Because the combinations of values of all such variables are infinite, an exact repeat occurrence of an event, although not impossible, is very unlikely.

The infinite number of possible rainfall and runoff events presents an improbable task of ever obtaining all of the unique data potentially available in the hope of predicting hydrologic events precisely and accurately. Statistics is a branch of mathematics, that studies the collection and organisation of numerical data. Based on statistical analysis of data, inferences are made about larger data sets using the results of related smaller data sets. That part of mathematics used to predict the likelihood of the occurrence of a random event is probability. Statistics and probability concepts are frequently used in hydrologic analysis.

Most hydrologic data do not follow "normal" distributions and are much better described by log-normal statistical distributions such as the Log-Pearson.

11.5 DESIGN FLOOD AND ACTUAL FLOOD

Much confusion has resulted from lack of recognition of the fundamental differences between design floods and actual floods in flood estimation exercises. Although the same mathematical procedures may be involved in both cases, the implications and assumptions involved and the validity of application are quite different.

11.5.1 Design Flood

A design flood is a probabilistic or statistical estimate, being generally based on some form of probability analysis of flood or rainfall data. An ARI or AEP is attributed to the estimate. This applies not only to normal routine design, but also to probable maximum flood estimates, where the intention is to obtain a design value with an extremely low probability of exceedance. In this Manual the term ARI is used.

If a design rainfall is used in the estimation of a flood, it is not intended to imply that if a rainfall of that amount occurred at a given time, the estimated flood would result. Occurrence of the rainfall when the catchment was wet might result in a very large flood of magnitude greater than the design estimate, while occurrence of the rainfall when the catchment was dry might result in relatively little, or even no runoff.

For the design flood, the conditions are not known and must be assumed, often implicitly in the design values that are adopted. The design methods given in this Manual have been constructed so that the ARI of the design rainfall and design runoff can be assumed to be equal.

11.5.2 Actual Flood

The approach to estimating an actual flood from a particular rainfall is quite different in concept and is of a deterministic nature. All causes and effects require consideration. The actual antecedent conditions prevailing at the time of occurrence of the rain are very important and must be allowed for in estimation of the resulting flood. No real information is given regarding the probability of the actual flood.

11.5.3 Practical Consequences

Although the differences in these two types of problems are often not recognised, they have three important practical consequences. The first is that a particular procedure may be good or satisfactory for one case, but quite unsuitable for the other. For example, the Rational Method using the probabilistic interpretation (refer to Chapter 14) can be a satisfactory approach to estimating design floods for small catchments, but it is not satisfactory for estimating the flood resulting from a given historical rainfall.

The second concerns the manner in which values of parameters are derived from recorded data and the manner in which designers regard these values and apply them. If actual floods are to be estimated, values for use in the calculations should be derived from calibration of individual observed events. If design floods are to be estimated, the values should be derived from statistical analyses of data from many observed floods. For example, if the runoff coefficient in the Rational Method is to be used to estimate floods resulting from actual rainfalls, values would have to be derived as the ratio of flood peak to observed rainfall intensity in individual floods. However, for the design case, coefficients should be derived as the ratio of values taken from frequency analyses of peak discharge and rainfall intensity.

The third practical consequence concerns the manner in which parameters are viewed by designers and analysts. For example, the common visualisation of the runoff coefficient as the fraction of rainfall that runs off in a design flood is incorrect, and fundamentally misleading. Rather, the coefficient should be viewed as a factor which converts design rainfall to design runoff. These particular examples are discussed further in Chapter 14.

11.6 MAJOR AND MINOR SYSTEM

Chapter 4 has introduced the concept of major and minor drainage systems. These systems can be understood in terms of *major and minor design storms*, the frequency of which is expressed in terms of ARI

The minor system is designed to convey runoff from a *minor storm*, which occurs relatively frequently, and would otherwise cause inconvenience and nuisance flooding. The minor system typically comprises a network of kerbs, gutters, inlets, open drains and pipes. The major system, on the other hand, comprises the many planned and unplanned drainage routes, which convey runoff from a *major storm* to waterways and rivers (AR&R, 1998). The major system is expected to protect the community from the consequences of large, reasonably rare events, which could cause severe flood damage, injury and even loss of life.

The design objectives of the major and minor systems are described in Table 11.1. Design concepts for the major and minor systems are diagramatically shown in Figure 11.2.

Ideally, the choice of design standards for both major and minor storms should be made by economic analysis, taking into account the tangible and intangible costs and benefits of different levels of protection. This type of analysis is comparable to the economic cost-benefit analyses sometimes undertaken for flood mitigation projects.

Table 11.1 Major and Minor System Design Objectives

Major System	Minor System
Reduced injury and loss of life	Improved aesthetics
Reduced disruption to normal business activities	Reduction in minor traffic accidents
Reduced damage to infrastructure services	Reduced health hazards (mosquitoes, flies)
Reduced emergency services costs	Reduced personal inconvenience
Reduced flood damage	Reduced roadway maintenance
Reduced loss of production	-
Reduced clean-up costs	-
Increased feeling of security	-
Increased land values	-
Improved aesthetics and recreational opportunities	-

Source: after Argue (1986)

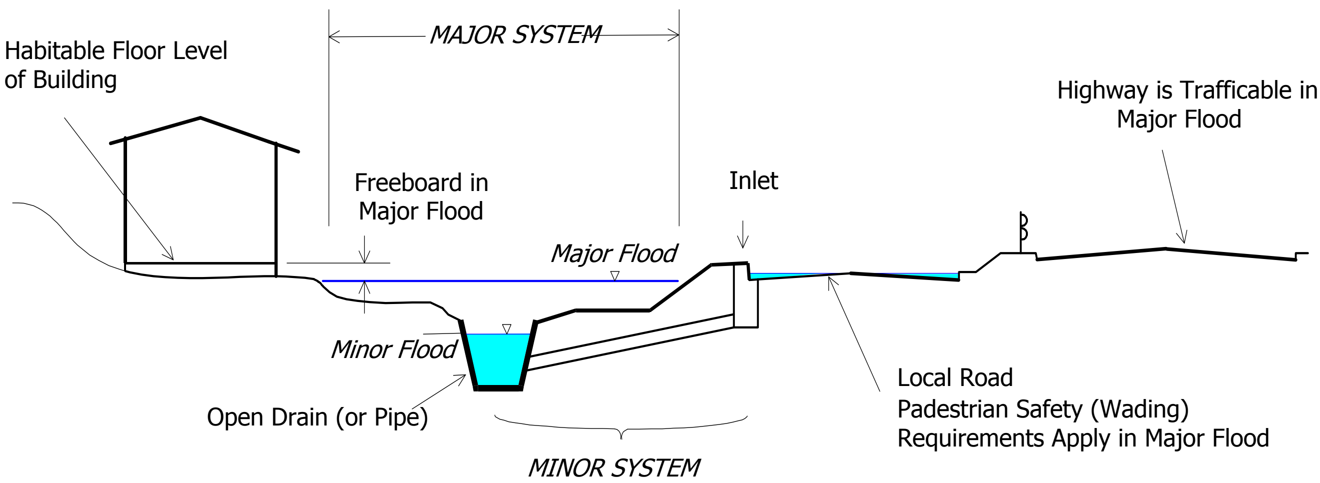


Figure 11.2 Major and Minor System Design Concepts

It is however, quite impractical to suggest that this kind of benefit-cost analysis should be done for every single project, especially small projects. It is also very difficult to quantify many of the social and economic factors involved (Argue, 1986). The preferred approach is to adopt standards which are found from experience to give acceptable performance at a reasonable cost.

The appropriate magnitude of the *minor design storm* depends on a wide variety of factors including community attitudes, technical considerations, cost and other economic factors. One major technical consideration, the magnitude of the 'gap' flow, is discussed in more detail in Chapter 16. Due to the wide variation in these factors between different locations, it is not surprising that the recommended magnitude of the minor design flood also varies. Values typically range between 2 year and 10 year ARI. Recommended values for Malaysia are given in Chapter 4.

Many countries have adopted (and in some cases, included in legislation) a 100 year ARI standard for the *major design storm*. Recently, this standard has been extended to apply to urban drainage as well as to flooding caused by rivers. While a case can be made out for varying the major design storm standard because of technical, social and economic considerations, an equally strong case can be made for a uniform standard on the grounds of social equity.

The major design storm standard recommended in Chapter 4 is 100 year ARI. This is consistent with the existing 100 year ARI standard for river engineering and flood mitigation.

The standards set out in Chapter 4 are typical of the latest practice in urban areas in developed countries. Because of differences in climate and other factors, it would be appropriate to review the standards for application under the Malaysian conditions from time to time. Future reviews should be based on representative local studies, taking into account economic and social factors.

11.7 DESIGN FOR RISK

Design of works to pass or safely contain a flood of a given frequency implies that a failure will result with the occurrence of a larger flood. However, failure in this sense does not necessarily mean that the structure will be destroyed or even damaged, but that it fails to perform (for a limited period of time) the service for which it was intended. The occurrence of a flood larger than the design event is referred to here as "surcharging". This usage of the term should be distinguished from its use for situations where stored water is above full supply level of a reservoir and spillway flow occurs, even though this flow may be much less than the design flood. A typical example of risk associated with the design storm selections for different ARIs is shown in Figure 11.3

All hydraulic works sized by a flood estimate are designed on a risk basis. None are '100% safe'. There is always a finite probability, that the structure will be surcharged either in a given year or during its economic life. Similar considerations apply to many other types of civil engineering works, but the high costs of increasing safety make the position more critical with design floods. Even with major dams, the concept of complete safety is unrealistic and misleading. The design intention is that surcharging will occur (albeit infrequently), but the resulting damages will be socially and politically acceptable, and with allowances for the resulting damages, the average annual costs will be less than those of constructing works for larger design floods and lower risks.

For minor and medium sized structures, a consequence of designing on a probability basis is that failure or surcharging should occur relatively frequently. Most minor bridges and culverts, and urban drainage systems for which the social and economic implications of surcharge are not great, have been designed for floods with average ARIs in the range of 2 to 50 years, with 10 years being a typical value. With thousands of these structures in Malaysia, about 5 percent of the total number should be surcharged every year. For a given region, however, many years may pass with very few, if any, occurrences of surcharging, as ARIs and AEPs refer to average numbers of occurrences over long periods of time. If, on the average, the expected numbers of failures do not occur, then the design procedures in use are not accomplishing their objectives, and structures are being over-designed relative to selected design or stated frequencies.

Isolated extreme floods, often resulting in spectacular failures and possibly involving loss of life, are sometimes cited as evidence that present design is not sufficiently conservative. However, the ARIs of such floods are very high. When it is considered that there are thousands of small catchments in Malaysia, it is highly probable that an extreme flood with an ARI of the order of thousands of years will occur on at least one of them in any given year. However, the probability of it occurring on a given catchment is extremely low. The cost of designing protection against a very rare flood would be excessive, and it cannot be justified on cost-benefit grounds. Therefore, extreme floods are not considered in the design of urban drainage systems. The exception to the rule is for structures such as dams or major community facilities where the consequences of failure would be extremely severe. Such structures are not covered in this Manual.

As surcharging is to be expected, one of the other objectives in design should be to provide for passage of floods that exceed the design flood with a minimum of social, physical and environmental damage. Examples of structural measures to accomplish this are:

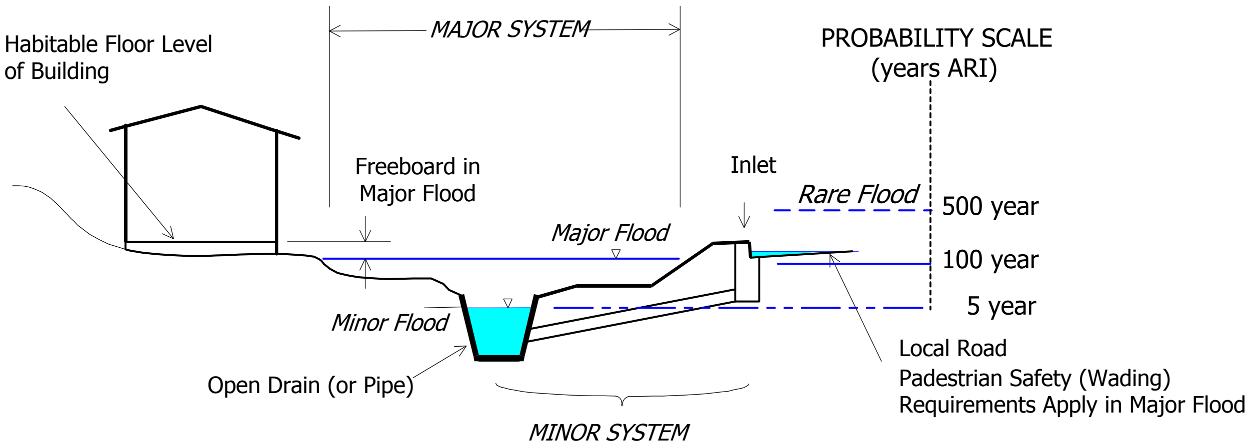


Figure 11.3 Risk as the Basis of Design Storm Selection (diagrammatic)

- long, flat overflow or causeway sections on roads at or adjacent to culverts and bridges. These sections should be capable of being made structurally safe when subject to overflow, which should occur at low depths and velocities. The availability of such sections should always be considered in selecting sites for stream crossings.
- fail-safe designs, where surcharge results in planned partial failure of sacrificial sections, thereby increasing the capacity of the structure to pass higher flows. Emergency spillways with erodible block embankments on dams that have main spillways of limited capacity are examples of this approach.
- spillway sections for controlled discharge of overtopping flows on levee and retardation banks
- use of floodways and linear parks and open-space areas flanking streams and drains, to carry excess flows.
- situations in urban drainage where excess flow at one inlet can be handled by a downstream inlet.

Non-structural measures may also be used to mitigate the effects of floods larger than the design event. They should be considered within the design process as possible alternative or complementary components of the overall design. Examples are:

- flood warning and forecasting systems coupled with evacuation strategies;
- permanent and temporary warning signs;
- land-use regulation to restrict high-risk development or activities in areas subject to damage from surcharged flows;
- building controls, including the setting of minimum floor levels and/or platform levels; and
- flood insurance schemes.

If implemented in the construction stages of development, these measures would incur relatively small additional cost. It is very much harder to retrofit measures after development occurs.

11.8 STORMWATER QUALITY DESIGN

11.8.1 Differences between Design for Quantity and Quality

Runoff from an impervious surface (roof, pavement) would have a greater volume peak discharge and smaller flow travel time than runoff from a pervious surface (grass) having similar size, shape, soil and slope characteristics. Uncontrolled land activities and practices in paved or grassed areas within a catchment however contribute to the accumulation of pollutant loads as a result of surface runoff wash off. These two examples show that quantity design analysis primarily deals with land imperviousness while quality with landuse practices. Most often, a qualitative description of landuse and landcover is transformed into a quantitative index of runoff potential, such as the runoff coefficient in the Rational Formula or percentage imperviousness in computer routing models, while event mean concentrations (EMC) for different land activities are used to derive pollutant loads.

Quantity design deals with sizing of structures for collecting, conveying, controlling, and disposing of stormwater runoff. Peak discharge and its characteristics are of primary importance as they can be used to derive the maximum cross-sectional area of the necessary structures at a selected event ARI for both minor and major systems. Stormwater pollutants are however transported and accumulated in the runoff and pollutant loads are thus estimated and designed for according to the pollutant concentration and total runoff volume in a certain time period. Basic differences between the considerations for quantity and quality designs are summarised in Table 11.2

Table 11.2 General Hydrologic Design Considerations

Quantity	Quality
Runoff peak	Runoff volume
Landuse % imperviousness	Landuse activities
Management of infrequent storms	Management of frequent storms
Multi storm ARI design approach (major/minor)	Single storm ARI design approach
Detention/retention may not perform in repeated/multiple storms	Ponds may not be efficient in infrequent storms
Event and continuous (retention only) modelling	Annual average load modelling

11.8.2 Theoretical Approach

One of the aims of an ecologically-based stormwater management and planning approach is to identify the sustainable pollutant exports from a site to protect the environmental values of the receiving water that receives discharges from the site. Ideally the identification of sustainable pollutant loads on a receiving water is based on the magnitude of overall catchment exports, the contribution of each landuse to the overall levels of pollutant export and the reduction in overall pollutant loads required in order to achieve the water quality objectives that are linked to the environmental values. This information should preferably be derived by a *Catchment Management Study*.

Catchment planning of stormwater quality allows the relative contributions of different pollutant sources and changes in pollutant loads with time (such as increased urban development) to be assessed. Catchment Planning is referred to in Part C.

Estimates of stormwater pollutant loadings generated by both existing and proposed catchment activities are prerequisite to the determination of the type and removal characteristics of proposed water quality control measures. Such estimates are the subject of Chapter 15.

Pollutant loads are normally assessed as point source loads plus non-point source loads. To be comprehensive, the design should include all significant inputs, especially point sources such as industrial sites and sewerage oxidation ponds. Point sources are not considered in this Manual.

In principle, non-point source loads can be determined by long-term monitoring (Chapter 30). Initially, some difficulty with planning and design will be experienced due to a lack of data on pollutant loadings and exports for Malaysia. There is much less data available for water quality than water quantity, and it normally exhibits much greater variability. Detailed long-term local studies are required in order to derive reliable estimates of pollutant exports. In the absence of any local data on pollutant exports, published data from external references may be used for preliminary studies only.

Modelling enables the relative effects of different management options to be tested and enables investigation of the relationship between pollutant loads and the resulting water quality in receiving waters. Different water quality models use different approaches to non-point sources but they all usually involve functions of catchment area, landuse, rainfall, and time period.

11.8.3 Design Standards

Lack of local data is likely to limit the application of the theoretical approach described in the previous sub-section. Many stormwater management decisions will have to be made in the absence of a Catchment Management Study or other planning investigations. Under the circumstances, the recommended approach is to adopt performance standards as set out in Chapter 4.

The form of the minimum criteria given in Chapter 4 is different for new development, and for redevelopment. For new development a minimum overall *percentage removal efficiency* is specified. This efficiency is readily achievable with current Best Management Practices (BMPs), as described in Part G. For redevelopment or drainage system upgrading, the criteria are set in terms of a *reduction in the average annual pollutant load* compared with the load under existing conditions.

11.8.4 Design Methods

Water quality design procedures are somewhat different from those more familiar procedures used for flow calculations. The emphasis is on smaller, more frequent events, and on the effects of a continuous time series of storms, rather than single event-based storms used for quantity calculations. Nevertheless, many of the design concepts will be already familiar to drainage engineers.

It will be shown in subsequent chapters that a high percentage of annual total volume of runoff comes from smaller/frequent storms. A high percentage of pollutant load also occurs in these storms. In larger storms, only the first flush is of real concern in water quality control and systems that are designed for small storms will also capture the first flush. To achieve either the minimum pollutant retention or load reduction criteria it is expected that around 90% of the average annual flow volume will need to be treated.

Most types of water quality improvement devices incorporate a bypass or overflow to prevent them from being overwhelmed by larger flows. The level or magnitude of this bypass is important in setting the overall cost and effectiveness of the device. Increasing the design standard from (say) 3 month to 6 month ARI will result in significant size/cost increase for only a minimal increase in pollutant removal and this can be expressed in terms of the *law of diminishing returns* that defines the point at which increasing the design standard is no longer cost-effective.

Therefore, the ARI used for sizing the detention and treatment components of water quality structures is based on single small/frequent storms. This Manual recommends the use of the 3 month ARI design storm for this purpose (see Chapter 15). This is equivalent to treating :

- all flows in events up to and including the 3 month ARI event for the critical storm duration for the catchment, and
- the rising limb of events that exceed the 3-month ARI event.

11.9 ON-SITE AND COMMUNITY SYSTEMS

On-site facilities are primarily minor drainage structures provided on individual housing, industrial and infrastructure sites. They are usually built and maintained by private parties/developers. For quantity design they are based on peak inflow estimates using the Rational Method with design storms between 2 year and 10 year ARI.

Community facilities are major drainage structures provided to cater for larger areas, which can combine different landuse areas. They are usually built and maintained by the regulatory authority. For quantity design they are based on peak inflow estimates using preferably the Hydrograph Method with larger design storms, up to 100 year ARI in some instances, depending on the downstream protection requirement (Figure 11.4).

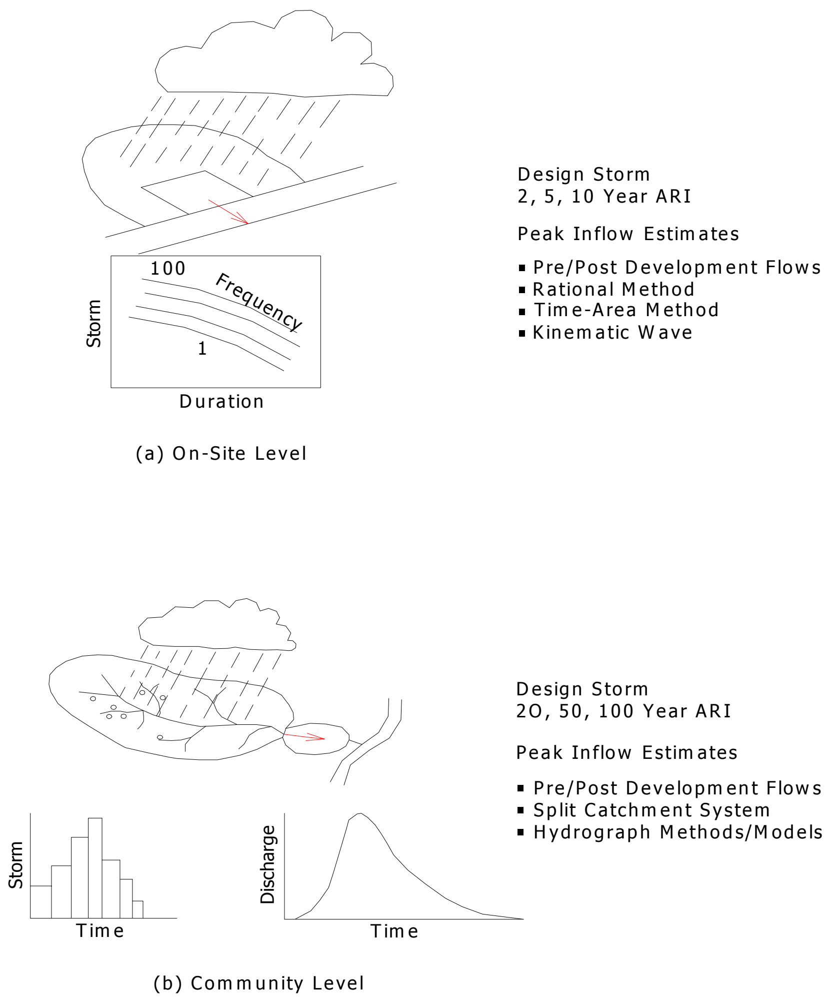


Figure 11.4 General Design Concept for Multilevel Stormwater System