15 POLLUTANT ESTIMATION, TRANSPORT AND RETENTION

15.1 INTRODUCTION

This chapter provides:

1. basic information on stormwater quality and proposes simple methods of pollutant load estimation for use in sizing water quality devices such as sediment ponds, wet ponds, wetlands, infiltration/filtration measures, GPTs and oil-water separators (Part G); and
2. treatment of particulate settling and retention capabilities in more detail as they normally occur in storage basins and other devices.

The analysis to be carried out requires knowledge of rainfall (refer to Chapter 13) and the runoff quantity estimation procedures in Chapter 14. For pollutant transport/ retention modelling, stormwater convective velocities are to be known and these are also covered in Chapter 14. These are important in designing and managing long term performance of the treatment system at both community and regional scales.

15.2 POLLUTANT CHARACTERISATION

15.2.1 Standard Stormwater Pollutants

Although many different constituents can be found in urban runoff, it helps to focus primarily on certain pollutants that can be used as representative indicators of others. The following constituents are recommended as 'standard' pollutants characterising urban runoff for Malaysia.

TSS	Total suspended solids
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
TP	Total phosphorus (as P)
SP	Soluble phosphorus (as P)
TKN	Total Kjedahl nitrogen (as N)
NO_2, NO_3	Nitrite & nitrate (as N)
Cu	Total copper
Pb	Total lead
Zn	Total zinc
Oil and grease	
Faecal Coliforms	

This selection is based on USEPA Nationwide Urban Runoff Program (1983). The EPA explains this selection as follows:

> *"The list includes pollutants of general interest which are usually examined in both point and non-point source studies and includes representatives of important categories of pollutants, namely, solids, oxygen consuming constituents, nutrients, and heavy metals."*

15.2.2 Flow, Concentration and Load Relationship

The primary measure of the quantity of a constituent is its concentration, C, defined as:

$$C = \frac{\text{quantity (mass) of constituent}}{\text{volume of fluid}} \quad (15.1)$$

Most constituents are measured in terms of their mass, and C usually has units such as mg/L or g/m^3. Because the density of water is nearly 1.0 g/cm^3, units of μg/cm^3, mg/L, and g/m^3 are numerically equivalent to parts per million (ppm) by mass in water, a convenient coincidence, whereas μg/L (micrograms per litre) is numerically equivalent to parts per billion (ppb) by mass.

Concentration may also be defined for variables not measured in mass units. For example, bacteria are often measured as a number (e.g. most probable number or MPN) per unit volume.

The impact of constituents on a water body may be influenced by both the concentration and by the load. Load may mean either the total mass M in a volume V of water:

$$M = C \times V \quad (15.2)$$

or the mass flow rate L (mass/time) in water flowing with a rate Q (volume/time):

$$L = C \times Q \quad (15.3)$$

The use of load measures is not appropriate for non-conservative pollutants, such as faecal coliforms which decay (see Section 15.6.2 for definition). For these substances it is the instantaneous value which is important.

15.2.3 Event Mean Concentration

The event mean concentration (EMC) is the flow-weighted mean concentration of a pollutant. The EMC is computed as the total storm load (mass) divided by the total runoff volume, although EMC estimates are usually obtained from a flow-weighted composite of concentration samples taken during a storm. Mathematically:

$$EMC = \bar{C} = \frac{M}{V} = \frac{\int C(t)\, Q(t)\, dt}{\int Q(t)\, dt} \quad (15.4)$$

where $C(t)$ and $Q(t)$ are the time-variable concentration and flow measured during the runoff event, and M and V are pollutant mass and runoff volume as defined in Equation 15.2. It is important to note that the EMC results from a flow-weighted average, not simply a time average of the concentration.

When the EMC is multiplied by the runoff volume, an estimate of the event loading to the receiving water is obtained. As is evident from Figure 15.1, the instantaneous concentration during a storm can be higher or lower than the EMC, but the use of the EMC as an event characterisation replaces the actual time variation of C versus t in a storm with a pulse of constant concentration having equal mass and duration as the actual event. This ensures that mass loadings from storms will be correctly represented.

Just as instantaneous concentrations vary within a storm, EMCs vary from storm to storm, as illustrated in Figure 15.2, and from site to site as well. The median or 50th percentile EMC at a site, estimated from a time series of the type illustrated in Figure 15.2, is called the site median EMC. When site median EMCs from different locations are aggregated, their variability can be quantified by their median and coefficient of variation to achieve an overall description of the runoff characteristics of a constituent across various sites.

In general, stormwater contaminant concentrations have considerable variations. Although variations among landuses are significant the differences are generally not statistically significant, and the data may be combined to characterise a typical urban site. In other words, the type of urban landuse has, at best, only a minor influence on pollutant concentrations in runoff. However, landuse does affect mass loads, since there are considerable differences in the percentage imperviousness between areas and thus in the volume of runoff.

15.2.4 Pollutant Variation and First Flush

Although point sources frequently exhibit daily and weekly variations, non-point source flows originate from rainfall events and follow the temporal and spatial characteristics of rainfall to a large degree. A plot of concentration versus time is often called a pollutograph, and a plot of load (concentration x flow rate or mass/ time) versus time is often called a loadograph (see Figure 15.1). If the concentration during a storm were constant, the shape of the loadograph would exactly match that of the hydrograph (Figure 15.1 (a), (b), and (c)). However, the pollutograph frequently exhibits considerably higher concentrations near the beginning of the storm (Figure 15.1 (d)).

This is known as the *first flush* phenomenon and is thought to be due to greater availability of solids that have built up on urban surfaces during dry weather. The wash-off of these solids is thus greater nearer the beginning of a storm (Figure 15.1 (e)). Urban runoff quality is sometimes simulated by conceptual models which portray the *pollutant build-up and wash-off* process (for example, SWMM).

The first flush is most evident in solids which are deposited during dry weather and scoured during the beginning of a wet weather event. The first flush is least evident in highly urbanised urban cores. As rainfall continues, the surface pollutant accumulation is depleted and pollutants are diluted by the larger flows in the stormwater conveyance system. Also, it is likely that the first flush depends on the intensity and the duration of rainfall and on the time between successive rainfall events.

On pervious surfaces, build-up plays a lesser role, and entrainment of water quality constituents in runoff is due more to erosion and solution mechanisms. Constituents may be adsorbed onto particulate matter and thus be subject to transport as solids.

However, some studies at other sites have not found an identifiable first flush (Stahre, 1990). As a result of the conflicting findings, it is not appropriate to assume that by merely capturing the first flush most of the pollutants will be captured. In fact, lacking local data, it is safer to assume that there is no first flush. If local investigations do find a significant first flush, then it is necessary to define its volume and duration as its quantification can significantly simplify the definition of the volume of runoff that has to be captured and treated.

15.2.5 Suspended Solids

Many pollutants occur in particulate form and appear to have a strong affinity to suspended solids. Therefore, the removal of TSS will very often remove many of the other particulate pollutants found in urban stormwater.

Observations show that the above principle does not apply to dissolved pollutants such as nitrites and nitrates (NO_2 , NO_3), and soluble phosphorus (SP). Dry detention basins (i.e. basins that drain fully between storm events and have no permanent pool of water) have consistently exhibited poor dissolved NO_2, NO_3, and SP removal efficiencies. The removal of soluble pollutants is best accomplished by other methods such as biological action.

Stormwater quality varies with time and from one location to the next. Of significance are the type and quantities of pollutants found in stormwater and to what degree these pollutants may be associated with sediments. Amongst others, the following factors seem to be of significance in describing the settling characteristics of TSS and associated pollutants:

- pollutant load in the stormwater by type
- the percentages of settleable pollutants
- particle size distribution
- distribution of the solids by their settling velocities
- distribution of pollutants by settling velocities
- particle volume distribution of the solids
- the density of settleable pollutants

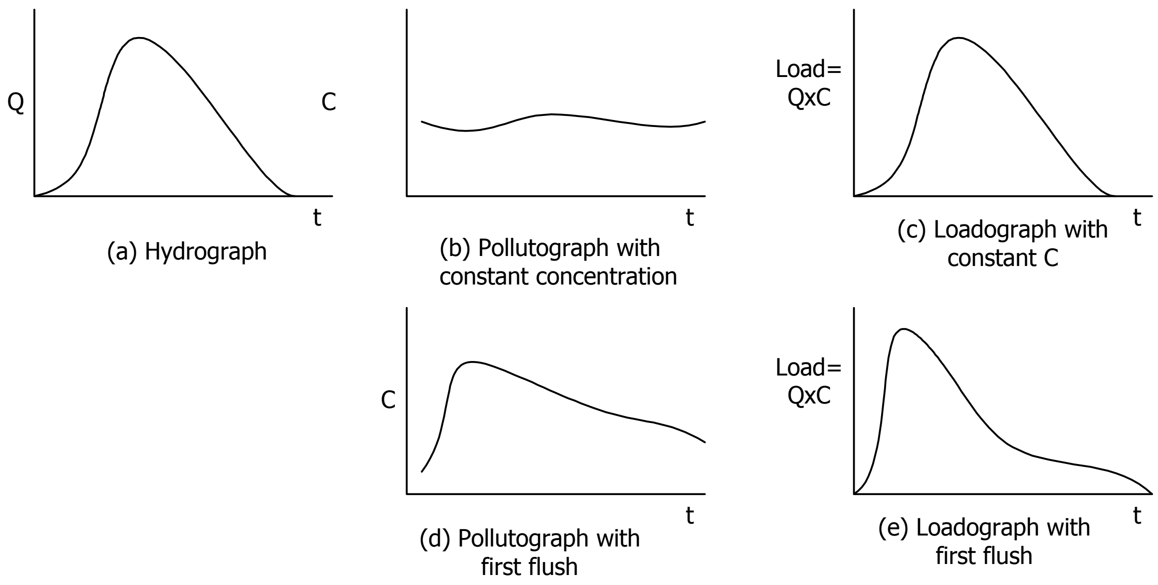

Figure 15.1 Effect of First Flush on Shapes of Pollutograph and Loadograph

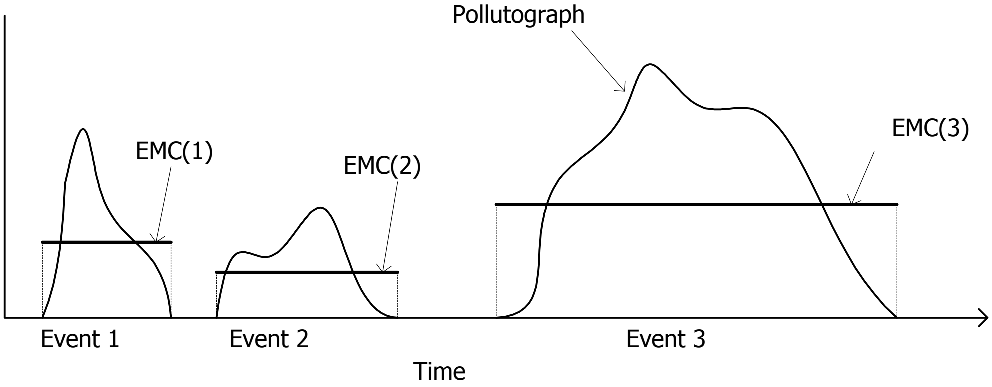

Figure 15.2 Inter-storm Variation of Pollutographs and EMCs

15.3 DESIGN CRITERIA

15.3.1 Water Quality Design Storm

Like most decisions on design standards, the selection of a suitable design standard for water quality control works involves considerations of economics. It requires a trade-off between the benefits of providing a higher level of protection, performance and the size and cost of works needed to provide that protection.

The preliminary calculations presented in Chapter 13 and in Example 15.C1 for Ipoh give a guideline to determine a suitable choice of design ARI flow to be treated by the water quality treatment measures. A plot of the relationship between ARI of the storm that is equalled or exceeded, and the cumulative percentage of runoff and pollutant load represented by those storms, is shown in Figure 15.3.

From Example 15.C1, for a typical urban area with 50% directly connected impervious area (DCIA):

- over 90% of annual runoff volume occurs in storms of 3 month ARI or less, and
- over 90% of the total annual load of sediment, total suspended solids (TSS) and total phosphorus (TP) occur in these storms.

These results lead to the following preliminary Guideline (see also Chapter 4):

For typical urban catchments in Malaysia,
the recommended design storm for stormwater
quality control works is 3 month ARI.

The application of this Guideline to water quality control and treatment measures will be discussed in Part G.

The calculation methods used to derive Figure 15.3 involve a number of assumptions. Further, more detailed study using continuous simulation techniques should be undertaken to confirm the validity of this Guideline. The nature of the pollutants and the need to protect the environment and receiving waters should also be considered. Local Authority or Government regulatory agencies may choose a different design standard for the water quality design storm because of these factors.

15.3.2 Rainfall Data for Water Quality Design Storm

This Chapter requires data on design rainfalls for storm events smaller than the 2 year ARI storm. Section 13.2.6 in Chapter 13 presents a method of calculating the 3 month ARI rainfall for the water quality design storm.

15.4 RUNOFF VOLUME ESTIMATES

15.4.1 Runoff Estimation

It is necessary to estimate runoff volumes before any assessment can be made of pollutant loads. The hydrograph methods described in Chapter 14 can be used although they are more suitable for event analysis rather than pollutant load calculations. For preliminary calculations, the Volumetric Rational Method discussed below can be used. Computer methods for volume calculation are discussed in Chapter 17.

15.4.2 Volumetric Rational Formula

A formula similar to the 'Rational Formula' can be used for preliminary volume calculations. The equation for the Volumetric Rational Method is:

$$R = D \, . \, C_v \qquad (15.5)$$

where,

R = average annual runoff depth (mm)

D = average annual rainfall depth (mm), and

C_v = weighted average annual runoff coefficient

There is no restriction on urban catchment size for the application of Volumetric Rational Formula.

(a) Volumetric Runoff Coefficient

It will be recalled from Chapter 14 that in the Rational Method, the runoff coefficient C is a function of rainfall intensity, and therefore of event ARI. In general, the average annual runoff coefficient C_v will be less than the Rational Method runoff coefficient C for events of large ARI (say >2 years), and C_v will be greater than C for events of small ARI.

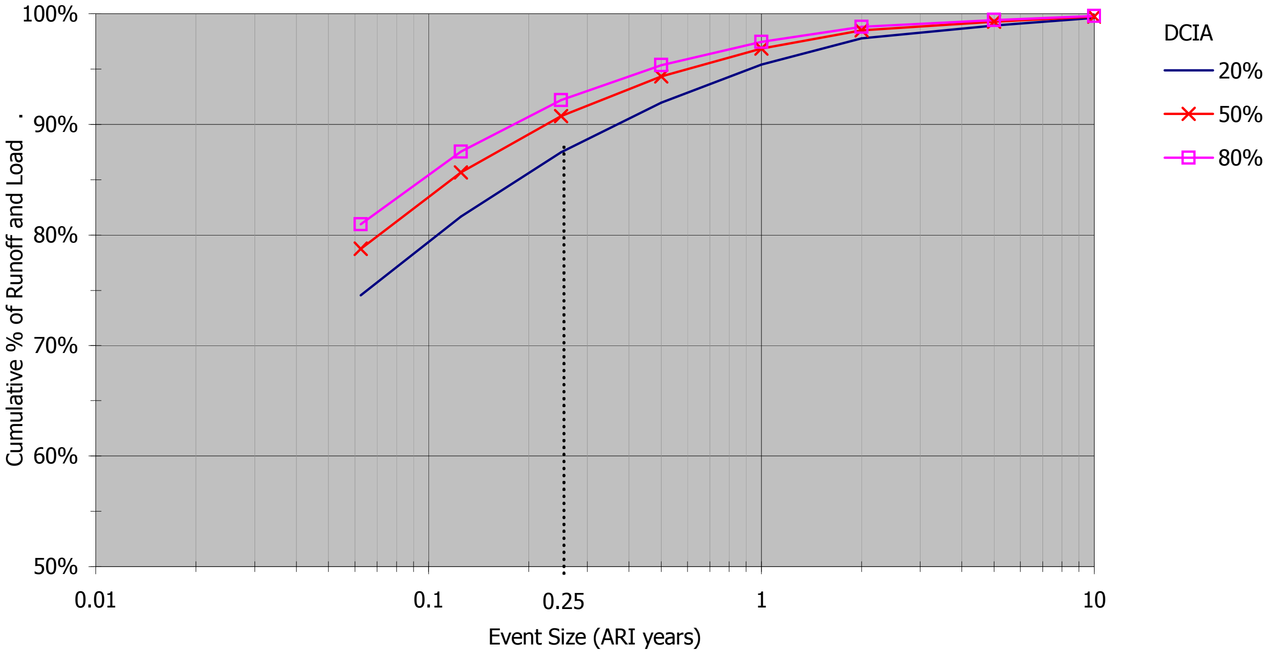

Figure 15.3 Most of the Annual Runoff Occurs in Storms of Small Intensity

The most reliable method to determine the average volumetric runoff coefficient C_v is from long-term flow gauging data. Flow gauging data should always be used where available. If computer modelling is being used, the model should be calibrated against the flow gauging data.

There is relatively little published data on values of C_v. CRCFE (1998) gives the values in Table 15.2 for Australian conditions.

Table 15.1 Typical Volumetric Runoff Coefficient Values

Landuse	C_v
Forest	0.1 – 0.3
Pasture	0.2 – 0.6
Urban	0.5 – 0.7

(Source: CRCFE, 1998)

(b) Runoff Estimation Procedure

If there is no gauging data available, an approximate method can be used to estimate runoff. The resulting runoff volume-frequency relationship then provides a basis for estimating catchment pollutant loads.

The estimation method uses the Rational Method runoff coefficient *C* to predict runoff depth from individual events. Event runoff R_n can be estimated from Equation 15.6:

$$R_n = D_n . C \tag{15.6}$$

where,

R_n = runoff depth (mm) in event with ARI *'n'*

D_n = rainfall depth (mm) in event with ARI *'n'*

C = the Rational Method runoff coefficient, from Design Chart 14.3 or 14.4

The Rational Method runoff coefficient *C* for each event is a function of the rainfall intensity. Recommended values of *C* are given in the Design Charts in Chapter 14. This method is not strictly accurate, since the Rational Formula predicts peak discharge rather than runoff volume, but it is a convenient simplification which gives satisfactory results.

An estimate of the weighted average annual volumetric runoff coefficient C_v can then be derived using Equation 15.6.

$$C_v = \frac{\sum_{n=1}^{\infty}(R_n \cdot P_n)}{\sum_{n=1}^{\infty}(D_n \cdot P_n)} \tag{15.7}$$

where,

R_n = runoff depth in event with ARI *'n'*

P_n = probability of event with ARI *'n'*

= 1/n

D_n = rainfall depth in event with ARI *'n'*

and the suffix *n* represents the range of ARI of storm events.

For estimating C_v from design charts 14.3 and 14.4, it is recommended that the 1 year ARI rainfall intensity be used.

Table 15.C1 in Appendix 15.C is a worked example giving runoff spreadsheet calculations for three sample 100 hectare catchments at Ipoh with different catchment imperviousness conditions.

15.5 POLLUTANT LOAD ESTIMATES

15.5.1 General

The next step in water quality design is to estimate the magnitude of the pollutant loads. Pollutant loads can vary as a result of a large number of factors, including:

- rainfall
- soils
- vegetation type
- landuse
- storm drainage practices
- wastewater management (sewerage) practices

All published studies confirm that pollutant loads are highly variable in both space and time, even in similar catchments. Because of their variability, pollutant loads are normally analysed using statistical methods. Any estimates of pollutant load that are not based on measured data are just that, estimates, and will be subject to a wide band of uncertainty.

Nevertheless it is useful to be able to estimate pollutant loads for comparative studies, such as assessing the impact of urbanisation of a catchment, and for predicting the performance of treatment measures.

There is very little measured data available on stormwater pollutant loads in Malaysia. Detailed long-term studies are required in order to derive reliable estimates of pollutant exports. Published data from other countries, climatic zones, and landuses may vary greatly from local conditions. In the absence of any local data on pollutant loads, published statistical data from references may be used for *preliminary* studies only. Preliminary studies based on such data can only give an approximate estimate of pollutant loads and therefore of volumes of material in lakes and ponds, or of management requirements and costs. Sensitivity testing should be carried out in order to assess the effects of uncertainty in the adopted pollutant load estimates.

15.5.2 Alternative Expressions for Pollutant Load

A number of empirical approaches have been proposed as a basis for calculating pollutant loads, based on the concepts discussed in Section 15.2. The best-known and widely applicable approaches are:

- Event Mean Concentration (EMC) Method
- Pollutant Export Rate Method
- Build-up and Washoff Method
- USLE Method

It is the responsibility of the user to select a suitable method for each application. EMC method is recommended for most application due to its simplicity, easy data acquisition and reasonable accuracy. It should supersede USLE for sediment load estimation.

For a large catchment with multiple landuses, loading calculations can be performed with computer water quality models as discussed in Chapter 17. These models generally allow the user to choose between alternative approaches for the estimation of pollutant loads.

(a) Event Mean Concentration Method

Although the definition of EMC relates to a single rainfall event, the assumption is often made that the EMC is the same for all events. Therefore in this method the load is approximated by the simple equation:

$$L = 10^{-4} \cdot \overline{C} \, . V_R \, . A \qquad (15.8)$$

where,

L = Annual load of pollutant (kg)
$\overline{C}$ = EMC of pollutant (mg/l)
V_R = Annual runoff depth (mm)
A = Catchment area (ha)

The EMC method is recommended for general application in Malaysia, unless sufficient local data is available to justify use of an alternative method.

Table 15.2 gives suggested guideline values of EMCs for selected pollutants in urban runoff in Malaysia. There is generally insufficient data to give guideline values for other pollutants.

Table 15.C2 in Appendix 15.C gives a worked example of pollutant load calculations using the EMC approach.

Table 15.2 Typical Event Mean Concentration (EMC) Values in mg/L

Pollutant	Landuse/vegetation categories				
	Native Vegetation/Forest	Rural Grazing	Industry	Urban	Construction
Sediment [1]	85 [3]	500	50 to 200	50 to 200	4,000
Suspended solids [2]	6	30	60	85	
Total Nitrogen [2]	0.2	0.8	1.0	1.2	
Total Phosphorus [2]	0.03	0.09	0.12	0.13	
Ammonia [4]	0.01 to 0.03	0.01 to 0.26		0.01 to 9.8	
Faecal coliforms [4]	260 to 4,000	700 – 3,000		4,000 – 200,000	
Copper				0.03 to 0.09	
Lead				0.2 to 0.5	
Zinc				0.27 to 1.1	

Sources:

1. Auckland Regional Council (1992)
2. Willing & Partners (1999)
3. from Sungai Kinta Dam Project, *Flood Hydrology Report*, Angkasa GHD Engineers (1998).
4. EPA, NSW (1997a)

(b) Pollutant Export Rates Method

An alternative to the use of the simple EMC is to represent event pollutant loads as a function of runoff. The form of the function should be derived by regression analysis of real data. If locally-collected data is to be used, the statistical effects of a small sample size and sampling errors should be taken into account.

The general form of the pollutant export equation is:

$$L = a \, . \, R^{e} \tag{15.9}$$

where,

L = event load in kg/km^2/ day,

R = event stormwater runoff(mm/day),

a = an empirical coefficient, and

e = an empirical exponent

Appendix 15.A gives empirical export rate relationships for Brisbane and Canberra, Australia (Willing & Partners, 1999). In the absence of local data it may be acceptable to apply similar relationships in Malaysia. However it is hoped that in future, studies will be undertaken to derive relationships using local Malaysian data.

It will be seen by comparison with Equation 15.8 that these relationships are non-linear, unlike the EMC which implies a linear response to runoff. The EMC method is a particular form of the Pollutant Export Rate method with e = 1.0.

(c) Build-up and Wash-off Method

Build-up refers to the processes whereby pollutants accumulate in an urban area, as a function of time. For example, a long dry period is likely to lead to a larger accumulation of pollutants in the urban catchment due to deposition and littering. Build-up is modified by management practices such as street sweeping. Washoff is the process whereby accumulated pollutants are washed into the stormwater system.

The pollutant build-up and washoff approach offers potentially a more accurate way of characterising pollutant loads, as it attempts to represent the physical processes rather than merely providing a statistical correlation. It is available, as an option, in several stormwater quality computer models such as SWMM but its use requires calibrated data.

The build-up and washoff approach is not recommended for general application in Malaysia at this time, because no local data is available to characterise the processes. It is not expected to give any significant advantage over the simpler methods described above.

(d) Universal Soil Loss Equation Method

Sediment load in watercourses typically does not follow a build-up / washoff process. Rather, it is more likely to be influenced by erosion processes in the catchment area. Sediment load on exposed areas, such as construction sites, is also largely dominated by erosion.

In the search for a model for planning erosion measures at the construction sites, the Universal Soil Loss Equation (USLE) developed by Wischmeier and other (1965, 1971) for the U.S. Department of Agriculture stands out as the most widely used predictive method.

The USLE method has been modified by FRIM for Malaysian conditions. In this form, the Modified Soil Loss Equation (MSLE) is written as:

$$q_c = R \, . \, K \, . \, LS \, . \, VM \tag{15.10}$$

It expresses the annual rate of soil erosion (q_c), from a site as the product of factors for rainfall erosivity (R), soil erodibility (K), length-slope factor (LS) , and vegetation management factor (VM). Detailed guidance on the use of the MSLE in forest areas is given in FRIM (1999). With suitable adaptations, the MSLE can also be used for other types of landuse. q_c is expressed in tonnes of soil loss per hectare per year.

The rainfall factor (R), is a measure of the erosive energy of the rainfall. It is expressed in units of cumulative value of storm rainfall erosivity index (EI), for a fixed period of time. The following relationships between R, EI and annual rainfall are given in FRIM (1999):

$$R = \left(E \cdot I_{30}\right) / \, 170.2 \tag{15.11a}$$

$$E = 9.28 \, P - 8838.15 \tag{15.11b}$$

where,

I_{30} = the maximum 30-minute rainfall intensity (mm/hr) for the storm of required ARI,

E = annual erosivity (units of J/m^2)

P = annual rainfall (mm)

The soil-erodibility factor, K, is a measure of the intrinsic susceptibility of a given soil to detachment and transport by rainfall and runoff, on the basis of five soil parameters : percent silt, percent sand, organic matter content, soil structure and permeability of the soil profile. K is defined by Equation 15.12. The K values can also be estimated from the nomograph in FRIM (1999) developed by Warrington et al (1980)

$$K = 2.1x10^{-6}(12 - OM)M^{1.14} + 0.0325(S - 2) + 0.025(P - 3) \tag{15.12}$$

Definitions of *OM*, *M*, *S* and *P* are given in FRIM (1999).

The length-steepness factor (LS) , combines the effects of slope and length of eroding surface. It is the ratio of soil loss per unit area from a slope land to that from a standardised measured plot. Wischmeier (1975) gives the following equation for LS:

$$LS = (\lambda / 22.13)^m (0.065 + 0.046S + 0.0065S^2) \tag{15.13}$$

where λ is the slope length (m) and S is the slope in percent. The exponent m has values of 0.2 for $S<1$, 0.3 for $1<S<3$, 0.4 for $3<S<5$, 0.5 for $5<S<12$ and 0.6 for $S>12\%$. Alternatively, the nomograph in FRIM (1999) can be used.

The vegetation management factor (VM), is defined as the ratio of soil loss from a field subject to a system of control measures to that from the same site without any control provision. It combines two factors C and P used in the original USLE.

The expression for VM given in FRIM (1999) is intended mainly for forest cover. It incorporates three sub-factors for forest canopy cover, mulch or ground vegetation cover, and bare ground with fine roots. A VM factor of unity can be assigned to a recently stripped surface at a construction site since the condition essentially resembles a continuous fallow condition.

In urban stormwater practice, the factor C accounts for the effect of various control practices related to surface stabilising treatment, runoff-reduction measures, sediment-trapping, scheduling in time and space of exposed areas, and other conventional or unconventional control practices. By definition, the overall VM factor of a system of control practices can be evaluated as the product of the control factors associated with each of the individual control measures.

At present there is insufficient data to give detailed guidance on suitable values of VM or C for Malaysia. This should be adjusted for the amount of exposed land surface in the urban area, assuming that impervious areas would not produce any sediment. It is recommended that Equation 15.14 be adopted for all urban drainage calculations.

$$VM = C \cdot (1 - IA) \tag{15.14}$$

where IA is the fraction of impervious area in the catchment, and C ranges from 1.0 for bare soil, to 0.45 for established grass cover (Goldman et al, 1986).

15.5.3 Floatables, Litter, and Debris Load Estimation

There is no particular method that can estimate these large floating objects in runoff as they are highly variable and are influenced by municipal- and social practices. Estimates of load can best be made from operational experience. Load calculations are not necessary for design as direct trapping is the most effective means of treatment.

15.5.4 Pollutants in Rainfall

There is a body of evidence, primarily from overseas, of small but significant concentrations of pollutants in rainfall in and near urban areas. Some at least of these pollutants probably originate from urban activities, eg lead from motor vehicle exhausts. When rain falls to the ground, these pollutants form part of the total pollutant load.

Obviously, measurements of pollutant concentrations or loads include the contribution from rainfall. Therefore it is not normally necessary to consider separately the contribution of pollutant loads due to rainfall.

For reference, Appendix 15.B provides a table of typical measured values of pollutant concentration in rainfall, from overseas data. It is believed that little or no comparable data yet exists for Malaysia.

15.5.5 Calculation of Pollutant Loads

The recommended method of pollutant load estimation is to use continuous simulation with a simple computer model or spreadsheet. Suitable models such as STORM and XP-AQUALM are discussed in Chapter 17.

This approach uses a recorded rainfall time series, preferably for 12 months or more. It takes into account the various size of storms, and the sequence of storms as reflected in the recorded data. It is not necessary to generate runoff hydrographs. The volumetric Rational Method (Equation 15.5) should be used to estimate runoff. Any of the pollutant load formulations discussed in Section 15.5.2 could be used, although the EMC is recommended for most purposes. This approach also allows the behaviour of detention storages, ponds and wetlands to be investigated.

15.6 POLLUTANT TRANSPORT AND SETTLING

15.6.1 Conservative Pollutants

The mass of most solid and dissolved pollutants is conserved as they are transported downstream in a drainage system. These substances are called *conservative* pollutants.

Nevertheless, conservative pollutants do undergo some changes as they are transported along a waterway. Two of the more significant effects are:

- Settling. Due to sedimentation processes, suspended sediments separate into bedload and suspended load during transport. In turn, deposited sediments can be re-suspended during high flows. This separation can be related to the hydraulic characteristics of the waterway as described in the following Section.
- Dispersion. "Slugs" of pollutant load will spread out as the are conveyed downstream due to a combination of effects including turbulence and variations in velocity profiles (see Figure 15.4).

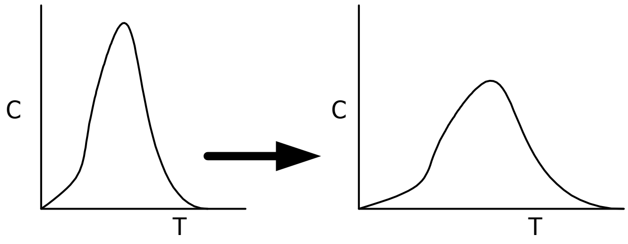

Figure 15.4 Dispersion of Conservative Pollutants during Transport

The effects described above can usually be neglected in an urban drainage situation. That is to say, that the mass of pollutants arriving at an outfall, pond or other location of interest is equal to the mass generated from runoff and rainfall.

15.6.2 Non-Conservative Pollutants

Some pollutants are non-conservative (meaning that their mass is not constant), due to either change of state such a change to gaseous form, or to biological growth and decay. An example of the first group is Ammonia, and an example of the second is Faecal Coliforms.

The time scales of most urban stormwater systems are so short that changes in the mass (or number) of non-conservative pollutants during transport, can be neglected. However they should not be neglected in a pond or wetland system. Most pond and wetland models incorporate procedures to model changes in non-conservative pollutants.

15.6.3 Settling Theory

The primary technology for removal of stormwater pollutants is through settling or sedimentation. Sedimentation occurs when particles have a greater density than the surrounding liquid. Under laboratory quiescent conditions, it is possible to settle out very small particles; the smallest practical settling size in the field is around 0.01 mm (Metcalf & Eddy, 1979). Sometimes, the smallest particles become electrically charged, which can further interfere with their ability to settle out. The fact is that we do not know if there is a particle size limit for separation by settling in water. If there is a lower limit, it probably is site-specific.

Sediment particles settle through water under the influence of gravity and follow one of three modes of settling:

1. Particles settle as separate elements with little or no interaction among them. This type of settling is usually found in waters with relatively low solids concentrations and is called free or ideal settling.
2. Independent particles coalesce or clump together during sedimentation. The larger resulting particles settle at a faster rate. This type of settling is often aided by the addition of chemicals which pull particles together.
3. At some concentration higher than in free settling, particles will start to interact and hinder settling. Instead of falling freely, the particles will settle as a group. This is called zone settling.

The Newton's and Stoke's laws are often used to quantify the sedimentation process.

For spherical particles falling through a liquid, Newton suggested the following formula to define their maximum settling velocity:

$$V_s = \sqrt{\frac{4}{3} \cdot \frac{d.g.(r_p - r_v)}{C_d.r_v}} \qquad (15.15)$$

where,

V_s = settling velocity of the particle
d = diameter of the particle
r_p = density of the particle
r_v = density of the fluid
g = acceleration of gravity, and
C_d = drag coefficient of the particle

The drag coefficient, C_d, will depend on whether the flow around the particle is laminar or turbulent and is a function of the Reynolds Number, Re. The drag coefficient can be approximated using the following equations:

For turbulent flow, $1 \le Re \le 10{,}000$

$$C_d = \frac{24}{R_e} + \frac{3}{\sqrt{R_e}} + 0.34 \qquad (15.16a)$$

For laminar flow, $Re \le 1.0$

$$C_d = \frac{24}{R_e} \qquad (15.16b)$$

Particle settling velocity V_s under laminar flow (Stoke's law) is as follows:

$$V_s = d^2 . g . \frac{(r_p - r_v)}{18\mu} \tag{15.17}$$

in which μ is the dynamic viscosity of the fluid.

The settling velocity is directly proportional to the square of the particle diameter and the difference in the densities between the particle and the fluid. In water, Stoke's law is applicable to particles having an equivalent spherical diameter of up to 0.10 mm. If the dynamic viscosity of the water and the density of the particles are known, the settling velocity can be calculated as a function of particle diameter.

V_s can be measured in the laboratory using a standard settling cylinder/tube. Settling velocities of round soil particles can be calculated and plotted for a range of particle sizes and water temperatures.

More information on sedimentation theory, including Stokes' and Newton's laws, can be found in other references (Hazen, 1904).

15.6.4 Pollutant Removalin Ponds and Settling Basins

The design of sediment basins assumes free or ideal settling. It also assumes round soil particles and relatively uniform specific gravities. In reality, suspended particles are often rods, disks, or irregular lumps which settle more slowly than round particles. Variations in parent material can result in small particles with mass greater than that of larger particles. However, for purposes of stormwater quality control, the generalised assumptions are adequate.

Once particles have settled to the bottom of a basin, they may be resting on other particles or be separated from them by electrostatic repulsion. Considerable water can be trapped among the particles. This water may be:

1. driven out as the weight of more particles is added to the top of the mass
2. drained slowly at the bottom of the mass through capillary action as particles shift and settle, or
3. evaporated when the overlying layer of water is removed

The efficiency, η, of a sedimentation basin or trap is measured as the proportion of the incoming pollutant load retained in the trap:

$$\eta = \left(\frac{Load_{in} - Load_{out}}{Load_{in}} \right) .100 \tag{15.18}$$

where $Load_{in}$ and $Load_{out}$ are the total incoming and outgoing pollutant loads obtained from the sums of the products of the flow and concentration ordinates and the routing interval.

(a) The Ideal Settling Basin

A simple model of an ideal sediment basin illustrates the fundamentals of basin design. For simplicity, it is assumed that soil particles have a uniform density. In Figure 15.5, a flow Q enters a basin of settling depth D, width W, and length L. It is assumed that a 'plug flow' in the basin i.e., uniform flow in one direction.

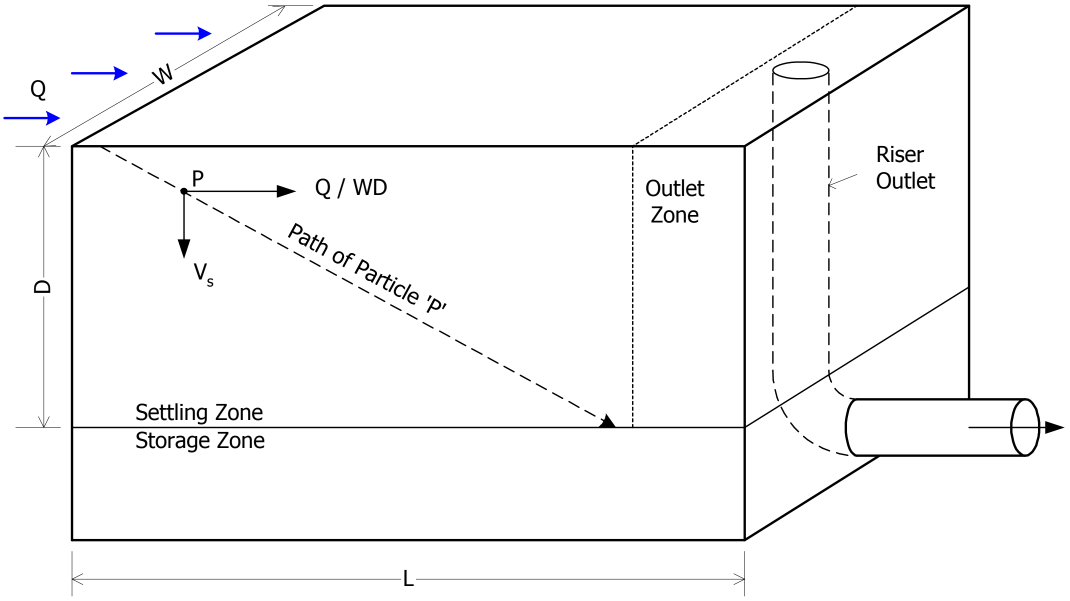

Figure 15.5 Ideal Sediment Basin

A particle will travel horizontally with the water through the basin and will fall at a vertical velocity V_s in accordance with Stoke's Law (see Chapter 12). The time (mean hydraulic residence time) for the particle to traverse the length of the basin will be:

$$t_h = \frac{L}{(Q / WD)} \qquad \text{(Horizontally)} \qquad (15.19a)$$

The time for the particle to fall to the storage zone will be:

$$t_v = \frac{D}{V_s} \qquad \text{(Vertically)} \qquad (15.19b)$$

In a properly designed basin, the smallest particle to be captured will fall to the storage zone just before or as it reaches the outlet zone. Thus $t_h = t_v$, and setting the transit and falling times equal gives the following surface area of the basin:

$$A = W \times L = \frac{Q}{V_s} \qquad (15.20)$$

We now have an ideal basin sized for removal of certain particles. The surface area has been established as a function of inflow Q and particle settling velocity. The trap efficiency η of an ideal basin is:

$$\eta = \frac{V_s t_h}{d_m} \qquad (15.21)$$

where d_m is the basin mean depth.

(b) Real Settling Basin

The ideal basin is never constructed; it is only approximated. Several factors affect performance; they include short circuiting, turbulence, bottom, scour, riser design, temperature and wind.

Turbulence in a basin is travel by water and particles in other than a straight line between inlet and outlet, i.e. travel in apparently random currents and swirls. Quiescent conditions, with little wasted motion of particles and laminar flow of the water, approximate the ideal sediment basin. *Turbulent condition will lower basin efficiency* (Hazen, 1904 and the US Bureau of Reclamation, 1971). To operate efficiently under turbulent conditions, a basin's surface area must be increased above the theoretical value of Q/V_s.

The recommended sizing method which is based on the work of Einstein (1965), is summarised in Equation 15.22:

$$P_h = 100\,(1 - e^{(-1.0548 L U_s / q_h)}) \qquad (15.22)$$

where,

L = basin length (m)

P_h = percentage of sediment deposited in any given hour

q_h = hourly discharge per unit width (m^2/s)

U_s = fall velocity of sediment particle (m/s)

The trapping efficiency of a basin is a function of the particle size distribution of the inflowing sediment. Assuming ideal settling conditions, all particles of size equal to or larger than those of the design particle will be retained in the basin.

Therefore, ideal basin efficiency corresponds to the percent of soil equal to or larger than the design particle size. For example, if a sediment basin on a site is designed to capture the 0.02 mm particle and 64 % of the particles on this site are greater than or equal to 0.02 mm, the maximum efficiency of the basin is 64 %. The only practical way to increase this efficiency is to increase surface area of the basin.

15.6.5 Transport Hydrology in Ponds

The previous section considered pollutant removal efficiency under constant discharge conditions, showing the effects of flow turbulence and short-circuiting. The procedures however need extending to determine pollutant removal under varied flow conditions as defined by an inflow hydrograph.

From the continuity equation principle, the sediment concentration variation with time in a fully mixed pond or reservoir is expressed as:

$$S\left(\frac{dC}{dt}\right) = I\,(C_i - C) - A.C.V_s \qquad (15.23)$$

where,

C = concentration of pollutant in the reservoir

C_i = concentration in the inflow, I

S = storage volume of the reservoir

A = surface area of the reservoir

t = time

V_s = pollutant settling velocity

This equation assumes no variation in pond volume. The equation is solved using the finite difference technique (Hall et al., 1993), which is similar to the storage routing procedure in Chapter 14.

$$\begin{aligned}\frac{1}{2\Delta t}(S_{n+1} + S_n)(C_{n+1} - C_n) \\ = (I_{n+1} + I_n)[(C_{i(n+1)} + C_{in})/2 - (C_{(n+1)} + C_n)/2]/2 \\ -AV_s(C_{(n+1)} + C_n)/2 \qquad (15.24)\end{aligned}$$

where, C_n is the concentration of pollutant in the reservoir and the outflow at time step n, C_{in} is the concentration in the inflow at time step n; S_n is the storage and Q_n the inflow at time step n, and Δt is the size of the time step. Equation 15.24 simplifies to:

$$C_{n+1} = C_n\left(\frac{K2_{n+1}}{K1_{n+1}}\right) + \left(\frac{K3_{n+1}}{K1_{n+1}}\right) \qquad (15.25)$$

where,

$$K1_{n+1} = (S_{n+1} + S_n) + \left(\frac{\Delta t}{2}\right)(I_{n+1} + I_n) + AV_s\Delta t \qquad (15.26a)$$

$$K2_{n+1} = (S_{n-1} + S_{n+1}) - \left(\frac{\Delta t}{2}\right)(I_{n+1} + I_n) - AV_s\Delta t \qquad (15.26b)$$

$$K3_{n+1} = \left(\frac{\Delta t}{2}\right)(I_{n+1} + I_n)(C_{i(n+1)} + C_{in}) \qquad (15.26c)$$

Equation 15.25 is recursive in form, with the concentration at time step $n + 1$ being computed from that at time step n using the coefficients $K1_{n+1}$ $K2_{n+1}$ and $K3_{n+1}$ obtained from Equation 15.26 a, b, and c. The calculation may be conveniently set out in tabular form, as shown in Table 15.3. Alternatively, one of a number of suitable computer models can be used for this type of calculation.

The tabular calculation is initiated by listing the known data (i.e. the inflows and the pollutant concentrations in the inflows) along with the information derived from the hydrologic routing, i.e. the variation of reservoir storage and the surface area of the reservoir with time in columns 2-5. Columns 6-8 are then used to form the sums of successive pairs of ordinates of the inflows, the reservoir storage and the pollutant concentrations in the inflows, respectively, starting at the second time increment.

The entries in these three columns provide the basic information on which the computations of the three routing coefficients of Equation 15.26 a, b, and c are based, e.g. $K1_2$ is obtained by adding: (1) entry in column 7, (2) half the time increment times the entry in column 6, and (3) the product of the water surface area at the second time increment, the representative particle settling velocity, and the time increment.

Estimation of the pollutant concentration in the outflow is then obtained from Equation 15.25 using the computed values of $K1_2$, $K2_2$ and $K3_2$ and the value of the outflow concentration at the previous time step. These calculations must be initiated by providing a value of C_i (initial condition) for the first time interval. This procedure is then repeated for all subsequent time intervals.

In practice, pollutant loads consist of a wide spectrum of particle sizes, each of which has a characteristic settling velocity. The settling characteristics will be greatly influenced by soil type. The practical applications of this method are discussed in Chapter 34 and 35.

15.6.6 Transport Hydraulics in Ponds

Maximising pollution removal efficiencies in ponds or lakes, requires consideration of flow patterns and hydraulic routing. As discussed in Chapter 12, the flow and mass transport equation must be solved in two or three-dimensions. The equation for two-dimension is:

$$\frac{\partial HC}{\partial t} + \frac{\partial HU_xC}{\partial x} + \frac{\partial HU_yC}{\partial y} = HD_x\frac{\partial^2 C}{\partial x^2} + HD_y\frac{\partial^2 C}{\partial y^2} \pm \sum HR \qquad (15.27)$$

in which D_x and D_y are dispersion coefficients in longitudinal and transverse directions. R is a reactive term and for particulate pollutants (e.g. total suspended sediments, organic nutrients and heavy metals), term R is determined by settling or deposition process. This procedure is solved together with Equation 14.18 and 14.19.

Practical guidelines for the design of ponds to maximise pollutant removal efficiency are given in Chapter 35.

15.6.7 Transport Hydraulic in Porous Media

As rainfall/stormwater percolates into the soil, it carries with it dissolved chemicals from pollutants accumulated on the land surface. Infiltration drives contamination into the soil through the vadose zone which extends from the ground surface to the water table and then past the water

Table 15.3 Tabular method for the routing of a pollutant through a storage reservoir

1	2	3	4	5	6	7	8	9	10	11	12
Time	Inflow	Concentration	Storage	Area	$I_{n+1}+I_n$	$S_{n+1}+S_n$	$C^i_{n+1}+C^i_n$	$K1_{n+1}$	$K2_{n+1}$	$K3_{n+1}$	C_n
t_1	I_1	C^i_1	S_1	A_1							C_1
t_2 etc	I_2	C^i_2	S_2	A_2	I_1+I_2	S_1+S_2	$C^i_1+C^i_2$	$K1_2$	$K2_2$	$K3_2$	C_2

table to the groundwater zone in which the chemicals may be transported laterally for distances of thousands of feet or meters. The presence of air in the soil complicates not only water flow but also flow of immiscible fluids such as hydrocarbons which may vaporise. In some cases losses through adsorption of the contamination on the soil, volatilisation to the atmosphere, degradation by micro-organisms, or through other physical, chemical or biological processes may prevent the contamination from reaching the water table.

These factors determine the ability of the soil to adsorb and degrade pollutants (the soils' assimilative capacity) and whether chemicals are likely to accumulate within the soil profile or leach through the profile and contaminate groundwater. Understanding these factors helps in identifying proper stormwater disposal sites and determining suitable remediation methods for contaminated sites.

Finally, these factors determine the appropriate mathematical models to predict transport and fate of chemicals in the unsaturated zone. For protection of public health and the environment, particularly groundwater, it is desirable to enhance losses and retardation of contamination in the soil.

Similarly the movement of dissolved constituents in unsaturated and saturated media is affected by three factors:

1. *advection* of the constituent with the water flowing through the media
2. *dispersion* of the constituent
3. *sources* and *sinks* of the constituent within the volume such as chemical reactions or adsorption onto the solid matrix

Mathematical models of solute transport are based on mass-balance equations that describe these factors.

(a) Unsaturated Media

The vertical convective dispersive equation that describes solute transport in unsaturated soils under steady state water flow (Equation 12.45) can be expressed as:

$$\theta \frac{\partial C}{\partial t} + \rho \frac{\partial S}{\partial t} = \theta . D \frac{\partial^2 C}{\partial z^2} - \theta . \upsilon \frac{\partial C}{\partial z} \tag{15.28}$$

where

t = time (T)
z = the distance (L)
C = the solute concentration in the liquid phase (M.L^{-3})
S = the sorbed concentration (M.L^{-3})
θ = the volumetric water content (L^3.L^{-3})
ρ = the bulk density of the porous medium (M.L^{-3})
D = a dispersion coefficient (L^2.T^{-1})
υ = the pore water velocity (L.T^{-1}).

The solution of Equation 15.28 requires the knowledge of $\partial S/\partial t$ or S in terms of C as given in the Freundlich isotherm often used to characterise adsorption equilibrium:

$$S = K_d C^b \tag{15.29}$$

where S is the sorbed concentration (M.L^{-3}), C is the solute concentration (M.L^{-3}), K_d is the sorption constant and b is a real exponent, $0 < b < 1$.

(b) Saturated Media

The governing transport equation in saturated media under similar conditions, is identical except that effective porosity (n_e) is used instead of water content (θ). As the stormwater spread into the larger groundwater system, the one-dimensional transport equation of saturated media can be extended to two-dimension and three-dimension for practical uses.

APPENDIX 15.A TYPICAL POLLUTANT EXPORT EQUATIONS

Table 15.A1 Storm Event Pollutant Exports (kg/km^2) for ACT and Brisbane, Australia

Pollutant	Landuse/vegetation categories		
	Native vegetation/ forest	Rural grazing	Established Urban
Sediment – ACT (no Brisbane data)	$200R^{1.1}$	$400R^{1.1}$	$1000R^{1.4}$
Suspended solids-ACT	$8R$	$20R$	$200R$
Brisbane	$130R^{0.75}$	$6.1R$	$166R^{0.75}$
Total phosphorus-ACT	$0.05R^{0.57}$	$0.12R^{0.57}$	$0.4R^{0.8}$
Brisbane	$0.17R^{0.9}$	$0.022R$	$0.15R^{0.9}$
Total nitrogen – ACT	$0.15R^{1.6}$	$0.3R^{1.6}$	$3R^{0.84}$
Brisbane	$1.5R^{0.86}$	$0.16R$	$1.45R^{0.86}$
Faecal coliforms ACT	$30\text{-}100 \times 10^9 R^{0.9}$	$300\text{-}1500 \times 10^9 R^{0.9}$	$400\text{-}1000 \times 10^9 R^{0.9}$
(cfu/km^2) Brisbane	$6.4 \times 10^9 R^{1.1}$	$1.0 \times 10^9 R^{0.95}$	$10.3 \times 10^9 R^{1.1}$

R = event runoff, in mm

Source: Willing & Partners (1999)

Reference areas: Brisbane and Canberra, Australia

It can be seen that there is a wide range in the values quoted. Either set of values should be used with care in Malaysia due to the significant climatic and other differences.

APPENDIX 15.B TYPICAL POLLUTANT CONCENTRATIONS IN RAINFALL

Sources: (a) Brezonik, 1975; (b) Mattraw & Sherwood, 1977

Parameter	Typical concentration range	Units
Acidity (pH) (a)	3 – 6	
Organics (a): BOD_5	1 – 13	mg/L
COD	9 - 16	mg/L
TOC (b)	1 - 3	mg/L
Inorganic C (b)	0 - 2	mg/L
Colour (b)	5 - 10	PCU
Solids: Total (b)	18 - 24	mg/L
Suspended solids (b)	2 - 10	mg/L
Turbidity (b)	4 – 7	JTU
Nutrients (a):		
Organic N	0.5 – 1.0	mg/L
NH_3-N (b)	0.01 – 0.04	mg/L
NO_2-N (b)	0.00 – 0.01	mg/L
NO_3-N	0.05 – 1.0	mg/L
Total N	0.02 – 1.5	mg/L
Orthophosphorus	0.0 – 0.05	mg/L
Total P	0.02 – 0.15	mg/L
Heavy metals: (a)		
lead	30 - 70	µg/L

APPENDIX 15.C WORKED EXAMPLE

15.C.1 Calculation of Typical Pollutant Loads as a function of Rainfall ARI

Problem: Estimate the average annual pollutant loads from a sample 100 hectare catchment with 50% directly-connected impervious area (DCIA). Prepare curves showing the average annual load carried in storms equal to or exceeding storms of different ARI. Use Ipoh IDF data and assume a 30 minute storm duration.

Solution:

1) The first step is the calculation of runoff volumes for a range of return periods using the Volumetric Rational Method. This step is shown in the following Table 15.C1.

   A ten year simulation period is assumed in order to simplify the calculations. The spreadsheet calculates event runoff by the Rational Formula as a function of rainfall intensity, and also calculates the total runoff from events of that size during a ten year period. The average number of events in this ten year period is equal to the ARI multiplied by ten. The method uses the probabilistic interpretation of storm exceedance, and ignores the effect of storms larger than 20 year ARI as the contribution of such storms on an annual basis is negligible.

   Calculations are performed row by row for storms of a range of ARIs. The total runoff volumes from storms of each size are summed to produce the expected total annual runoff. This method is a simplification of the real situation because it assumes that there is no runoff from storms of less than the smallest size (1/16 year ARI). The error introduced by this assumption is negligible.

Table 15.C1 Runoff Volume Calculation for 50% DCIA

50% Directly-connected Impervious Area

Size of Event (ARI)	Average no. of Events in 10 years	Rainfall		Runoff Coefficient C	Runoff (m^3)				Cumulative Runoff as % of Total
		mm per Event	Intensity (mm/hr)		mm per Event	Total per Event	Total in 10 years	Amount in Larger Events	
0.0625	160	9.0	18.0	0.49	4.4	4,410	705,600	2,713,924	78.7%
0.125	80	17.5	35.0	0.63	11.0	11,025	882,000	1,831,924	85.7%
0.25	40	24.0	48.0	0.68	16.3	16,320	652,800	1,179,124	90.8%
0.5	20	31.7	63.4	0.72	22.8	22,824	456,480	722,644	94.3%
1	10	42.3	84.5	0.76	32.1	32,110	321,100	401,544	96.9%
2	5	52.8	105.6	0.80	42.2	42,240	211,200	190,344	98.5%
5	2	61.7	123.4	0.82	50.6	50,594	101,188	89,156	99.3%
10	1	68.9	137.8	0.84	57.9	57,876	57,876	31,280	99.8%
20	0.5	73.6	147.2	0.85	62.6	62,560	31,280	0	100%

Assumptions:
Rainfall IDF data for Ipoh, extrapolated to small ARI
Sample catchment area = 100 ha
DCIA = 50%
t_c = 30 minutes

Use Curve 3 on Design Chart 14.3

References:
Methodology based on CRCFE (1998), Case Study 2

Weighted C_v 0.58
Annual Runoff 1277 mm
Annual Volume 1,277,000 m^3
Percentage (%) = $\frac{\text{(total- amount in larger events)}}{\text{total}}$

2) The second step is the calculation of annual loads of selected pollutants for a range of return periods using the runoff calculated in Table 15.C1. This step is shown in the following Table 15.C2. The Table follows a similar structure to Table 15.C1. For storms of each ARI, the runoff is obtained from the previous table and is multiplied by the EMC to give pollutant load.

Note that in this example the EMC formulation is used for each of the selected pollutants. Therefore pollutant load is directly proportional to flow. This would not be the case if an alternative formulation for pollutant load was used.

Table 15.C2 Pollutant Load Calculation for 50% DCIA

Sediment Loading

Size of Event (ARI)	Average no. of Events in 10 years	Runoff (mm per Event)	Sediment Export (t)				Amount in Larger Events	Cumulative Export as % of Total
			Urban	Rural	Total per Event	Total in 10 years		
0.0625	160	4.4	0.53	0.88	1.4	225	867	20.6%
0.125	80	11.0	1.32	2.20	3.5	282	586	46.4%
0.25	40	16.3	1.96	3.26	5.2	209	377	65.5%
0.5	20	22.8	2.74	4.56	7.3	146	231	78.8%
1	10	32.1	3.85	6.42	10.3	103	128	88.2%
2	5	42.2	5.06	8.44	13.5	68	61	94.4%
5	2	50.6	6.07	10.12	16.2	32	29	97.4%
10	1	57.9	6.95	11.58	18.5	19	10	99.1%
20	0.5	62.6	7.51	12.52	20.0	10	0	100%
					Total	1,093		

Assumptions:
Sediment EMC Urban 200
(mg/L) Rural 500
Rainfall IDF data for Ipoh, extrapolated
30 minute duration event
60.0 ha Urban @ 80% DCIA
40.0 ha Rural @ 5% DCIA
100.0 ha total DCIA %= 50.0

References:
Methodology based on CRCFE (1998), Case Study 2
Events larger than 20 year are not significant

Estimated annual sediment yield (t)
109

Suspended Solids Loading

Size of Event (ARI)	Average no. of Events in 10 years	Runoff (mm per Event)	SS Export (t)				Amount in Larger Events	Cumulative Export as % of Total
			Urban	Rural	Total per Event	Total in 10 years		
0.0625	160	4.4	0.22	0.05	0.28	44.4	170.8	20.6%
0.125	80	11.0	0.56	0.13	0.69	55.4	115.3	46.4%
0.25	40	16.3	0.83	0.20	1.03	41.1	74.2	65.5%
0.5	20	22.8	1.16	0.27	1.44	28.7	45.5	78.8%
1	10	32.1	1.64	0.39	2.02	20.2	25.3	88.2%
2	5	42.2	2.15	0.51	2.66	13.3	12.0	94.4%
5	2	50.6	2.58	0.61	3.19	6.4	5.6	97.4%
10	1	57.9	2.95	0.69	3.65	3.6	2.0	99.1%
20	0.5	62.6	3.19	0.75	3.94	2.0	0.0	100%
					Total	215.1		

Assumptions:
SS EMC Urban 85
(mg/L) Rural 30

References:
Methodology based on CRCFE (1998), Case Study 2
Events larger than 20 year are not significant
Estimated annual SS yield (t)
21.5

Total Phosphorus Loading

Size of Event (ARI)	Average no. of Events in 10 years	Runoff (mm per Event)	TP Export (kg)				Amount in lLarger Events	Cumulative Export as % of Total
			Urban	Rural	Total per Event	Total in 10 years		
0.0625	160	4.4	0.34	0.16	0.50	80.26	308.99	20.6%
0.125	80	11.0	0.86	0.40	1.25	100.32	208.67	46.4%
0.25	40	16.3	1.27	0.59	1.86	74.33	134.34	65.5%
0.5	20	22.8	1.78	0.82	2.60	51.98	82.35	78.8%
1	10	32.1	2.50	1.16	3.66	36.59	45.76	88.2%
2	5	42.2	3.29	1.52	4.81	24.05	21.71	94.4%
5	2	50.6	3.95	1.82	5.77	11.54	10.17	97.4%
10	1	57.9	4.52	2.08	6.60	6.60	3.57	99.1%
20	0.5	62.6	4.88	2.25	7.14	3.57	0.00	100%
					Total	389.2		

Assumptions:
TP EMC Urban 0.13
(mg/L) Rural 0.09

References:
Methodology based on CRCFE (1998), Case Study 2
Events larger than 20 year are not significant

Estimated annual TP yield (kg)
38.9

15.C.2 Calculation of Sediment Loads

Problem:

For a 50 hectare catchment, estimate the expected annual sediment loads for pre, during, and post medium residential development (35% imperviousness) in an area where the annual rainfall is 1800 mm.

Solution: The calculations are shown in the following Table.

Condition	C_v	EMC (g/m^3)	Annual Runoff Depth (mm)	Annual Runoff Volume (m^3)	Load (tonnes)
Pre-development	0.20	500	360	180,000	90.0
Construction	0.40	4000	720	360,000	1440
Post-development	0.55	120	990	495,000	59.4

When the sediment is deposited it will be poorly consolidated. For estimating the volume (m^3) of deposited material, an in-situ sediment dry density of 750 kg/m^3 is recommended. Also when considering the likely variation in deposited quantities, the concentration could vary depending on landuse and catchment characteristics.

15.C.3 Hydrologic Routing Through Pond

Problem (from Hall et al. 1993)

A 2 year ARI flood hydrograph with an average sediment concentration of 185 mg/l passes through a storage reservoir having an outlet control consisting of a broad-crested weir for which the outflow discharge, Q (m^3/s), is related to head, h (m) by $Q = 8.3\,h^{1.5}$ and the water surface area, A (m^2) and storage volume S (m^3), of the reservoir are related to the head, h by $A = 140{,}000\,h^{0.25}$;: $S = 112{,}000\,h^{1.25}$. Estimate the trap efficiency.

The soil data is shown in the following table.

Particle Size	Percentage (%)	Settling Velocity (m/s)
Large	31	0.07
Medium	54	0.0067
Small	15	0.000016

Solution:

The first step involves the hydrologic routing of the given inflow hydrograph through the storage reservoir using the full routing methods described earlier. These calculations produce the variations with time of the water surface area and storage volume in the reservoir and the outflow discharge. Routing of the pollutants is then carried out using the approach described in Section 15.6.5, using in turn each of the three settling velocities (adjusted for the effect of turbulence). The loadings (g/s) for each time increment are obtained by multiplying the ordinates of the inflow hydrograph (m^3/s) by the average inflow concentration of 185 mg/l and the ordinates of the outflow hydrograph by the derived values of the concentration of pollutant in the outflow. Trap efficiency is then computed from Equation 15.18. The values of trap efficiency for the three representative particle sizes are then weighted according to the above size distribution to give an overall value. Part of the calculations for the medium-size fraction are presented in Table 15.C3 in order to illustrate the procedure.

The calculations are also carried out for the smallest and the largest size fractions. The results show that the trap efficiencies are 99.5, 95.12 and 9.9 % for the largest, the medium, and the smallest size ranges respectively, leading to an overall (weighted) trap efficiency of 83.7 %.

Table 15.C3 Typical Calculation for the Routing of Pollutants using a 2 year ARI Hydrograph for a Storm Duration of 12.5 hrs and the Medium Size Fraction with a Settling Velocity of 0.00074 m/s

Time (h)	Inflow (m^3/s)	Conc. in (mg/l)	Outflow (m^3/s)	Head (m)	Storage (m^3)	Area (m^2)	Sum Inflow	Sum Storage	Sum Conc in
0.0	0.412	185	0.262	0.100	6,289	78,704			
0.5	0.451	185	0.276	0.103	6,568	79,390	0.863	12,856	370
1.0	0.571	185	0.296	0.108	6,962	80,321	1.022	13530	370
1.5	0.768	185	0.328	0.116	7,584	81,707	1.339	14546	370
2.0	1.016	185	0.379	0.128	8,554	83,699	1.784	16138	370
2.5	1.291	185	0.452	0.144	9,907	86,193	2.307	18461	370
3.0	1.584	185	0.546	0.163	11,596	88,950	2.875	21503	370
etc.									

Time (h)	*K1*	*K2*	*K3*	Conc. out (mg/l)	Load in (g/s)	Load out (g/s)
0.0						
0.5	120,016	-94,303	287,379	2.395	83.4	0.661
1.0	122,080	-95,021	340,326	0.924	105.6	0.273
1.5	125,238	-96,147	445,887	2.851	142.1	0.935
2.0	129,901	-97,625	594,072	2.431	188.0	0.921
2.5	136,036	-99,114	768,231	3.876	238.8	1.752
3.0	143,284	-100,278	957,375	3.969	293.0	2.167

15.C.4 Sedimentation in Ideal Storage Basin

Problem: (From Hall et al, 1993)

A 805.2 m long (L), flood storage basin of mean depth 2.024 m (d_I) , cross-sectional area 217.2 m^2 has a steady state inflow/outflow discharge (Q), of 10.64 m^3/s. Calculate the trap efficiency for clay (0.004 mm, $V_s = 1.6 \times 10^{-5}$ m/sec) and fine sand (0.2 mm, $V_s = 2.2 \times 10^{-2}$ m/sec) particles.

Solution:

1) Volume (Vol) = $L \times W \times D =$ 805.2 x 217.2 = 0.175×10^6 m^3

2) Mean hydraulic residence time $t_h = LWD/Q$

   = $0.175 \times 10^6/10.64 = 1.64 \times 10^4$ sec (4.6 hr)

3) Mean through-flow velocity = L/ residence time = $805.2/1.64\ 10^4 = 0.049$ m/sec

4) For clay particles, 0.004 mm in diameter and $V_s = 1.6 \times 10^{-5}$ m/sec, efficiency is:

   $\eta = V_s t_h / d_m = 1.6 \times 10^{-5} \times 1.64 \times 10^4/2.04 = 0.13$

5) For fine sand 0.2 mm in diameter and $V_s = 2.2 \times 10^{-2}$ m/sec, efficiency is:

   $\eta = 2.2 \times 10^{-2} \times 1.64 \times 10^4/2.04 = 177$

Therefore the reservoir would trap 13 % of the clay while all the sand (100 %) would be trapped within 1/177 of the basin length. This approach nevertheless assumes steady-state conditions and does not consider the effects of flow turbulence which would retard settlement, or of short-circuiting routing sediments through the reservoir.