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Pollution Due to Urban Runoff: Unit Loads and Abatement Measures

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INTERNATIONAL REFERENCE GROUP ON GREAT LAKES POLLUTION FROM LAND USE ACTIVITIES

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POLLUTION DUE TO URBAN RUNOFF: UNIT LOADS AND ABATEMENT MEASURES

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1. INTRODUCTION

One of the objectives of the PLUARG Modelling Task Force is to develop an overview model of outputs of land derived pollutants subject to selected management scenarios in a search for cost-effective strategies to meet target reductions. Towards this end, a pilot model has been developed. The model is based on the conceptualization of watersheds as sets of identifiable units of specified land form and land use. These units contribute pollution loads to the main river in series from headwaters to the river mouth. To evaluate the contribution of individual units, one needs to develop unit loads for various land forms and land uses.

The Hydraulics Research Division (HRD) of the National Water Research Institute has been asked by PLUARG to provide estimates of pollution loads for watershed units with urban land use and to evaluate various pollution abatement measures for urban runoff. To meet the PLUARG deadline, the information requested had to be produced in a short time period using the existing information to a maximum possible extent. Two short reports [5, 6] were submitted by HRD to PLUARG to comply with the original request. Eventually, these reports were integrated into a single report which is presented here.

The terms of reference of the integrated report may be summarized as follows:

(a) Provide estimates of annual unit loads of selected pollutants in urban runoff.

(b) Provide estimates of efficiencies and costs of selected abatement measures for pollution due to urban runoff.

2. ANNUAL POLLUTANT UNIT LOADS IN URBAN RUNOFF

The annual pollutant unit load in urban runoff is defined here as the pollutant weight which is conveyed by urban runoff from a one-hectare area over a one-year period. These loads are presented in the following for various pollutants, land uses, and sewer systems.

2.1 PLUARG Requirements on Unit Loads

2.1.1 Land use

To maintain consistency with the previous PLUARG work, the annual unit loads were to be provided for a number of urban land uses. A conventional land use classification system was used originally [5]. This classification included the following types of land use:

(a) Residential (low, medium and high density)
(b) Commercial
(c) Industrial
(d) Other developed

This conventional land use classification was found inappropriate for PLUARG modelling activities because of the following reasons:

(1) The conventional classification was not fully compatible with the land use data available to the PLUARG researchers.
(2) The conventional classification did not fully reflect the potential of various land uses to contribute to pollutant loadings in urban runoff. For example, in the conventional classification, low-nuisance non-manufacturing industrial activities fall into the same category as hazardous or noxious industrial activities.

Consequently, an amended classification of urban land use was adopted. Basically, four types of land use are considered.

Land Use Group 1

This type of land use contributes relatively low pollutant loads. Among typical land uses included in this group, one could name low and medium density residential land use, and limited-nuisance industrial activities (wholesale, warehouses).

Land Use Group 2

This type of land use generates intermediate pollutant loads. Typical land uses included in this group are high density residential (125 people/hectare), and commercial land use.

Land Use Group 3

This type of land use contributes the highest pollutant loads. Typical land uses included in this group are medium and high intensity industrial land use.

Land Use Group 4

This type of land use contributes very low pollutant loads. Typical land uses included in this group are parks, playgrounds, etc. In many cases, the pollution contribution of this group may be neglected.

Finally, a mention should be made of newly developed urban land. This stage of land development is characterized, for all land uses, by high production of suspended solids because of soil erosion. If no erosion prevention measures are taken during the development, the suspended solids loads from newly developed urban land reach levels of about 1700 kg/hectare/year. It is, therefore, necessary to differentiate between the established and newly developed urban land. In the PLUARG model, the urban areas are considered to be fully established one year after the completion of the development. Note that this differentiation is made here only for the loads of suspended solids.

2.1.2 Pollutants to be studied

The selection of water quality parameters investigated in urban runoff studies varies widely. The parameters studied in this report were specified by PLUARG as follows:

Biochemical Oxygen Demand	BOD
Nitrogen	N
Phosphorus	P
Suspended Solids	SS
Cadmium	Cd
Chromium	Cr
Copper	Cu
Mercury	Hg
Nickel	Ni
Lead	Pb
Zinc	Zn

2.1.3 Sewer systems

The pollution due to urban runoff has different forms depending on the sewer system. In the separate sewer system, urban runoff is conveyed by storm sewers and one is therefore interested in the loads discharged from storm sewers.

In the combined sewer system, the pollution loads can be divided into two components. The first component is the load which is conveyed by the combined sewer interceptors to the wastewater treatment plant. This load represents a point source and was not included in the terms of reference of this study.

The second component is conveyed by combined sewer overflows. These overflows occur during the wet weather when the interceptor capacity is exceeded because of large inflows of surface runoff into the sewers. The load conveyed by overflows which is sometimes referred to as the wet weather load was quantified in this report.

2.2 Literature Survey of Urban Runoff Unit Loads

The main objective of the literature survey was to review the available unit loads with regard to the PLUARG requirements. Two types of unit loads were found in the literature - the loads calculated from the equation proposed by the American Public Works Association (APWA) [9], and the loads derived for several Ontario test catchments [8].

2.2.1 APWA unit loads

The APWA unit loads were prepared under a contract commissioned by the Urban Drainage Subcommittee [9]. Although APWA was to use the Ontario field data to the maximum possible extent, very little such data were available in the early stages of the APWA project and, consequently, the loads were based mainly on U.S. field data. In fact, APWA used pollutant concentration data from one Canadian (Windsor) and seven American cities.

BOD effluent data from 19 residential catchments were used by APWA to derive a general load equation in the following form:

$$L = a\,P\,(b + c\,D^{d}) \qquad (1)$$

where L is the annual unit load (kg/ha), P is the annual precipitation (m), D is the population density (people/ha), and a, b, c, d are experimental parameters. By substituting proper values of these parameters into Equation 1, it is possible to calculate the annual unit loads of various pollutants for both storm and combined sewers, and for various land uses.

The selection of the independent variables, P and D, was based on the following reasoning:

The annual unit loads will increase with an increasing annual precipitation.

The population density then determines the proportion of precipitation converted into runoff and also composition of runoff.

To gain a better appreciation of the accuracy of loads calculated from Equation 1, the derivation of Equation 1 is briefly examined below for both storm and combined sewers.

2.2.1.1 Storm water loads. Pollution loads in runoff from urban areas served by storm sewers were reported for numerous locations and could be used by APWA to compute the annual unit loads. Fairly extensive effluent data were available for residential areas; for other land uses, the data available were rather limited. The effluent data expressed in flow-weighted mean concentrations were multiplied by the annual runoff per unit area to obtain the annual unit loads.

For residential areas, Equation 1 was fitted to annual unit BOD loads from 19 catchments. The goodness of fit deserves further attention and is examined below. For that purpose, Equation 1 was rearranged into the form

$$\frac{L}{P} = a\,(b + c\,D^{d}) \qquad (2)$$

and the field data were rearranged accordingly. Using the method of least squares, Equation 2 was fitted to the field data as shown in Fig. 1. The goodness of fit was rather poor because of the large scatter in field data. Under these circumstances, one may consider approximating the field data by simpler relationships than Equation 2. In particular, one could consider a linear relationship, or simply assume that the pollutant loads are constant for various population densities (i.e. L/P=const., for a particular land use). All the relationships considered are plotted in Fig. 1. The goodness of fit for all these relationships was evaluated by calculating total variations of observed loads about the calculated ones. The least variation was obtained for the linear regression equation and was only slightly smaller (by 2%) than the variation about the mean. The largest variation was obtained for Equation 2. It is evident, therefore, that Equation 2 is based on intuition rather than on a statistical analysis of the observed loads. This point is illustrated in Figure 1 in which the observed loads as well as the calculated loads are plotted. The accuracy of loads computed from Equation 1 will not be better than plus minus several hundred percent.

For other pollutants, corresponding values of parameters a, b, c, d were derived by APWA from the analysis of surface accumulations of dust and dirt. Knowing the daily accumulation rates and the composition of dust and dirt, the annual unit pollutant accumulations were taken as the annual unit loads.

Unit loads for other than residential land use were determined from the following equation:

$$L_i = L_r \frac{d_i}{d_r} \frac{G_i}{G_r} \frac{F_i}{F_r}$$

where d is the dust and dirt accumulation rate in weight units/unit curb length/day, G is the length of curb per unit area, F is the fraction of dust and dirt that is a particular pollutant, and indices i and r refer to a particular land use and the residential land use, respectively. The ratios d_i/d_r and F_i/F_r were adopted from a previous study in Chicago, and the ratios G_i/G_r were taken as averages of the data collected in Tulsa (Oklahoma) and in three cities in Ontario.

The use of Equation 3 for calculation of unit loads is consistent with the concept of surface accumulation and wash-off of pollutants as a main source of pollution in urban runoff. However, there are hardly any effluent data to verify the calculated loads which are likely to contain very large uncertainties. Some limited effluent data for a commercial area in Burlington agreed quite well with the APWA estimates.

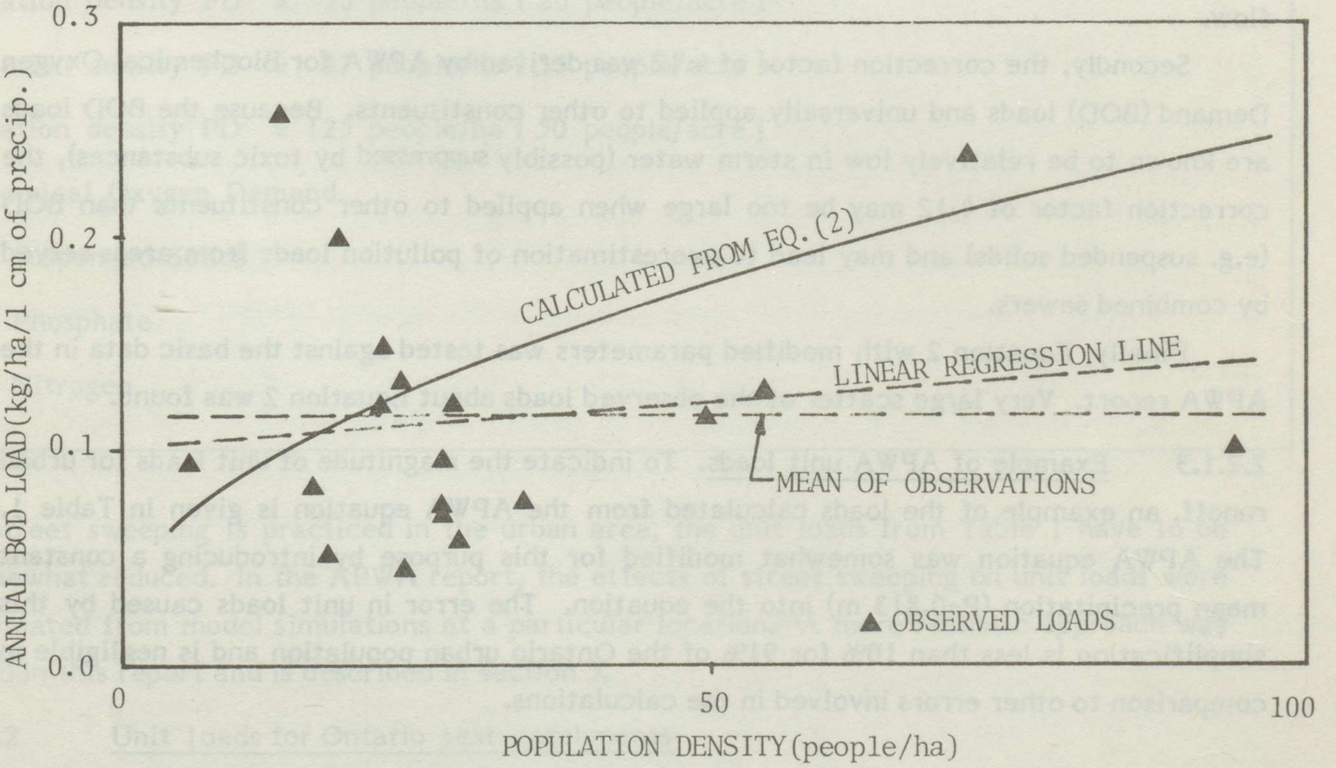

FIGURE 1 **OBSERVED AND CALCULATED ANNUAL BOD LOADS**

2.2.1.2 Combined sewer overflow loads. Pollution loads in combined sewer overflows are difficult to quantify, because these loads depend on a large number of factors including the climate, interceptor capacity, sewer system maintenance and operation, and land use. Because of these difficulties, numerous assumptions had to be adopted by APWA to produce wet weather loads from areas served by combined sewers. Among these assumptions, the most important are the following:

(a) The annual volume of flow which bypasses the waste treatment plant is equal to the annual surface runoff from the area.

(b) Pollutant concentrations in combined sewer flow are 4.12 times higher than those in storm water.

Consequently, the unit loads from areas served by combined sewers were obtained by multiplying the loads from separate sewerage areas by 4.12 and Equation 1 with appropriate values of parameters a, b, c, d is again applicable.

The validity of assumptions (a) and (b) is examined here. Firstly, the volume of flow bypassing the treatment plant will be smaller than the volume of surface runoff, because combined sewer interceptors have capacities larger (1.5 - 3 times) than the dry weather flow. Consequently, not only the dry weather flow but also some runoff are conveyed to the waste treatment plant of which capacity also exceeds the average daily dry weather flow.

Secondly, the correction factor of 4.12 was derived by APWA for Biochemical Oxygen Demand (BOD) loads and universally applied to other constituents. Because the BOD loads are known to be relatively low in storm water (possibly suppressed by toxic substances), the correction factor of 4.12 may be too large when applied to other constituents than BOD (e.g. suspended solids) and may lead to overestimation of pollution loads from areas served by combined sewers.

Finally, Equation 2 with modified parameters was tested against the basic data in the APWA report. Very large scatter of the observed loads about Equation 2 was found.

2.2.1.3 Example of APWA unit loads. To indicate the magnitude of unit loads for urban runoff, an example of the loads calculated from the APWA equation is given in Table 1. The APWA equation was somewhat modified for this purpose by introducing a constant mean precipitation (P=0.813 m) into the equation. The error in unit loads caused by this simplification is less than 10% for 91% of the Ontario urban population and is negligible in comparison to other errors involved in the calculations.

TABLE 1 MODIFIED APWA UNIT LOADS[KG/HA/YEAR] FOR VARIOUS LAND USES AND SEWER SYSTEMS

	SEPARATE SEWERS STORM WATER				COMBINED SEWERS OVERFLOW			
	BOD[4]	SS[5]	PO_4[6]	N[7]	BOD	SS	PO_4	N
1. RESIDENTIAL								
(a) Low density[1]	36	730	1.46	5.8	148	3000	6.00	24.0
(b) Medium density[2]	46	956	1.90	7.6	194	3940	7.84	31.4
(c) High density[3]	56	1131	2.24	9.1	231	4660	9.23	37.4
2. COMMERCIAL	93	645	2.24	8.5	383	2658	9.23	35.0
3. INDUSTRIAL	36	853	2.13	8.1	148	3516	8.77	33.3
4. OTHER	.49	11.8	.04	.27	2.01	48.5	.18	1.12

[1]Population density PD = 50 people/ha [20 people/acre]

[2]Population density PD = 87 people/ha [35 people/acre]

[3]Population density PD = 125 people/ha [50 people/acre]

[4]Biochemical Oxygen Demand

[5]Total Suspended Solids

[6]Total Phosphate

[7]Total Nitrogen

If street sweeping is practiced in the urban area, the unit loads from Table 1 have to be somewhat reduced. In the APWA report, the effects of street sweeping on unit loads were estimated from model simulations at a particular location. A more realistic approach was used in this report and is described in section 3.

2.2.2 Unit loads for Ontario test catchments

The quantity and quality of urban runoff have been monitored in several Ontario test catchments. These data were then used to derive experimental unit loads for urban runoff.

2.2.2.1 Separate sewers. A number of studies of drainage effluent composition have been undertaken in areas served by storm sewers. Two land uses have been studied - a residential land use and a commercial land use.

Residential Areas

Effluent data from four catchments were available. None of the data records spanned over the entire 12 month period and the data had to be extrapolated by various methods. The simplest extrapolation was to determine the flow-weighted mean concentrations of individual pollutants and calculate the annual loadings by multiplying these concentrations by the annual runoff volume per unit area [8]. In other approaches, a simulation model was used to fill gaps in the data [11], or the existing data were used to develop a simple regression model of runoff quality and this model was then run for a one year period to produce the annual loadings [4]. The summary of the annual loadings derived for several Ontario catchments appears in Table 2.

TABLE 2 UNIT LOADS [KG/HA/YEAR] FOR ONTARIO URBAN TEST CATCHMENTS (AFTER REF. 8)

CATCHMENT	BOD	SS	P	N
Windsor "A"	35.3	608	0.65	1.40
Windsor "B"	24.6	493	8.91*	3.18
North York	18.9	208	2.62	13.00
Burlington (Malvern)	30.5	240	1.34	11.20
Mean	27.3	388	1.53	7.20
Standard Deviation	7.1	195	1.00	5.75

* Not considered for calculating the mean.

With the exception of SS, the mean values from Table 2 agree reasonably well with the APWA estimates (see Table 1). Modern residential areas, such as North York and Burlington, produced relatively low loads of suspended solids. Older residential areas, such as both Windsor catchments, produced SS-loads comparable to the APWA estimates. On the other hand, the modern urban areas produced N and P loads which were higher than those from the older areas.

Other Land Use

Limited effluent data were available for a commercial plaza in Burlington [5]. These data were used to produce average concentrations and, after multiplication by the annual runoff, annual unit loads. These unit loads are shown in Table 3 below.

TABLE 3 UNIT LOADS [KG/HA/YEAR].

	BOD	SS	P	N
Burlington Commercial Area	101	233	3.5	15.0

The agreement between the Burlington data and the APWA estimates is acceptable. As in the case of residential land use, the largest discrepancies were found for suspended solids. It is conceivable that these discrepancies could be partly caused by street sweeping. The Burlington data are affected by street sweeping, whereas the APWA estimates were presented without considering any street sweeping effects.

No other than commercial land use has been monitored to any reasonable extent.

2.2.2.2 Combined sewers. Combined sewer overflows have not been regularly monitored in any Ontario test catchments. However, the composition of wet weather flows in combined sewers has been monitored in two catchments in Hamilton [2] and Toronto [11]. The unit loads for areas served by combined sewers can be calculated by using the flow quality data for wet weather flows and estimating the annual overflow volumes.

Residential Land Use

The composition of wet weather flows in combined sewer areas was determined first followed by the calculation of the annual volume of overflows.

The compositions of wet weather flows were available for two Ontario test catchments and for some U.S. test catchments. These experimental data were supplemented by the compositions calculated for a mixture of sanitary sewage and storm water. All the data are shown in Table 4.

The concentrations reported by U.S. EPA were adopted for the calculation of unit loads, because these concentrations represent means of data from a large number of catchments.

TABLE 4 COMPOSITION OF FLOWS IN COMBINED SEWERS

Source	Reference	CONCENTRATION (mg/litre)			
		BOD	SS	P	N
Dry weather flow	Ontario Data [3]	130	130	8	35
Storm water	Malvern [4]	14	120	.6	5
Combined sewage	Frankdale Catchment [11]	40	130	1.9	10.9
Combined sewage	Hamilton [2]	21	515	3.4	5.6
Combined Sewage	Mean values reported by EPA [10]	119	198	6.45	16.5
Mixture of sanitary sewage and storm water	Calculated from the above data	107	128	7.4	28.3

To estimate the annual volume of overflows, it is assumed that this volume is equal to the annual runoff reduced by the volume of runoff which is conveyed by sewer interceptors during the wet weather. Interceptors in combined sewer systems are designed to convey the dry weather flow (DWF) plus some portion of surface runoff. For the typical interceptor capacities of 1.5 - 3 times the dry weather flow, the excess capacity available for urban runoff is 0.5 -2 times DWF. The calculation of annual overflows from residential areas served by combined sewers is given in Table 5. All the assumptions made in these calculations can be inferred from the table.

TABLE 5 VOLUME OF COMBINED SEWER OVERFLOWS

	Population Density (People/hectare)		
	50	87.5	125
Annual Precipitation [m]	.813	.813	.813
Catchment Imperviousness [%]	35	45	55
Annual Runoff [m^3/ha]	2845	3658	4471
Volume of Runoff Conveyed to the Waste Treatment Plant (Estimated as 1000 times the hourly dry weather flow) [m^3/ha]	948	1659	2370
Annual Overflow Volume [m^3/ha]	1897	1999	2101

Finally, the unit loads for both dry weather flow and combined sewer overflows can be calculated by combining the data from Tables 4 and 5. The results of these calculations are given in Table 6.

TABLE 6 ESTIMATED UNIT LOADS FOR DRY WEATHER FLOW AND COMBINED SEWER OVERFLOWS

Population Density (people/ha)	Annual Loads in DWF (kg/ha/year)				Annual Loads in Overflows (kg/ha/year)			
	BOD	SS	P	N	BOD	SS	P	N
50	1079	1079	66.4	290.5	225.7	565	12.2	31.3
87	1888	1888	116	508	238	596	12.9	33.0
125	2697.5	2697.5	166	726.2	250	626	13.6	34.7
Load Estimates for Frankdale Catchment [11]					231	640	10.6	63

The loads calculated in Table 6 compared quite well with those estimated for the Frankdale catchment [11].

When comparing the data in Table 6 with the APWA estimates (Table 1), good agreement was found for BOD, P, and N. For suspended solids, the APWA loads seem to be overestimated. In fact, the APWA suspended solids loads exceed the sum of suspended solids in dry weather flow and surface runoff.

Other Land Use

No other than residential land has been monitored in urban catchments served by combined sewers. Consequently, the APWA estimates cannot be verified against field data. Because the APWA residential loads of solids seem to be overestimated and served as a basis for calculations for other land uses, the latter loads will be also overestimated.

2.3 Recommended Unit Loads

Neither of the two data sources, the APWA report and Ontario data, offers a clear advantage to be used as a sole source. The main advantages of the APWA data are their presentation in an analytical form, which makes it possible to calculate unit loads for all land uses and population densities. On the other hand, the APWA formulas have been derived from a limited data base and the choice of the two independent variables, the annual precipitation and population density, is not supported by this data base.

The data from Ontario test catchments have sufficient scope only for residential areas served by separate sewers. Four such areas have been monitored. Fairly extensive data are available for the Burlington and Windsor catchments. About 10% of the annual runoff were sampled in Burlington, at a 6.5 minute interval. About 50% of the annual runoff were sampled in Windsor, at hourly intervals.

Some limited data exist for a commercial plaza served by separate sewers. No other land uses have been monitored.

In general, the APWA and Ontario unit loads for storm water agreed fairly well.

Combined sewer catchments in Hamilton and Toronto produced good data on the composition of wet weather flows in combined sewers. As expected, the Hamilton catchment produced high loads of suspended solids caused by construction activities in the catchment.

With the exception of suspended solids, fair agreement between the APWA and Ontario data was found for residential areas served by storm as well as combined sewers. It was therefore possible to use the APWA as a basis for estimating the unit loads of BOD, N, and P in storm water and overflows from all the land uses. For suspended solids, the recommended unit loads were based on the Ontario data.

In addition to the four basic constituents dealt with previously, it was necessary to derive new unit loads for selected metals. Extensive data on metals in urban runoff were available for the Malvern and Hamilton catchments [5, 2].

The Malvern catchment represents a modern residential area which is served by storm sewers. The Malvern loads of selected metals were adopted as typical loads for storm water and the land use group 1; for other land uses, these loads were corrected by means of the coefficients analogous to those given in the APWA report [9]. In particular, the following relations among unit loads for various land uses were adopted:

$$L_2 = 1.10\,L_1 \quad L_3 = 1.71\,L_1 \quad L_4 = 0.14\,L_1$$

where L is the unit pollutant load (kg/ha/year), subscripts 1-4 refer to the land use groups described earlier in this section.

For areas served by combined sewers, the data from the Hamilton test catchment were used [2]. The Hamilton test catchment represents an older residential area which is served by combined sewers. Considering combined sewage as a mixture of sanitary sewage and storm water, pollutant concentrations in combined sewage were estimated as weighted averages of concentrations observed in sanitary sewage and in storm water. Pollutant loads were then determined for appropriate flow volumes and taken as the loads which correspond to the land use group 1. For other land uses, the APWA correction coefficients (listed above) were again applied.

All the annual unit pollutant loads recommended for use in the PLUARG model are given in Table 7. Very little information is available to estimate uncertainties in the recommended loads. Judging from the range of values reported in the literature [5], these uncertainties may be in the order of several hundred percent.

Note that street sweeping will reduce the annual unit loads. This subject is dealt with in the following section.

TABLE 7 ANNUAL UNIT POLLUTANT LOADS IN KILOGRAMS/HECTARE/YEAR

Sewerage System	Constituent	Land Use Group 1[1]	Land Use Group 2[2]	Land Use Group 3[3]	Land Use Group 4[4]
Storm Sewers	BOD	34.0	90.0	34.0	1.12
	N	9.0	11.2	7.8	.22
	P	1.6	3.4	2.2	.04
	SS	390.0	560.0	672.0	11.2
	Cd	.013	.016	.024	.002
	Cr	.026	.028	.044	.003
	Cu	.045	.049	.077	.007
	Hg	.038	.043	.065	.006
	Ni	.029	.032	.050	.004
	Pb	.157	.174	.269	.022
	Zn	.570	.630	.980	.081
Combined Sewers	BOD	134.0	293.0	112.0	1.6
	N	31.5	36.5	34.5	1.1
	P	10.2	11.4	10.9	.34
	SS	773.0	672.0	740.0	11.2
	Cd	.016	.017	.027	.002
	Cr	.028	.031	.048	.003
	Cu	.064	.071	.109	.009
	Hg	.043	.047	.073	.006
	Ni	.034	.037	.057	.004
	Pb	.162	.180	.277	.022
	Zn	.640	.703	1.088	.090

[1] Land Use Group 1 - Low-to-medium density residential, light industry

[2] Land Use Group 2 - High density residential, commercial

[3] Land Use Group 3 - Industrial land

[4] Open land - parks, etc.

Note: For newly developed urban land, increase the SS-loads to 1700 kg/ha/year for all the land uses.

3. ABATEMENT MEASURES FOR POLLUTION DUE TO URBAN RUNOFF

The abatement of pollution due to urban runoff has been extensively studied during the last ten years. During this period, new pollution abatement measures have been developed. Such measures include source controls, collection system controls, storage, and treatment. Quite often, various combinations of these basic techniques are used to achieve the most cost-effective abatement of urban runoff pollution.

Although many pollution abatement measures have been proposed and studied in the laboratory or a pilot plant, the actual experience with designing and building such abatement facilities is rather limited, particularly in Canada. This lack of hard data then contributes to relatively large uncertainties in the efficiencies and costs of the abatement measures discussed in this report.

As recommended by PLUARG, three levels of pollution abatement were considered. The first level, street cleaning, belongs to the source control category. The second level includes runoff storage and basic treatment by sedimentation. The third level combined runoff storage and advanced treatment.

Pollutant removal efficiencies and associated costs for the first abatement level were established in this report. For the second and third levels, analogous information was adopted from a recent report [9] which was prepared by the American Public Works Association (APWA) for the Urban Drainage Subcommittee. The contribution made in this report consisted in expanding the original APWA analysis for additional constituents and assuming that pollutant removals depend on the pollutant association with solid particles of certain sizes.

3.1 First Level Abatement Measures

3.1.1 General description

Street cleaning was considered here as a first-level abatement measure for areas served by separate sewers as well as for areas served by combined sewers. While most cities undertake some form of street cleaning for aesthetic reasons, only recently has street cleaning been recognized as a pollution control measure which reduces the pollutant loadings available for wash-off by surface runoff. There is still a relative lack of data on cost effectiveness of street cleaning and on its relation to the effectiveness of the controls which are implemented at the drainage outlet.

The most common form of street cleaning is sweeping. In general, the effectiveness of street sweeping in removal of pollutants is a function of the following factors [7]:

- sweeper efficiency
- number of passes
- speed of equipment
- pavement conditions
- pollutant association with particles of certain sizes .
- frequency of sweeping
- frequency of rainfall, and
- public participation and awareness.

3.1.1.1 Sweeper efficiency. A variety of street sweepers are available on the market. Two basic types are referred to as mechanical broom sweepers and vacuum sweepers. Mechanical broom sweepers are less expensive and fulfill the main objective of current street cleaning practices - aesthetics. It is well established, however, that broom sweepers are ineffective in removing fine particles which may contain high concentrations of such pollutants as phosphorus or heavy metals. Vacuum sweepers, which are more expensive, possess good removal efficiencies throughout the full range of particle sizes.

The sweeper efficiencies which were used in this report were adopted from references [7, 12]. These efficiencies are shown in Table 8 for various particle sizes.

TABLE 8 EFFICIENCY OF STREET SWEEPERS

PARTICLE SIZE [mm]	PERCENT OF PARTICLES REMOVED (By Weight)		
	Broom Sweepers [7]		Vacuum Sweepers [12]
	1 Pass	2 Passes	
> 2	79%	95.6%	80%
0.84 - 2.00	66%	88.4%	90%
0.246 - 0.84	60%	84.0%	95%
0.104 - 0.246	48%	77.0%	
0.043 - 0.104	20%	36.0%	
< 0.043			

It can be inferred from Table 8 that sweeper efficiencies vary with the particle size and this variation is particularly large in the case of mechanical broom sweepers. The efficiency of broom sweepers can be as low as 15% for the smallest particles and one sweeping pass.

3.1.1.2 Number of passes. The removal efficiency of street sweeping can be increased by making more than one sweeping pass. This is particularly true for broom sweepers; the greater the number of passes, the greater the amount of fine particles that will be removed. For this reason, two passes were considered in this report for mechanical broom sweepers (see Table 8).

3.1.1.3 Speed of equipment. The majority of sweepers are designed to provide the maximum efficiency at a certain operating speed. If this speed is exceeded, the sweeper efficiency will fall significantly. The efficiencies in Table 8 correspond to the optimal operating speed (typically about 6.4-12.8 km/hour).

3.1.1.4 Pavement conditions. Depressions in a road surface provide hard to reach places for sweepers. In addition, further deterioration continually adds materials to the pollutant accumulations on the surface. Consequently, effective street sweeping is possible only on adequately maintained road surfaces.

3.1.1.5 Pollutant association with particles of certain sizes. Particle removal from the street surface is a selective process which depends on the particle size. Because pollutants tend to be nonuniformly associated with particles of certain size ranges, the removal of pollutants will also be selective. Several sources of information on pollutant association with certain particle sizes were reviewed and reference [7] was found to provide the most complete information. The basic data from reference [7], which were adopted in this report, appear in Table 9.

It can be inferred from Table 9 that practically all the pollutants tend to be associated more with fine particles than with coarse particles. This tendency is particularly strong in the case of phosphates.

3.1.1.6 Street sweeping frequency and rainfall frequency. Particles resting on the catchment surface are removed by either surface runoff or sweeping. To quantify the pollutant removal by sweeping at a certain frequency, one has to determine the number of dry days preceding each sweeping operation. Such information was presented in reference [4] for a particular rainfall record and three sweeping frequencies. The data from reference [4] which were adopted in this report are summarized in Table 10.

TABLE 9 FRACTION OF POLLUTANT ASSOCIATED WITH EACH PARTICLE SIZE RANGE (% by Weight) [7]

	PARTICLE SIZE (μ)					
	>2,000	840→2,000	246→840	104→246	43→104	<43
Total Solids	24.4	7.6	24.6	27.8	9.7	5.9
BOD	7.4	20.1	15.7	15.2	17.3	24.3
COD	2.4	4.5	13.0	12.4	45.0	22.7
Nitrates	8.6	6.5	7.9	16.7	28.4	31.9
Phosphates	0	0.9	6.9	6.4	29.6	56.2
Total Heavy Metals	16.3	17.5	14.9	23.5	27.8	

TABLE 10 POLLUTANT REMOVAL VS SWEEPING INTERVAL [4]

SWEEPING INTERVAL (DAYS)	POLLUTANT REMOVAL [Weight Percent]
30	0.146 e
15	0.296 e
7	0.463 e

e = the efficiency of sweeping (typically varies from 0.6 to 0.9)

3.1.1.7 Public participation and awareness. Public participation is important from several points of view. Parked cars are major obstacles to efficient cleaning. The public should be informed on the need for cleaning and the need for streets to be clear of parked vehicles in order to accomplish effective cleaning.

The public also should be informed on the contributions individuals can make to reduce the amount of material that end up on a road surface.

3.1.2 Removal of pollutants by street sweeping

The removal of pollutants by street sweeping can be determined from Tables 8-10 and the pollutant loads for separate sewerage areas (Table 7). First, sweeper efficiencies in removing a particular pollutant were determined by applying the sweeper efficiency (Table 8), for a certain particle size, to the weight fraction of the pollutant associated with the same particle size (Table 9). The resulting pollutant removal efficiencies were then substituted into the expressions for pollutant removals for various sweeping intervals (Table 10). The final data represent pollutant removals, by sweeping at various time intervals, expressed in weight percent of the total loading. These removals are given in Table 11(a).

A few observations regarding the data in Table 11 are of interest. Vacuum sweepers appear to be significantly more efficient than mechanical broom sweepers. This difference is particularly marked for phosphates which tend to be associated with fine particles. The annual pollutant removals increase with an increasing frequency of street sweeping. The resulting increase in removals is not, however, linearly proportional to the sweeping frequency. This nonlinearity is caused by the climatic factors (rainfall frequency).

Finally, the removal rates from Table 11(a) were applied to the annual unit loadings for separate sewerage areas to obtain pollutant removals in kg/ha/year. These annual pollutant removals are given in Table 12 (a)-(c) for various land uses and are assumed to be valid for both separate and combined sewerage areas.

In the case of combined sewers, only the load component originating in surface accumulations is controlled by street sweeping. The other load component, which is contributed by the dry weather flow, is not controlled. Consequently, the percentage removals by street sweeping of combined sewerage areas will be lower than those for separate sewerage areas. The percentage removals for combined sewerage areas were calculated by dividing the weight removals (Table 12) by the annual loads from Table 7. The results of this calculation are given in Table 11(b).

3.1.3 Cost of street sweeping

The costs of street sweeping are typically reported in dollars per curb mile swept. In a recent EPA report [7], these costs were found to vary as much as four times. Such a

TABLE 11 (a) FRACTIONS OF ANNUAL POLLUTANT LOADING REMOVED BY STREET SWEEPING OF SEPARATE SEWERAGE AREAS

Pollutant	Type of Sweeping Operation	Fractions of Pollutant Removed [Weight Percent]		
		I=30 days[3]	I=15 days	I=7 days
BOD	B.SW.[1] -1 Pass	7.0	12.7	19.9
	B.SW. -2 Pass	9.2	18.6	29.0
	V.SW.[2] -1 Pass	13.6	27.5	43.0
N	B.SW. -1 Pass	5.0	10.2	15.9
	B.SW. -2 Pass	7.7	15.6	24.3
	V.SW. -1 Pass	13.6	27.6	43.2
P	B.SW. -1 Pass	3.2	6.6	10.3
	B.SW. -2 Pass	5.5	11.2	17.5
	V.SW. -1 Pass	13.9	28.1	44.0
SS	B.SW. -1 Pass	8.1	16.3	25.6
	B.SW. -2 Pass	11.3	22.9	35.8
	V.SW. -1 Pass	13.3	27.0	42.2
Heavy Metals	B.SW. -1 Pass	7.2	14.7	22.9
	B.SW. -2 Pass	10.3	20.9	32.7
	V.SW. -1 Pass	13.4	27.1	42.4

[1] Broom Sweeper

[2] Vacuum Sweeper

[3] I=Sweeping Interval

TABLE 11(b) **FRACTIONS OF ANNUAL POLLUTANT LOADING REMOVED BY STREET SWEEPING OF COMBINED SEWERAGE AREAS**

Pollutant	Type of Sweeping Operation	Fractions of Pollutant Removed Weight Percent								
		Land Use Group 1			Land Use Group 2			Land Use Group 3		
		I[3]=30	I=15	I=7	I=30	I=15	I=7	I=30	I=15	I=7
BOD	B.SW.[1] -1 Pass	1.8	1.5	5.0	2.2	3.9	6.1	2.1	3.8	6.0
	B.SW. -2 Passes	2.3	2.2	7.4	2.8	5.7	8.9	2.8	5.7	8.8
	V.SW.[2] -1 Pass	3.4	3.2	10.8	4.2	8.4	13.1	4.1	8.3	12.9
N	B.SW. -1 Pass	1.4	2.9	4.5	1.5	3.1	4.9	1.1	2.3	3.6
	B.SW. -2 Passes	2.2	4.4	6.9	2.4	4.8	7.5	1.7	3.5	5.5
	V.SW. -1 Pass	2.1	4.3	6.8	4.1	8.3	13.0	2.9	5.8	9.1
P	B.SW. -1 Pass	0.5	1.0	1.6	1.0	2.0	3.0	0.7	1.4	2.1
	B.SW. -2 Passes	0.8	1.7	2.7	1.6	3.3	5.2	1.1	2.3	3.6
	V.SW. -1 Pass	2.1	4.3	6.8	4.1	8.3	13.0	2.9	5.8	9.1
SS	B.SW. -1 Pass	4.1	8.3	13.0	6.8	13.6	21.3	7.4	14.8	23.2
	B.SW. -2 Passes	5.7	11.6	18.2	9.4	19.1	29.8	10.3	20.8	32.5
	V.SW. -1 Pass	6.8	13.7	21.4	11.1	22.5	35.2	12.1	24.5	38.3
Cd, Cr Hg, Ni Zn	B.SW. -1 Pass	6.4	13.0	20.2	6.5	13.0	20.2	6.4	13.1	20.4
	B.SW. -2 Passes	9.1	18.4	28.7	9.2	18.6	29.1	9.2	18.6	29.1
	V.SW. -1 Pass	11.8	23.8	42.1	11.9	24.0	42.4	11.9	24.2	42.4
Cu	B.SW. -1 Pass	5.0	10.3	16.1	5.1	10.1	15.9	5.1	10.5	16.2
	B.SW. -2 Passes	7.2	14.7	22.8	7.2	14.5	22.7	7.3	14.9	23.2
	V.SW. -1 Pass	9.4	18.9	42.3	9.3	18.9	42.1	9.5	19.2	42.3
Pb	B.SW. -1 Pass	7.0	14.2	22.2	6.9	14.2	22.1	7.0	14.3	22.2
	B.SW. -2 Passes	9.9	20.3	31.7	9.9	20.2	31.6	10.0	20.3	31.7
	V.SW. -1 Pass	13.3	26.2	42.5	12.9	26.1	42.2	13.0	26.3	42.4

TABLE 12 POLLUTANT REMOVALS BY SWEEPING [KG/HA/YEAR]
(These data apply to both separate and combined areas)

(A) MECHANICAL BROOM SWEEPERS - One Pass

Constituent	Land Use Group 1			Land Use Group 2			Land Use Group 3		
	I*=30 days	I=15 days	I=7 days	I=30 days	I=15 days	I=7 days	I=30 days	I=15 days	I=7 days
BOD	2.4	4.3	6.7	6.3	11.4	17.8	2.4	4.3	6.7
N	.45	.92	1.42	.56	1.14	1.78	.39	.80	1.24
P	.050	.103	.161	.108	.222	.346	.072	.148	.231
SS	31.8	64.0	100.4	45.4	91.3	143.4	54.4	109.5	172.0
Cd	.0010	.0020	.0031	.0011	.0021	.0033	.0017	.0035	.0054
Cr	.0019	.0038	.0059	.0020	.0041	.0064	.0031	.0064	.0100
Cu	.0032	.0066	.0103	.0036	.0072	.0113	.0056	.0114	.0177
Hg	.0027	.0056	.0087	.0031	.0063	.0097	.0047	.0096	.0149
Ni	.0021	.0043	.0067	.0023	.0048	.0074	.0036	.0074	.0115
Pb	.0113	.0230	.0359	.0125	.0255	.0398	.0194	.0395	.0616
Zn	.0411	.0840	.1308	.0454	.0927	.1444	.0705	.1439	.224

(B) MECHANICAL BROOM SWEEPERS - Two Passes

Constituent	Land Use Group 1			Land Use Group 2			Land Use Group 3		
	I=30 days	I=15 days	I=7 days	I=30 days	I=15 days	I=7 days	I=30 days	I=15 days	I=7 days
BOD	3.1	6.4	9.9	8.3	16.8	26.1	3.1	6.4	9.9
N	.69	1.40	2.17	.86	1.75	2.72	.60	1.22	1.90
P	.086	.176	.274	.185	.376	.588	.123	.251	.392
SS	44.4	89.8	140.3	63.3	128.2	200.5	75.9	153.9	240.6
Cd	.0014	.0028	.0044	.0015	.0030	.0048	.0024	.0049	.0077
Cr	.0027	.0054	.0084	.0029	.0059	.0092	.0045	.0091	.0143
Cu	.0046	.0094	.0146	.0051	.0103	.0161	.0080	.0162	.0253
Hg	.0039	.0080	.0124	.0044	.0089	.0139	.0067	.0136	.0212
Ni	.0030	.0061	.0095	.0033	.0068	.0106	.0052	.0105	.0165
Pb	.0161	.0328	.0513	.0179	.0363	.0568	.0277	.0562	.0879
Zn	.0588	.1194	.1868	.0650	.1318	.2062	.1008	.2046	.3200

(C) VACUUM SWEEPERS - One Pass

Constituent	Land Use Group 1			Land Use Group 2			Land Use Group 3		
	I=30 days	I=15 days	I=7 days	I=30 days	I=15 days	I=7 days	I=30 days	I=15 days	I=7 days
BOD	4.6	9.3	14.4	12.2	24.6	38.5	4.6	9.3	14.4
N	1.22	2.48	3.88	1.52	3.09	4.84	1.06	2.15	3.38
P	.218	.440	.690	.467	.944	1.478	.311	.629	.986
SS	52.2	105.8	165.4	74.5	151.2	236.3	89.4	181.4	283.6
Cd	.0018	.0036	.0067	.0019	.0039	.0071	.0031	.0064	.0114
Cr	.0034	.0070	.0119	.0038	.0076	.0133	.0059	.0118	.0204
Cu	.0060	.0121	.0271	.0066	.0134	.0299	.0104	.0209	.0461
Hg	.0051	.0103	.0180	.0057	.0115	.0199	.0087	.0176	.0309
Ni	.0039	.0079	.0142	.0044	.0088	.0157	.0068	.0137	.0242
Pb	.0210	.0425	.0689	.0233	.0470	.0760	.0360	.0728	.1173
Zn	.0765	.1548	.2712	.0845	.1709	.2983	.1312	.2653	.4611

*I=Sweeping Interval

wide cost range was partly attributed to varying labour rates and labour utilization [7]. Equipment costs are also known to vary widely, with depreciation and maintenance costs varying considerably between cities. Finally, cities typically use different overhead rates and accounting procedures.

For the purpose of this report, approximate cost estimates for street sweeping were obtained from several municipalities and combined with updated data from reference [12]. The final cost data appear in Table 13.

TABLE 13 COSTS OF STREET SWEEPING [$/curb kilometre]

Equipment	Total Costs $/Curb Km	Capital Costs $/Curb Km	O & M Costs $/Curb Km
Mechanical Sweepers	4.54	2.50	2.04
Vacuum Sweepers	6.09	3.78	2.31

The costs in dollars per curb kilometre have to be converted into annual costs per hectare, in order to make these costs fully compatible with the pollutant loadings and removals given previously. Towards this end, the total curb kilometres swept per hectare per year were first determined for various land uses and sweeping intervals. The results are given in Table 14.

TABLE 14 KILOMETRES SWEPT/HECTARE/YEAR

SWEEPING INTERVAL (DAYS)	KILOMETRES SWEPT/HECTARE/YEAR		
	LAND USE GROUP 1	LAND USE GROUP 2	LAND USE GROUP 3
30	3.46	3.32	1.63
15	6.92	6.64	3.27
7	14.90	14.31	7.03

Finally, the annual costs of street sweeping per hectare were calculated from Tables 13 and 14 and are given in Table 15. These costs (Table 15) are to be used in conjunction with the pollutant removals which were presented in Table 12.

3.2 Second Level Abatement Measures

The second level abatement measures are considered here as combinations of watershed storage, downstream storage, and treatment of runoff by sedimentation. Such measures are consistent with those proposed by APWA for control of urban runoff pollution

TABLE 15 ANNUAL COSTS OF SWEEPING [DOLLARS/HECTARE]

SWEEPING OPERATION	SWEEPING INTERVAL days	ANNUAL COSTS OF SWEEPING [DOLLARS/HECTARE] LAND USE GROUP 1			LAND USE GROUP 2			LAND USE GROUP 3		
		Capital Costs *	O&M Costs	Total Costs	Capital Costs *	O&M Costs	Total Costs	Capital Costs *	O&M Costs	Total Costs
Mechanical	30	8.67	7.05	15.72	8.33	6.75	15.08	4.10	3.31	7.41
Sweepers -	15	17.35	14.08	31.43	16.65	13.49	30.14	8.20	6.62	14.82
1 Pass	7	37.34	30.32	67.66	35.85	29.08	64.93	17.62	14.31	31.93
Mechanical	30	17.35	14.08	31.43	16.65	13.49	30.14	8.20	6.62	14.82
Sweepers -	15	34.69	28.17	62.86	33.31	26.98	60.29	16.41	13.24	29.65
2 Passes	7	74.67	60.64	135.31	71.70	58.17	129.87	35.24	28.61	63.85
Vacuum	30	13.10	8.00	21.10	12.58	7.64	20.22	6.18	3.78	9.96
Sweepers -	15	26.19	16.01	42.20	25.15	15.27	40.42	12.35	7.56	19.91
1 Pass	7	56.44	34.37	90.81	54.16	33.01	87.17	26.64	16.23	42.87

* Amortized annual costs

TABLE 16 POLLUTANT REMOVALS-SECOND ABATEMENT LEVEL

	POLLUTANT BOD	N	P	SS	Heavy Metals
Removal Rate Weight Percent	25%	14.3%	0.8%	31.6%	31.6%

in Ontario [9] and, consequently, much information from the APWA report may be used in this report.

Watershed storage is understood here as runoff storage on such dual purpose sites as parking lots, roof tops, and playgrounds. As the retention period of storm runoff in such areas must be rather short, it has been assumed that no treatment takes place in these storage areas. Typically, this type of storage might be used for a maximum of several hours after the end of a storm event. There is a practical limitation to watershed storage - the total volume of storage available. This volume is likely to be limited unless it is possible to create depressions in which water can be detained. At some point, the cost of creating additional watershed storage would become excessive and that is the point when conventional storage ponds would become more economical than watershed storage. Such ponds were considered here also as primary treatment devices with average residence times in the order of a day.

To evaluate the effectiveness and costs of the first level abatement measures, data from the APWA report [9] were used. According to this source, it was assumed that these abatement measures could be characterized by a 25% control of BOD and the associated minimal costs would vary from \$20/hectare/year to \$150/hectare/year (an area-weighted mean cost is \$64/ha/year). Considering that particle removal by sedimentation will be governed by the particle size (for a constant specific gravity), one can use again Table 9 to estimate pollutant removals which correspond to the BOD removal of 25%. The resulting removal rates are given in Table 16.

The removal rates from Table 16 were applied to the annual loadings presented in section 2 to obtain annual pollutant removals which are given in Table 17 together with the associated costs.

3.3 Third Level Abatement Measures

The third level abatement measures are considered here as combinations of watershed storage, downstream storage, and advanced treatment of runoff. As in the previous case, the main function of watershed storage is to detain runoff and therefore increase the utilization of the downstream storage and treatment facilities. These types of pollution abatement were studied by APWA, and BOD removal rates as well as the associated minimal costs were reported for Ontario [9].

Removal rates for other constituents than BOD had to be estimated for the third level abatement. Two types of estimates were produced. Firstly, a constant removal rate of 50% was assumed for all the constituents. Secondly, removal rates were assumed to be somehow affected by the particle sizes with which the pollutants tend to be mostly associated. These assumed removal rates are given in Table 18.

TABLE 17 SECOND ABATEMENT LEVEL - POLLUTANT REMOVALS AND ASSOCIATED COSTS

CONSTITUENT	ANNUAL POLLUTANT REMOVALS [KG/HA/YEAR]					
	SEPARATE SEWERS			COMBINED SEWERS		
	Land Use #1	Land Use #2	Land Use #3	Land Use #1	Land Use #2	Land Use #3
BOD	8.4	22.4	8.4	33.6	73.4	28.0
N	1.28	1.60	1.12	4.50	5.22	4.93
P	.012	.027	.018	.082	.092	.087
SS	123.9	177.0	212.4	244.2	212.4	233.6
Cd	.0043	.0046	.0074	.0049	.0053	.0085
Cr	.0082	.0088	.0138	.0088	.0099	.0152
Cu	.0141	.0156	.0244	.0202	.0223	.0344
Hg	.0120	.0134	.0205	.0134	.0149	.0230
Ni	.0092	.0103	.0159	.0106	.0116	.0180
Pb	.0495	.0549	.0849	.0513	.0567	.0875
Zn	.1805	.1992	.3093	.2020	.2222	.3436
Initial Capital Costs [$/ha] [1]	535.00			1543.00		
Annual Capital Costs [$/ha/year] [1]	51.40			148.30		
Annual O&M Cost [$/ha/year] [1]	12.85			37.00		
Total Annual Costs [$/ha/year] [1]	64.25			185.30		

[1] Weighted-mean cost adopted from the APWA report [9]. The annual capital costs are amortized.

TABLE 18 THIRD LEVEL ABATEMENT MEASURES - REMOVAL RATES

	CONSTITUENT				
	BOD	N	P	SS	Heavy Metals
Constant Removal Rates [Weight Percent]	50%	50%	50%	50%	50%
Variable Removal Rates [Weight Percent]	50%	40%	30%	70%	60%

Finally, the removal rates from Table 18 were applied to the annual pollutant loadings (see section 2) and the resulting annual removals (kg/ha/year) are given in Table 19 for both constant and variable removal rates.

3.4 Soil Erosion Control in Urbanizing Catchments

During the development of urban areas, the rates of soil erosion increase dramatically as a result of construction activities. The removal of natural ground cover allows immediate soil-water contact, thus increasing the sheet erosion. Newly built structures result in an increased catchment imperviousness and increased rates of transport of eroded soil. Estimates of sediment yield for urban areas undergoing construction range from 1-400 tons/hectare/year [1] . Sediment yields from single construction sites may vary from 2 to 200 times as much as from naturally vegetated areas [1]. Because of these large erosion rates, erosion control measures are often implemented in urbanizing catchments.

Soil erosion is controlled by various nonstructural and structural measures. The most cost-effective measure appears to be a good project planning in which the exposure of soil without ground cover is limited. On-site methods of erosion control include stabilizing treatments and small sediment basins. Among stabilizing treatments, the least expensive alternatives are seeding and chemical stabilization (see Table 20).

Small sediment basins are designed to serve areas of 0.8 to 1.2 hectares. The capital and maintenance costs for these basins are given in Table 20.

TABLE 20 COSTS OF EROSION CONTROL MEASURES (After Ref. 1)

	COSTS	
Control Measure	Initial Cost/ha	Maintenance Costs/ha/year
Seeding	$ 815	$500
Chemical Stabilization	$1,186	$500
Sediment Basins	$ 670	$500

TABLE 19 ANNUAL POLLUTANT REMOVALS [KG/HECTARE/YEAR]

(A) Constant Removal Rate of 50%

CONSTITUENT	ANNUAL POLLUTANT REMOVALS KG/HA/YEAR					
	SEPARATE SEWERS			COMBINED SEWERS		
	Land Use #1	Land Use #2	Land Use #3	Land Use #1	Land Use #2	Land Use #3
BOD	16.8	44.8	16.8	67.2	146.7	56.0
N	4.5	5.6	3.9	15.7	18.3	17.1
P	.8	1.7	1.1	5.1	5.7	5.4
SS	196.0	280.0	336.0	386.0	336.0	370.0
Cd	.0067	.0073	.0118	.0078	.0084	.0134
Cr	.0129	.0140	.0218	.0140	.0157	.0241
Cu	.0224	.0246	.0386	.0319	.0353	.0543
Hg	.0190	.0213	.0325	.0213	.0235	.0364
Ni	.0146	.0162	.0252	.0168	.0185	.0286
Pb	.0784	.0868	.1344	.0812	.0896	.1383
Zn	.2856	.3153	.4894	.3198	.3517	.5438
Initial Capital Costs [$/ha]	1400.00			4937.00		
Annual Capital Costs [$/ha/year]	134.40			474.40		
Annual O&M Costs [$/ha/year]	33.60			118.60		
Total Annual Costs [$/ha/year]	168.00			593.00		

TABLE 19 cont ANNUAL POLLUTANT REMOVALS [KG/HECTARE/YEAR]

(B) Variable Removal Rates (see Table 18)

CONSTITUENT	ANNUAL POLLUTANT REMOVALS SEPARATE SEWERS			KG/HA/YEAR COMBINED SEWERS		
	Land Use #1	Land Use #2	Land Use #3	Land Use #1	Land Use #2	Land Use #3
BOD	16.8	44.8	16.8	67.2	146.7	56.0
N	3.6	4.5	3.1	12.5	14.6	13.8
P	.47	1.01	.67	3.06	3.43	3.26
SS	174.0	390.0	470.0	541.0	470.0	517.0
Cd	.0081	.0087	.0141	.0094	.0101	.0161
Cr	.0155	.0168	.0262	.0168	.0188	.0289
Cu	.0269	.0296	.0464	.0383	.0423	.0652
Hg	.228	.0255	.0390	.0255	.0282	.0437
Ni	.0175	.0195	.0302	.0202	.0222	.0343
Pb	.0941	.1042	.1613	.0974	.1075	.1660
Zn	.3427	.3783	.5873	.3837	.4220	.6525
Initial Capital Cost [$/ha]	1399.00			4937.00		
Annual Capital Costs [$/ha/year]	134.40			474.40		
Annual O&M Costs [$/ha/year]	33.60			118.60		
Total Annual Costs [$/ha/year]	168.00			593.00		

Note: All the costs are from the APWA report [9]. The annual capital costs are amortized.

3.5 Discussion

Because of the limited time available for writing this report, it was necessary to rely as much as possible on the relatively scarce data which were found in the literature. In some cases, the published data, particularly the costs of abatement measures, could not be verified within the constraints of this study. Consequently, the results presented in this report contain appreciable uncertainties which must be borne in mind when interpreting these results. Detailed comments on the accuracy and reliability of results follow.

3.5.1 First level abatement measures

Street sweeping was considered in this report as a first level abatement measure. It was assumed that the amount of pollutants removed from separate sewer areas would be identical to that removed from combined sewer areas.

Numerous uncertainties were involved in the computation of pollutant removals by street sweeping. Among the sources of these uncertainties, one could name the efficiency of sweepers, sweeping frequency, and association of pollutants with particles of certain sizes.

The efficiencies of sweepers were adopted from references [7, 12]. It would appear that the efficiency of mechanical broom sweepers was fairly well established. Only limited data were available for vacuum sweepers and these data were derived for relatively small sweepers which are used on sidewalks [12]. It is conceivable that the efficiency of vacuum sweepers used in street cleaning will be somewhat smaller than that given in this report. Note that according to the data from references [7, 12], mechanical broom sweepers would have to make up to three passes to achieve the same efficiency as vacuum sweepers.

The frequency of street sweeping has a pronounced effect on the removal of pollutants. In fact, one deals here with a joint probability distribution of the particle removal by either sweeping or rain. The removal rates in this report were derived by studying such joint probabilities (reference [4]) for a rainfall record from Burlington. It is conceivable that somewhat different distributions and results would be obtained at other locations. The higher the rainfall occurrence frequency, the lower the probability of particle removal by sweeping.

Since sweepers remove solid particles from the street surface rather selectively, depending on the particle size, the pollutant removal is also selective because of highly nonuniform association of pollutants with particles of various sizes. To evaluate this selective removal, the data on pollutant association with certain particle sizes were adopted from reference [7]. No other source of data was available for verification. It was felt, however, that the data from reference [7] were fairly extensive and reliable.

The costs of street sweeping were determined by making several enquiries to local municipalities. These costs are known to vary widely, depending on the local practices. Therefore, the costs presented in this report should be considered as first-cut estimates.

In the overall assessment of street sweeping, vacuum sweepers appeared to be more effective in pollution abatement than mechanical broom sweepers. This higher effectiveness more than outweighs the higher costs of vacuum sweepers. To achieve significant pollutant removals, street sweeping should be done at least once every two weeks. Even more frequent street sweeping could be considered as a higher level abatement measure.

3.5.2 Second level abatement measures

These measures consist of watershed storage, downstream storage, and runoff treatment by sedimentation. Both removal rates and costs of these measures were adopted from the APWA report [9].

The APWA removal rates were supplemented in this report by removal rates for additional constituents. A selective removal of pollutants by sedimentation was considered using the data in Table 9 to describe the pollutant association with particles of certain sizes. Consequently, above average removal rates were obtained for suspended solids and heavy metals, below average removals were obtained for nitrogen and phosphorus. There are no experimental data to verify these assumptions.

The costs of abatement measures were adopted from the APWA report [9] and represented minimal costs which were derived for optimum combinations of storage and treatment in various cities in Ontario. Limited experience with constructing such facilities prevents any thorough verification by means of actual case histories. It would appear that the costs given by APWA and adopted here indeed represent minimal costs which would be quite often exceeded.

3.5.3 Third level abatement measures

The third level abatement measures are similar to those applied at the second level. To achieve a higher pollution abatement, more storage capacity has to be provided and advanced treatment has to be implemented at the third level. BOD removal rates and costs were adopted from the APWA report [9].

Two kinds of removal rates were considered in this report. Firstly, identical removal rates (50%) were considered for all pollutants. Secondly, various removal rates were assumed for the individual pollutants. These latter rates were based on an assumption that the removal rate depends on the pollutant association with certain particle sizes, however, not to the extent indicated earlier for sedimentation. Again, no experimental data were available to verify these removal rates.

The costs of abatement represent minimal costs which are likely to be exceeded under many circumstances.

3.5.4 Soil erosion control

As specified by PLUARG, controls of urban soil erosion were examined only very briefly. Because of lack of Canadian data, all the erosion rates and control costs given in this report were adopted from U.S. sources. Note that the unit costs given in this report refer to one hectare of the controlled area rather than to one hectare of the catchment. Typically, only some parts of the catchment would require the implementation of erosion controls.

4. CONCLUSIONS

Annual unit pollutant loads from urban runoff were established and recommended for use in the PLUARG model. The recommended loads are based on both the APWA loads and the selected Ontario data. The APWA loads for BOD, Nitrogen, and Phosphorus agreed fairly well with the loads derived from the Ontario data and formed a basis for the recommended loads. The loads recommended for suspended solids and selected metals were derived from the Ontario field data. As obvious from the range of unit loads reported in the literature, the recommended loads are likely to contain large uncertainties which could be as high as several hundred percent.

Three levels of abatement of pollution due to urban runoff were proposed and the associated costs determined. The first level is represented by street sweeping. In terms of pollutant removal from the street surface, vacuum sweepers appeared to be considerably more efficient than broom sweepers. However, the efficiency data available for vacuum sweepers were rather limited and were obtained for small sweeper units. Consequently, all the conclusions regarding the vacuum sweepers are tentative.

Vacuum sweepers employed once every two weeks were found effective in removing pollutants from the catchment surface and thus preventing their wash off by runoff. In areas served by storm sewers, the annual pollutant loadings could be reduced, by street sweeping once every two weeks, by about 27% at an average cost of about $38/hectare/-year. The same sweeping practices can be applied in the areas served by combined sewers. Because of pollutant loadings in the dry weather flow, the relative reduction in the total loading, due to street sweeping, will be lower (10%). The costs would remain the same.

In the second level, abatement schemes consisting of watershed storage, downstream storage, and runoff treatment by sedimentation were considered. Average reductions in pollutant loadings of 20% could be achieved, for both storm and combined sewer areas, at the annual costs of $64/hectare/year and $185/hectare/year, respectively. These abatement schemes would be practical only for combined sewer areas, since for storm sewers, better removals and economies were achieved at the first level. Under these circumstances, frequent street sweeping could be considered as a second level abatement measure for areas served by storm sewers. Weekly sweeping could reduce the annual pollutant loadings by as much as 40% at a cost of $81/hectare/year.

The third level abatement measures were proposed as combinations of watershed storage, downstream storage, and advanced treatment of runoff. About one half of annual pollutant loadings from storm and combined sewer areas could be removed at annual costs $168/hectare/year and $593/hectare/year, respectively.

REFERENCES

1. Brandt, G. H. et al (1972). "An Economic Analysis of Erosion and Sediment Control Methods for Watersheds Undergoing Urbanization", Final Report, OWWR Contract No. 14-31-001-3392, Dow Chemical Co., Midland, Michigan.
2. Gore & Storrie, Ltd. (1977). "Hamilton Test Catchment - Progress Report", A draft report submitted to the Hydraulics Research Division, National Water Research Institute.
3. Hutchison, W. R., A. P. Galati and Z. K. Khan (1978). "Water Plant Waste Discharge in the Province of Ontario", Research Report No. 77, Canada-Ontario Agreement, Ottawa.
4. Marsalek J. (1977). "Monthly Pollution Loads in Urban Runoff from the Malvern Test Catchment", Unpublished Report, Hydraulics Research Division, Canada Centre for Inland Waters, Burlington, September 1977.
5. Marsalek, J. (1978). "Overview of Annual Unit Pollutant Loads for Urban Runoff and Combined Sewer Overflows", Technical Note No. 78-02, Hydraulics Research Division, National Water Research Institute, Burlington, January 1978. An addendum to this report was published as T.N. 78-02 (A), May 1978.
6. Marsalek, J. (1978). "Abatement Measures for Pollution due to Urban Runoff", Unpublished Report, Hydraulics Research Division, National Water Research Institute, Burlington, April 1978.
7. Sartor, J. D. and G. B. Boyd (1972). "Water Pollution Aspects of Street Surface Contaminants, Report EPA-R2-72-081, Environmental Protection Agency, Washington, D. C., November 1972.
8. Singer, S. N. (1977). "Preliminary Estimates of Urban Storm Water Unit Loadings for the Canadian Great Lakes Basin", Technical Memorandum, Water Resources Branch, Ontario Ministry of the Environment, Toronto, July 1977.
9. Sullivan, R. H., W. D. Hurst, T. M. Kipp, J. P. Heaney, W. C. Huber and S. Nix (1978). "Evaluation of the Magnitude and Significance of Pollution Loading from Urban Storm Water Runoff - Ontario", Research Report No. 81, Canada-Ontario Agreement, Ottawa, 1978.

10. "Urban Storm Water Management and Technology : An Assessment", Report EPA-670/2-74-040, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, Ohio, December 1974.

11. Waller, D. H. and Z. Novak (1978). "Municipal Pollutant Loadings to the Great Lakes from Ontario Communities", A draft report submitted for publication in the Research Report Series, Canada-Ontario Agreement.

12. "Water Pollution Aspects of Urban Runoff", U. S. Department of the Interior, Federal Water Pollution Control Administration, Report WP-20-15, January 1969.