# A TECHNIQUE FOR ACCURATE URBAN RUNOFF LOAD ESTIMATION

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## ABSTRACT

It has been estimated that within the next ten years Total Maximum Daily Load (TMDL) analyses will be required on over 20,000 water quality impaired waterways throughout the United States. The great majority of these waterways are receiving significant amounts of pollutants from urban and urbanizing landscapes via stormwater. One of the greatest technical challenges associated with the development of a TMDL is the ability to accurately quantify the specific amount of these stormwater pollutants that are entering a given waterway in any given year. Another challenge is the development of specific actions or activities that need to be taken to significantly reduce these pollutant loadings. Finally, perhaps the greatest technical challenge is the ability to identify the most cost effective and optimum level of effort for each activity and accurately quantify the pollutant load reductions that will result.

Pacific Water Resources, Inc. has developed and successfully implemented a load estimation procedure that can be used to quantify urban pollutant loadings and provide accurate estimates of optimum street and catchbasin cleaning practices. The load estimation procedure involves the selection and monitoring of specific pilot test areas that are representative of the various built land uses found within a watershed of interest. Instead of the costly monitoring of actual stormwater quality at each test area, the load estimation procedure calls for the intensive monitoring of the accumulation and physical/chemical characteristics of the sediment found on the streets or parking lots and within the catchbasins of a given land use. This data along with monitored rainfall is then used to calibrate a stormwater quality model called SIMPTM. Once the model has been calibrated to the various monitoring periods, an average or representative rainfall year is used to evaluate various street and catchbasin cleaning practices. Classical economic production theory and marginal cost analyses are then used to identify the optimal mix of these practices for each targeted land use. The costs associated with monitoring street dirt accumulation and catchbasin accumulations are relatively inexpensive compared to the cost of traditional stormwater runoff sampling and analyses.

The paper will specifically describe the results of this same load estimation procedure used in two different and separate projects within two Michigan watersheds. The first project was conducted in association with Hubbell Roth and Clark, Inc. (HRC) for the City of Livonia's portion of the Bell Branch and Tarabusi Creek Subwatershed of the Rouge River in southeastern Michigan. The second project was conducted in association with Tetra Tech/MPS for the City of Jackson and Jackson County's portion of the Grand River in southwestern Michigan. Both projects concluded that sweeping with high-efficiency sweepers every 15 to 30 days in combination with annual catchbasin cleaning were the optimal and most cost effective practice that could reduce total suspended solids loadings by up to 80% annually. A serious re-

examination of the actual stormwater quality benefits associated with these maintenance practices is needed throughout the United States and the world.

## KEYWORDS

Urban runoff, stormwater quality, stormwater quality modeling, load estimation procedure, street sweeping, catchbasin cleaning, sediment accumulation monitoring

## INTRODUCTION

Based on the most recent 305(b) lists of impaired waters submitted to the EPA, there are about 21,000 river segments, lakes and estuaries making up over 300,000 river and shore miles and 5 million lake acres whose water quality does not appear to support the waterway's designated beneficial uses. The number of Total Maximum Daily Loads (TMDLs) that need to be established for these impaired waterways is currently over 40,000. The great majority of these impaired waterways are receiving significant amounts of pollutants from urban and urbanizing landscapes via stormwater.

One of the greatest technical challenges associated with the development of a TMDL is the ability to accurately quantify the specific amount of these stormwater pollutants that are entering a given waterway in any given year. Another challenge is the development of specific actions or activities that need to be taken to significantly reduce these pollutant loadings. Finally, perhaps the greatest technical challenge is the ability to identify the most cost effective and optimum level of effort for each activity and accurately quantify the pollutant load reductions that will result.

Pacific Water Resources, Inc. (PWR) has developed and successfully implemented a study design that can be used to quantify urban pollutant loadings and provide accurate estimates of optimum street and catchbasin cleaning practices. The study design involves the selection and monitoring of specific test areas that are representative of the various built land uses found within a watershed of interest. Instead of the costly monitoring of actual stormwater quality at each test area, the study design calls for the intensive monitoring of the accumulation and both the physical and chemical characteristics of the contaminated sediment found on the streets or parking lots and within the catchbasins of a given land use. It is widely believed that this contaminated sediment-like material, referred to as street dirt, is the primary source of pollutants found in urban stormwater runoff.

The accumulation data along with monitored rainfall is then used to calibrate the SIMplified Particulate Transport Model (SIMPTM). SIMPTM is a continuous stormwater quality model that can accurately simulate the accumulation, washoff and BMP related removal of this sediment and its associated pollutants. Once the model has been calibrated to the various monitoring periods, an average or representative rainfall year is used to both estimate pollutant washoffs and evaluate various street and catchbasin cleaning practices. Classical economic production theory and marginal cost analyses are then used to identify the optimal mix of these practices for each targeted land use. The costs associated with monitoring street dirt accumulation and catchbasin accumulations are relatively inexpensive compared to the cost of traditional stormwater runoff sampling and analyses.

This paper will outline the study design and describe the results of two separate studies that used this approach to quantify pollutant loadings and optimize load reductions for two Michigan watersheds. The first study was conducted in association with Hubbell Roth and Clark, Inc. (HRC) for the City of Livonia's portion of the Bell Branch and Tarabusi Creek Subwatershed of the Rouge River in southeastern Michigan (HRC, 2001). The second study was conducted in association with Tetra Tech/MPS for the City of Jackson and Jackson County's portion of the Grand River in southwestern Michigan (Tetra Tech/MPS, 2001).

## OVERVIEW OF SIMPTM

The successful implementation of the basic study design described above is predicated on the existence of a model that can accurately simulate the accumulation and washoff via stormwater of urban street dirt and the appropriate interaction that certain BMPs have in the removal and/or capture of this material and its associated pollutants. Without an accurate model of this type, a study design which relies heavily on the monitoring of street dirt accumulation as the basic calibration data set would not be very useful. Over the last decade, the authors have developed, tested, calibrated, and verified such a model which is named SIMPTM. Although SIMPTM is not intended to be the focal point of this paper, some background information on the model itself should help the reader reach a full understanding of the benefits associated with the study design described herein.

SIMPTM (Sutherland and Jelen, 1998) is a continuous stormwater quality model that can simulate the stormwater pollutant loadings and expected load reductions from best management practices (BMPs) such as street cleaning and using and cleaning sediment trapping catchbasins and manholes. SIMPTM is unique in its ability to accurately simulate the accumulation, washoff and BMP removal of sediment and its associated pollutants. Other applications of the model have demonstrated its ability to simulate the observed pollutant loads and concentrations from gauged urban basins with outstanding accuracy. These examples involve monitoring for the City of Portland, Oregon's NPDES stormwater permit (Sutherland and Jelen, 1996) and the City of Bellevue, Washington's Nationwide Urban Runoff Program (NURP) (Sutherland, 1991).

SIMPTM is a continuous, self-contained stormwater quality model. It divides hourly precipitation records into rainfall events and provides monthly and annual statistics for later analysis. For each event, it forms a runoff hydrograph, used to continually simulate the capacity of the stormwater inlet hydrograph to transport available accumulated sediment and associated pollutants from paved areas using the Yalin-Einstein and Foster-Meyer sediment transport equations. These equations have been shown by Ellis and Sutherland (1979) to be much more accurate than the empirically based exponential washoff used, for example, in almost all other stormwater quality models, such as EPA's Storm Water Management Model (SWMM).

The model also accounts for sediment deposition, armoring, and resuspension processes. Between events, SIMPTM calculates dry deposition and resuspension processes and models scheduled cleaning of streets, parking lots, catchbasins, or maintenance hatches. Overall removals from these practices are provided by SIMPTM based upon measurable data, rather than input by the user as most stormwater quality models require. Any excess erosion remains available for further simulation, so that actual accumulations may often exceed the *equilibrium* load previously assumed by many to be a *maximum* limit to accumulation.

Existing accumulation equations use by other models such as U.S. EPA's SWMM work contrary to the accumulation patterns *observed* during many urban runoff events. While accumulated loadings on paved surface have been observed to be greater during times of large rainfalls (i.e., wet season), it is almost always *modeled* as being much less, because the rainfall washes accumulated street sediment into the drainage system. Seldom is any provision made for *washon*, the increase that is often observed to result when washoff from adjoining unpaved areas (e.g., landscaped areas) actually increases the accumulation on paved surfaces following an event. A few models require seasonal parameters to model accumulation differently during wet and dry seasons, but the season is arbitrary and seldom correlates well with rainfall depth. And furthermore, even during the wet season, the model is using the dry weather accumulation algorithms, albeit with larger values.

Figure 1 illustrates the dry weather accumulation function that exists within SIMPTM. It shows how the traditional maximum accumulation is better considered as an equilibrium accumulation, and accumulations both above and below tend towards it at the same rate as before. The underlying process of deposition balanced by removal from traffic and wind remains unchanged. Wet weather accumulations or *washon* from higher volume and intensity runoff events result in sediment accumulations that exceed the equilibrium accumulation level. When this occurs, the net result of dry weather that follows is a decrease in sediment accumulation not an increase as is always assumed to be the case by other models such as SWMM, STORM and NPS to name a few.

SIMPTM has been used extensively in the Portland, Oregon area as part of surface water management and water quality management plan development since 1988. As stated earlier, it has been recently used in two Michigan studies. It has also been used in the Seattle area several times and its predecessor in Anchorage, Alaska, Reno/Sparks, Nevada, and throughout urban Illinois. The United States Geological Survey (USGS) applied the model in the Dallas, Texas area and concluded that it provided the most accurate simulation results when compared to several other models that were tested including SWMM (USGS, 1992). For a more detailed description of SIMPTM and a discussion of how it was calibrated to an extensive NPDES data set collected in Portland, Oregon, please refer to Sutherland and Jelen (1996).

It is the understanding of the authors that an effort is currently underway by USEPA, Camp Dresser and McKee (CDM) and Dr. Wayne Huber to significantly improve the existing SWMM code and create SWMM Version 5.0. In an effort to fully cooperate, the authors have provided Mr. Robert Dickerson of CDM with existing SIMPTM computer code and documentation. The hope would be that all of the water quality related algorithms in SIMPTM will be included in the new SWMM 5.0. If that occurs, SWMM 5.0 can then be used, instead of SIMPTM, as part of the load estimation procedure that this paper will present.

## LOAD ESTIMATION PROCEDURE

The load estimation procedure which will now be outlined was developed and refined over the last ten years. It was used to evaluate stormwater pollution from a cargo container handling facility at the Port of Seattle (Sutherland, Jelen and Minton, 1998) and it is currently being used along with stormwater monitoring to quantify and eventually control stormwater pollution from the Cross Israel Highway now under construction (Sutherland and Minton, 2002) near Tel Aviv, Israel.

The basic steps in the procedure are as follows:

- Select test areas representative of the predominant urban land uses in the study area or watershed of interest.
- Monitor the initial accumulations of the sediment on streets and/or parking areas and within catchbasins throughout these test areas.
- Arrange to have the catchbasins cleaned after the initial monitoring.
- Periodically monitor over time the sediment accumulations of streets, parking lots and catchbasins within these test areas.
- Obtain hourly precipitation from a nearby gauge or monitor precipitation at these test areas during the accumulation monitoring period.
- Conduct mechanical analyses (i.e., sieve) on the collected sediment samples.
- Conduct chemical analyses on three composted fractions of the sieved sediment samples.
- Calibrate SIMPTM using sediment accumulation observations over the monitoring period.
- Develop an average rainfall year through the analysis of rainfall data from a nearby gauge with a long period of record.
- Document existing cleaning practices including unit costs (includes snow and ice control, if applicable).
- Use SIMPTM to conduct a BMP evaluation for the average rainfall year.
- Use SIMPTM to simulate pollutant washoffs during the average rainfall year.

In regard to TMDL analyses, the pollutant washoff loadings could be used directly to establish TMDLs or they could serve as needed input to in-stream water quality models whose output could establish TMDLs. In both of the Michigan studies, TMDLs were not developed; instead, the focus was identifying the costs and pollutant reduction benefits associated with optimal efforts to clean streets and sediment trapping catchbasins.

## SELECTION OF TEST AREAS

An important aspect of the study procedure is the selection of test areas that best represent the land use/physical characteristics that are predominate throughout the study basin or study area. If the study objective is to evaluate loadings within a specific watershed as was the case in Livonia, the best available topography and information of the location of various storm sewer systems including catchbasins, pipes and outfalls are used to delineate small drainage subareas.

A reconnaissance (i.e., windshield) survey of these subareas is then conducted by automobile to gather additional land use and physical characteristics data that was not currently available from other sources. This data included: (1) Type of surface drainage system, such as curb and gutter versus roadside swales, (2) Street pavement condition and texture, (3) The slope along the upland stormwater flow path, (4) Whether the direct connection of roof drains to the gutter line existed and, (5) The average dimensions of stormwater inlets.

In the Livonia study, four representative test areas were selected for monitoring of the sediment found on directly connected paved areas and trapped within catchbasins. One area was a commercial shopping center (Newburgh), two were single-family residential (Munger and Riverside) and one was recreational (Fox Creek). Each test area was relatively small with anywhere from 7 to 14 sediment trapping catchbasins to be monitored. Sediment accumulation monitoring sites (pilot test sites) within each test area were selected and included a shopping center parking lot, two residential streets and a golf course parking lot. These monitoring sites for accumulation varied from 55.7 $m^2$ (600 $ft^2$) to 139 $m^2$ (1500 $ft^2$) and were paved areas directly tributary to a single stormwater inlet (i.e., catchbasin) within a given test area.

In the Jackson study, the objective was to evaluate loadings from land uses that were typical of the greater Jackson, Michigan metropolitan area. Consequently, the test area selection was not as intense but involved selecting six test areas that appeared to be typical of the predominant land uses in Jackson. These test areas were all paved street areas that were directly tributary to a single catchbasin which was the only catchbasin monitored in each test area. Three single-family residential test areas (i.e., Durand, Jackson, and Seymour) were selected. One downtown commercial site (Cortland), one industrial site (Carroll) and one highway site (Parnell) were also selected. These six accumulation monitoring sites varied from 29.7 $m^2$ to 84.5 $m^2$.

## SEDIMENT SAMPLE COLLECTION

In the Livonia study, initial samples of street and parking lot dirt (obtained by industrial vacuum) and catchbasin sediments (obtained by soil sampler and shovel) were collected at all four sites in mid-September 1999. These samples were weighed then analyzed for particle size and chemical characteristics. All paved surfaces were swept and all catchbasin sumps and laterals were cleaned by city staff in early October. No street sweeping was supposed to occur from early October 1999 through May 2000.

Street and parking lot dirt accumulations were monitored on 11/4/99, 1/6/00, 3/24/00, and 5/16/00. A second accumulation monitoring site in each test area was also sampled on 3/24/00. Both of these sites were monitored for accumulation at the two residential areas on 5/16/00. Sediment accumulations were monitored in the catchbasin sumps on 11/5/99, 12/9/99, 3/24/00, and 5/11/00. Following the monitoring on 5/11/00, composite samples were analyzed for particle size and chemical characteristics.

In the Jackson study, initial samples of street dirt and catchbasin sediments were collected at all six sites in early April 2000. The catchbasin sumps and laterals were cleaned by City and County staff in mid-April. These samples were weighed then analyzed for particle size and chemical characteristics. Street sweeping was suspended for these areas during the monitoring period from April through mid-September 2000. Street and catchbasin accumulations were monitored on 5/4/00, 6/8/00, 7/11/00, 8/9/00, and 9/6/00.

## MECHANICAL ANALYSIS OF SEDIMENT SAMPLES

Grain size analyses of the collected street dirt and catchbasin sediments were performed. The results of these analyses were used to calibrate the SIMPTM model. The dry weights for each of the eight sieve fractions were totaled and compared to the sample net dry weight. Weight gain/loss was noted. The total dry weight for the eight fractions provided the total street dirt accumulation for that time period. The eight particle size ranges (microns) and sieve numbers used were: less than 63 (No. 230); 63 to 125 (No. 120); 125 to 250 (No. 60); 250 to 600 (No. 30); 600 to 1000 (No. 18); 1000 to 2000 (No. 10); 2000 to 6370 (0.25 inch) and greater than 6370.

The mean particle size fractions observed at each of the various project test areas are represented in Table 1. The sieve analysis shows that on the average the greatest fraction of approximately 24 to 30% is in the 250 to 600 micron range (PS4). This is significant since the runoff in the gutter and on the parking lot can rarely transport sediment of this size. As a result, this size and greater is generally unavailable for transport and actually impedes the transport of smaller particles through a process called armoring (i.e., larger particles rest upon and pin smaller particles). The fraction generally considered available for transport (i.e., less than 250 microns) averaged from 26% to 36% of the total in Jackson and Livonia, respectively.

After the mechanical analyses of the first, third and fifth set of samples (i.e., collected in both study areas), fractions were recombined into three size groups for chemical analysis by a certified laboratory. These composite samples were compiled as follows: (1) <63 microns (μm), labeled Fine; (2) 63 to 250 μm, labeled Medium; (3) 251 to 6370 μm, labeled Coarse. The fraction greater than 6370 μm was discarded.

## Table 1 Observed Mean Particle Size (PS) Fraction of Accumulated Sediments

| Land Use/Site Name | Test Area | Type | PS1 <63 um | PS2 63-125 | PS3 125-250 | PS4 250-600 | PS5 600-1000 | PS6 1000-2000 | PS7 2000-6370 | PS8 >6370 |
|---|---|---|---|---|---|---|---|---|---|---|
| **PROJECT: LIVONIA** | | | | | | | | | | |
| Shopping Center<br>Commercial<br>Newburgh | 1 | Parking Lot | 0.032 | 0.082 | 0.216 | 0.244 | 0.166 | 0.144 | 0.099 | 0.017 |
| Recreational Area<br>Parking<br>Fox Creek | 2A | Parking Lot | 0.037 | 0.055 | 0.093 | 0.199 | 0.204 | 0.333 | 0.077 | 0.002 |
| Single-Family Residential<br>Munger | 15 | Street | 0.085 | 0.113 | 0.221 | 0.294 | 0.095 | 0.095 | 0.079 | 0.018 |
| Single-Family Residential<br>Riverside | 20 | Street | 0.079 | 0.140 | 0.271 | 0.221 | 0.084 | 0.093 | 0.081 | 0.031 |
| **Overall Project Average** | | | **0.058** | **0.098** | **0.200** | **0.240** | **0.137** | **0.166** | **0.084** | **0.017** |
| ***PROJECT: JACKSON*** | | | | | | | | | | |
| Single-Family Residential<br>Durand | 1 | Street | 0.023 | 0.051 | 0.143 | 0.270 | 0.140 | 0.107 | 0.192 | 0.073 |
| Single-Family Residential<br>Jackson | 2 | Street | 0.057 | 0.105 | 0.218 | 0.340 | 0.086 | 0.072 | 0.096 | 0.025 |
| Central Business District<br>Cortland | 3 | Street | 0.030 | 0.063 | 0.154 | 0.337 | 0.134 | 0.112 | 0.132 | 0.038 |
| Highway<br>Parnell | 4 | Street | 0.025 | 0.043 | 0.139 | 0.271 | 0.103 | 0.142 | 0.218 | 0.058 |
| Industrial<br>Carroll | 5 | Street | 0.029 | 0.050 | 0.162 | 0.216 | 0.129 | 0.134 | 0.218 | 0.062 |
| Single-Family Residential<br>Seymour | 6 | Street | 0.031 | 0.059 | 0.171 | 0.338 | 0.137 | 0.090 | 0.123 | 0.051 |
| **Overall Project Average** | | | **0.033** | **0.062** | **0.164** | **0.295** | **0.122** | **0.110** | **0.163** | **0.051** |

## CHEMICAL ANALYSIS OF SEDIMENT SAMPLES

The three particle size ranges documented above for the initial, third, and fifth set of sediment samples obtained for both studies were analyzed for total phosphorus, COD and the ten stormwater metals recommended by Michigan Department of Environmental Quality (MDEQ). Chloride was also tested for in the Jackson project. The final set of samples was tested for the above list of parameters along with a modified Synthetic Precipitation Leaching Procedure (SPLP) for leachable metals. The SPLP was selected over a Toxic Characteristic Leaching

Procedure (TCLP) extraction because it would provide a more realistic assessment of dissolved pollutant mobility under actual rainfall to runoff conditions rather than a worst case scenario.

The modified SPLP simulates the sediment leaching process that is the result of rainfall and runoff conditions in this region. The SPLP involved weighing out a sample and adding 20 times the samples weight in an acidic fluid, with a pH of 4.5, which represents the average pH of rainfall in the region. The sample and fluid is then tumbled for eight hours which represents the average duration of rainfall in the region. The solution is then put through a digestion process, method 3020, where nitric acid is added. Table 2 lists the various chemical parameters tested for, the test method used and the associated detection limits.

The SIMPTM model relates sediment washoff to washoff of other pollutants by mass fractions or potency factors assigned to each of the eight particle size groups of accumulated sediment. These factors are generally set from observed fractions of accumulated sediment or from observed sediment and pollutants washed off during sampled events. Since no washoff data was obtained, the pollutant simulations conducted for these two projects were based on the chemical analyses of the collected samples. In addition, the focal point of the SIMPTM calibration and simulation presented later will be solids washoff to support BMP evaluation. Simulations of other pollutants were omitted to conserve space.

Table 3 represents the average mass fractions or potency factors found by composited particle size group for each pollutant tested and for both Michigan projects and an older Portland, Oregon project (completed in 1992) used for comparison purposes. Total phosphorus potency was found to be relatively uniform by particle size group and significantly higher in Livonia when compared to Jackson. COD potency was somewhat uniform by particle size group with a tendency to increase with increasing particle size. COD concentrations were significantly higher in Livonia when compared to Jackson and those found in Portland were significantly higher than Livonia. Seven of the ten metals tested for were detected. Mercury, selenium and silver were not detected. The potency of each metal by particle size group was generally uniform with a tendency to increase with decreasing particle size.

Dissolved metals were rarely detected with the SPLP which seems to suggest that almost all of the metals were particulate in nature. It is interesting to note that when detected, the dissolved metal potency of the Coarse fraction which is not generally available for transport by runoff was greater than that for the Fine and Medium fractions (i.e., see copper and zinc). However, it is quite possible that a significant portion of the dissolved metals generally observed in urban runoff is actually being leached from this Coarse immobile fraction which represents 64% to 74% of accumulated sediment. If one could remove this material through effective cleaning practices before rainfall occurred, it could result in a significant reduction in dissolved metal concentrations found in stormwater.

## Table 2 Chemical Analysis Parameters and Test Methods

| Parameter | USEPA Method | Detection Limit (ppm) | SPLP Detection Limit (ppm) |
|---|---|---|---|
| Total Phosphorus | 365.3 | 0.2 | - |
| COD | 410.1 | 1.0 | - |
| Chloride | 300 | 0.1 | - |
| Arsenic | 7060A | 1.0 | 0.05 |
| Barium | 6010 | 1.0 | 0.01 |
| Cadmium | 7131A | 0.05 | 0.02 |
| Chromium | 6010 | 2.5 | 0.05 |
| Lead | 6010 | 1.0 | - |
| Mercury | 7471A | 0.1 | - |
| Selenium | 7740 | 0.5 | - |
| Silver | 7761 | 0.5 | 0.02 |
| Copper | 6010 | 1.0 | 0.01 |
| Zinc | 6010 | 1.0 | 0.05 |

## Table 3 Average Mass Fraction or Pollutant Potency by Composited Particle Group

| Parameter | Jackson, MI | | | Livonia, MI | | | Portland, OR | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Fine (ppm)* | *Med. (ppm)* | *Coarse (ppm)* | *Fine (ppm)* | *Med. (ppm)* | *Coarse (ppm)* | *Fine (ppm)* | *Med. (ppm)* | *Coarse (ppm)* |
| Total Phosphorus | 0.9 | 0.8 | 0.7 | 22.3 | 31.5 | 26.6 | NT | NT | NT |
| COD | 140.7 | 49.4 | 549.9 | 5,735 | 7,501 | 6,312 | 144,444 | 153,909 | 345,833 |
| Chloride | 239.0 | 73.7 | 89.2 | NT | NT | NT | NT | NT | NT |
| Arsenic | 4.9 | 2.7 | 3.8 | 5.2 | 3.3 | 3.7 | 3 | 4 | 1 |
| Arsenic (SPLP) | ND | ND | ND | NT | NT | NT | NT | NT | NT |
| Barium | 124.4 | 60.7 | 45.3 | 67.0 | 98.0 | 62.4 | 330 | 362 | 322 |
| Barium (SPLP) | ND | ND | ND | NT | NT | NT | NT | NT | NT |
| Cadmium | 1.0 | 0.4 | 0.2 | 1.3 | 0.8 | 0.8 | 2 | 4 | 1 |
| Cadmium (SPLP) | ND | ND | ND | NT | NT | NT | NT | NT | NT |
| Chromium | 45.2 | 31.3 | 60.6 | 78.1 | 51.1 | 60.4 | 74 | 83 | 32 |
| Chromium (SPLP) | ND | ND | ND | NT | NT | NT | NT | NT | NT |
| Copper | 102.6 | 46.8 | 47.3 | 0.8 | ND | ND | 220 | 159 | 86 |
| Copper (SPLP) | 0.01 | 0.03 | 0.20 | NT | NT | NT | NT | NT | NT |
| Lead | 128.7 | 68.1 | 48.0 | 59.6 | 38.2 | 39.9 | 328 | 372 | 210 |
| Lead (SPLP) | ND | ND | ND | NT | NT | NT | NT | NT | NT |
| Zinc | 269.9 | 115.3 | 74.8 | 227.6 | 138.0 | 140.3 | 470 | 463 | 324 |
| Zinc (SPLP) | ND | 0.02 | 0.03 | NT | NT | NT | NT | NT | NT |

## PRECIPITATION DURING ACCUMULATION MONITORING PERIOD

It is important to ensure that hourly precipitation data is being recorded throughout the entire accumulation monitoring period at a station that is relatively close to the test areas. If the precipitation data is being collected by others, make sure the information can be available within four to six weeks of its collection. This data is needed to calibrate the SIMPTM model and that task generally needs to occur right after the monitoring period ends and the mechanical and chemical analyses have been completed. If these conditions cannot be met, the project will need to install and maintain a precipitation gauge at some location central to the various test areas.

Using the hourly rainfall data observed during the six-month sampling period at the Battle Creek gauging station located at the Battle Creek airport some 64 km west of Jackson (closest location with good available hourly data), approximately 41 runoff producing rainfall events were identified whose total depth was 557 mm (21.94 in). Runoff producing rainfall events were those events that satisfied one of the three minimum depth versus time criteria: (1) 1.0 mm (0.04 in) in one hour (2) 1.8 mm (0.07 in) in three hours, or (3) 2.3 mm (0.09 in) in six hours.

For the Livonia project, precipitation data was available from the Southeast Michigan Council of Governments (SEMCOG) extensive network of recording stations throughout the Detroit Metropolitan area. Using the hourly rainfall data observed during the eight-month sampling period within 5.6 km (3.5 mi) or less of the Livonia monitoring areas, it was determined that approximately 52 runoff producing rainfall events were identified whose total depth was 418 mm (16.46 in).

## SIMPTM CALIBRATION

As noted earlier, the SIMPTM program has the ability to simulate the accumulation and washoff of sediments and their associated pollutants. The model calibration process involves the adjustments of parameter values to reproduce observed runoff volumes and pollutant loads. However, because of the high cost involved, no end-of-pipe stormwater flow and pollutant concentration data was obtained, thus, the calibration focused on reproducing the observed sediment accumulations on the paved surfaces and within the catchbasins for each of the land use test areas during their respective sampling periods.

The actual sampling event was simulated by the model to be a “perfect” sweeping event in which all of the accumulated material would be removed. A “perfect” sweeping event was simulated by SIMPTM within a few days of each of the days in which an accumulation sample was obtained on a given land use test area. With all the washoff parameters set to reasonable values observed during other calibrations involving end-of-the-pipe data, the accumulation rate and equilibrium value were varied for each of the pilot test areas until one set of numbers was found to provide the best overall match. The best overall match was determined by visually examining the model’s simulated sediment accumulation values (mass/area) against the actual sample weight that was obtained.

A further complication occurred on the residential monitoring sites in the Livonia project. These sites were to be swept on October 7, 1999 with no other sweeping scheduled to occur throughout the rest of the sampling period. Unfortunately, due to excessive leaf debris and a miscommunication, these residential sites were also swept on December 2, 1999 and again on March 22, 2000. During the model calibration for these pilot test areas, street sweeping parameter values established for a *Newer Mechanical* sweeping operation (Sutherland and Jelen,

1997) were used to simulate each of these three street sweeping events. (It is interesting to note that the authors did not know about these later sweepings until the model calibration process suggested that two non-scheduled sweepings must have occurred.)

The results of the SIMPTM calibration for all ten of the test areas are presented in Table 4. Using the Durand single-family residential site in the Jackson study as an example, Figure 2 illustrates the simulated behavior of the street dirt accumulations throughout the six-month sampling period with emphasis placed on both the simulated and observed accumulations for each sampling date.

Table 4 clearly demonstrates the ability of SIMPTM to provide reasonable estimates of the magnitude of accumulated sediments found on the test areas throughout the various sampling periods. Keep in mind that during these time periods 41 to 52 runoff producing rainfall events occurred (depending upon the site location) which would also effect these observed accumulations. The underlying assumption here is that if the model can accurately simulate these accumulations over time then it should be providing reasonable estimates of the washoff events. A few comments are in order.

## Table 4  Observed Versus Simulated Street Dirt Accumulations

**PROJECT: LIVONIA**

| Land Use/Site Name | Test Area | Sampling Data | Observed Accumulation kg/ha (lbs/acre) | Simulated Accumulation kg/ha (lbs/acre) | Difference % |
|---|---|---|---|---|---|
| | 1-G | 9/10/99 | 209 (184) | 214 (189) | +3 |
| Shopping Center | 1-G | 11/4/99 | 151 (133) | 179 (158) | +16 |
| Commercial | 1-G | 1/6/00 | 874 (771) | - | - |
| | 1-G | 3/24/00 | 127 (144) | 194 (171) | +16 |
| Newburgh | 1-P | 3/24/00 | 447 (394) | 447 (394) | 0 |
| | 1-P | 5/16/00 | 192 (169) | 200 (176) | +4 |
| | 2A-G | 9/10/99 | 210 (185) | 210 (185) | 0 |
| Recreational Area | 2A-G | 11/4/99 | 109 (96) | 134 (118) | +18 |
| Parking | 2A-G | 1/6/00 | 152 (134) | 158 (139) | +4 |
| | 2A-G | 3/24/00 | 138 (122) | 120 (106) | -15 |
| Fox Creek | 2A-P | 3/24/00 | 296 (261) | 296 (261) | 0 |
| | 2A-P | 5/16/00 | 350 (309) | 172 (152) | -103 |
| | 15-G | 9/10/99 | 152 (134) | 152 (134) | 0 |
| Single-Family Residential (SFR) | 15-G | 11/4/99 | 26 (23) | 107 (94) | +75 |
| | 15-G | 1/6/00 | 48 (42) | 74 (65) | +35 |
| Munger | 15-G | 3/24/00 | 23 (20) | 39 (34) | +41 |
| | 15-P | 3/24/00 | 32 (28) | 42 (37) | +24 |
| | 15-G | 5/16/00 | 314 (277) | 87 (77) | -259 |
| | 15-P | 5/16/00 | 23 (20) | 87 (77) | +74 |
| | 20-G | 9/10/99 | 40 (35) | 40 (35) | 0 |
| Single-Family Residential (SFR) | 20-G | 11/4/99 | 44 (39) | 51 (45) | +13 |
| | 20-G | 1/6/00 | 45 (40) | 71 (63) | +36 |
| Riverside | 20-G | 3/24/00 | 29 (26) | 34 (30) | +13 |
| | 20-P | 3/24/00 | 66 (58) | 39 (34) | -70 |
| | 20-G | 5/22/00 | 126 (111) | 99 (87) | -27 |
| | 20-P | 5/22/00 | 40 (35) | 99 (87) | +59 |

**PROJECT:  JACKSON**

| Land Use/Site Name | Test Area | Sampling Data | Observed Accumulation kg/curb km (lbs/curb mi) | Simulated Accumulation kg/curb km (lbs/curb mi) | Difference % |
|---|---|---|---|---|---|
| | | 4/6/00 | 51 (180) | 51 (182) | +1 |
| Single-Family Residential (SFR) | 1 | 5/4/00 | 39 (140) | 37 (132) | -6 |
| | | 6/8/00 | 46 (163) | 52 (186) | +14 |
| Durand | | 7/11/00 | 37 (132) | 33 (118) | -11 |
| | | 8/9/00 | 24 (85) | 28 (100) | +18 |
| | | 9/6/00 | 43 (152) | 29 (103) | -32 |
| | | 4/7/00 | 87 (309) | 88 (312) | +1 |
| Single-Family Residential (SFR) | 2 | 5/4/00 | 59 (209) | 75 (264) | +26 |
| | | 6/8/00 | 69 (243) | 71 (247) | +2 |
| Jackson | | 7/11/00 | 44 (157) | 64 (228) | +45 |
| | | 8/9/00 | 82 (289) | 62 (217) | -25 |
| | | 9/6/00 | 69 (243) | 64 (227) | -7 |
| | | 4/7/00 | 56 (198) | 56 (197) | <1 |
| Central Business District (CBD) | 3 | 5/11/00 | 28 (98) | 41 (144) | +47 |
| | | 6/8/00 | 38 (135) | 45 (160) | +19 |
| Cortland | | 7/12/00 | 32 (113) | 33 (117) | +4 |
| | | 8/10/00 | 51 (180) | 29 (103) | -43 |
| | | 9/6/00 | 30 (108) | 31 (112) | +4 |
| | | 4/6/00 | 109 (385) | 109 (386) | <1 |
| Highway (HWY) | 4 | 5/4/00 | 102 (359) | 77 (272) | -24 |
| | | 6/6/00 | 72 (256) | 88 (311) | +22 |
| Parnell | | 7/17/00 | 52 (186) | 68 (242) | +30 |
| | | 8/8/00 | 73 (260) | 62 (218) | -16 |
| | | 9/13/00 | 51 (180) | 66 (235) | +31 |
| | | 4/6/00 | 187 (660) | 188 (663) | <1 |
| Industrial (IND) | 5 | 5/4/00 | 142 (501) | 146 (517) | +3 |
| | | 6/9/00 | 166 (587) | 137 (484) | -18 |
| Carroll | | 7/11/00 | 103 (364) | 132 (468) | +29 |
| | | 8/9/00 | 127 (449) | 123 (435) | -3 |
| | | 9/6/00 | 92 (324) | 135 (478) | +48 |
| | | 4/6/00 | 70 (247) | 73 (257) | +4 |
| Single-Family Residential (SFR) | 6 | 5/11/00 | 27 (97) | 61 (215) | +122 |
| | | 6/8/00 | 69 (244) | 70 (249) | +2 |
| Seymour | | 7/12/00 | 53 (188) | 53 (189) | <1 |
| | | 8/9/00 | 52 (185) | 50 (177) | -4 |

In the Livonia study area, the 1/6/00 sample collected at the Newburgh shopping center (i.e., Test Area 1-G) was not considered in the calibration since it was primarily road salt. The 5/16/00 sample collected at the Fox Creek parking area may have been affected by the landscaping activities that were occurring immediately adjacent to the parking lot. This would explain why the observed loading was twice as great as the simulated. And finally, please note on the two SFR sites during the May 2000 samplings, significant accumulation differences were observed between the *G* and *P* sites although they experienced accumulation over the same identical time period. This demonstrates the considerable variability that can exist when monitoring accumulation at sites that are almost adjacent and essentially identical. The objective of the calibration, in this case, was to simulate an accumulation that was close to the average of both observations.

In the Jackson study area, the greatest difference between the observed and simulated accumulations occurred on the May 11 sampling of the Seymour site. This very large difference appears to be the results of a current model limitation. The current version of SIMPTM cannot simulate the exact date of a sampling event (i.e., perfect sweeping event) unless the frequency of sampling in days turned out to be exactly the same time frame between sample collection. Currently, the user must specify the first sampling event and the frequency of subsequent sample collection in days. The project generally sampled on a monthly basis staring on 4/6/00. If one uses a start date of 4/7/00 with a 30-day frequency, the model's simulation of the sampling date lands within four days of all of the actual sampling dates. This generally would not create much modeling error provided runoff events did not occur within the four-day period. In fact, this was the case in 23 of the 35 samplings where no significant runoff interference occurred in these periods that lasted up to four days.

However, runoff interference did occur for all of the samplings in July 2000, the 5/11/00 samplings and the 9/13/00 sampling. In July, three storms totaling 14.7 mm (0.58 in) were recorded between the modeled sampling date of July 6 and the actual July 11 and 12 sampling dates. However, these storms were mild with average intensities of less than 0.5 mm (0.02 in) per hour so their effect on accumulation would not be very great.

The runoff interference in May and September was much more significant. On May 9 it rained 38 mm (1.50 in) with an average intensity of almost 2.5 mm (0.10 in) per hour. This runoff event occurred after the simulated sampling on May 4 and before the actual sampling on May 11 which could easily explain the large difference at the Seymour SFR site mentioned earlier and the 47% difference at the Cortland CBD site. And finally, on September 10 it rained 47 mm (1.86 in) in 5 hours. This runoff event occurred after the simulated sampling on September 4 and before the actual sampling of September 13 which could also explain the 31% difference at the Parnell HWY site shown in Table 4. The newest version of SIMPTM, which has not been completed at this time, will allow one to specify the exact dates of sweeping or sampling (i.e., perfect sweeping event).

As discussed earlier, the accumulation of sediments within the catchbasin located throughout the test areas were also monitored over the sampling period. The initial monitoring that occurred on

9/13/99 in Livonia and 4/7/00 in Jackson showed a wide range of initial catchbasin accumulations from empty to 1.08 m (3.55 ft) deep. As part of the SIMPTM calibration, catchbasin cleaning was simulated on 10/7/99 in Livonia and on 4/10/00 in Jackson. The simulated accumulations in the catchbasins were then compared to those values observed near the end of the monitoring period at each of the sites. The results of this comparison are shown in Table 5.

**Table 5 Observed Versus Simulated Catchbasin Accumulations**

| Project | Site Name | Monitoring Date | No. of Catchbasins | Observed Accumulation Avg. Depth of Material cm (ft) | Simulated Accumulation Avg. Depth of Material cm (ft) |
|---|---|---|---|---|---|
| Livonia | Newburgh | 5/11/00 | 7 | 1.8 (.06) | 0.6 (.02) |
| | Fox Creek | 3/24/00 | 8 | 1.2 (.04) | 1.5 (.05) |
| | Munger | 5/11/00 | 8 | 1.5 (.05) | 0.6 (.02) |
| | Riverside | 3/24/00 | 14 | 0.9 (.03) | 0.3 (.01) |
| Jackson | Durand | 9/6/00 | 1 | 4.3 (.14) | 1.2 (.04) |
| | Jackson | 8/9/00 | 1 | 46.3 (1.52) | 1.5 (.05) |
| | Cortland | 9/16/00 | 1 | 2.4 (.08) | 0.6 (.02) |
| | Parnell | 9/13/00 | 1 | 61.0 (2.00) | 0.9 (.03) |
| | Carroll | 9/6/00 | 1 | 31.4 (1.03) | 6.4 (.21) |
| | Seymour | 8/9/00 | 1 | 1.8 (.06) | 0.9 (.03) |

For the Livonia project where 7 to 14 catchbasins were monitored throughout each test area, SIMPTM is providing reasonable estimates of the magnitude of average accumulated sediment found in the catchbasins over a short period of time. Note that the model is generally underestimating these accumulations which means that any conclusions regarding the reduction in pollution due to catchbasin cleaning should be conservative estimates since actual observed catchbasin accumulations appeared to be somewhat greater.

For the Jackson project where only one catchbasin was monitored at each of the test areas, the comparison suggests that the model is significantly underestimating the amount of sediment accumulating in the catchbasins over time. However, there are several issues that concern the authors about the Jackson catchbasin data. First, only one catchbasin was monitored in each test area. Given the large range of accumulations found within each of the Livonia test areas during each of the samplings, the decision to sample only one catchbasin at each test area was an obvious mistake in the study design that should not be repeated in the future. Second, the depth measurement may have included organic material which can occupy a considerable amount of volume when compared to sediment alone. SIMPTM simulates sediment accumulations not the accumulation of organic material. It is unclear as to whether the field monitoring crews were aware of the distinction between sediment and organic material, or were simply measuring and reporting the depth of material accumulation which was their basic instructions.

In light of these catchbasin related issues, the authors decided not to change the model's parameter values in an effort to achieve higher catchbasin accumulations. The catchbasin accumulation parameters currently being used by the SIMPTM model were the result of a detailed calibration to the City of Bellevue's Nationwide Urban Runoff Program (NURP) data that involved the cleaning and monitoring over a two-year period of over 100 catchbasins found throughout two residential drainage basins located in this eastern suburb of Seattle, Washington.

## AVERAGE RAINFALL YEAR DEVELOPMENT

Rather than simulate many runs using many years of rainfall and summarize the extensive results, a long precipitation record was processed into many precipitation events, which were then evaluated. The twelve *best* months were combined to synthesize an average year that was used for the annual runs to evaluate different best management practices (BMPs). The development of an average rainfall year using RAINEV (a rainfall analysis program included in the SIMPTM package) has been documented several times. For a more detailed description of average rainfall year development please refer to Sutherland, Jelen and Minton (1998).

For the Livonia project, high quality, continuous hourly precipitation data for 1961 through 1998 was obtained from a SEMCOG gauging station located approximately 4.0 km (2.5 mi) south of the study's test areas. For the Jackson project, continuous hourly precipitation data for 1948 through 1999 observed at the Jackson 3N2 station was obtained from the National Climatological Data Center (NCDC). These hourly precipitation recorders were processed into discrete runoff producing events using the thresholds of runoff presented earlier. For each long precipitation record, these events were then summarized by the following parameters for each month of each year: (1) Number of events, (2) Total duration of events, (3) Total depth of events, (4) Maximum hourly precipitation, (5) Average intensity and, (6) Average dry time preceding events.

These parameters were then analyzed graphically in a spreadsheet month by month. Each statistic for each year was compared to its average for all years. The absolute error or departure from mean was graphed by year, with emphasis on the error in total monthly depth. Months whose parameters that closely approximate the long-term mean were found by looking for years where all data points (i.e., errors) neared 0. In this manner, each of the twelve months was examined and the best month for each month was found. The hourly data for each were then combined to create a representative, average year, which was analyzed by RAINEV to generate the events used by SIMPTM in its average annual simulations.

One final modification had to occur before the average year could be considered complete. It is important that the average year was a representative rainfall year which means it must exclude the period of time where on the average frozen conditions exist. For Livonia, we obtained and examined the long-term temperature records for the Detroit Metropolitan Airport and concluded that the average long-term freeze up period was from December 21 to February 21. For Jackson, we obtained and examined the long-term temperature records for the Jackson Airport and concluded that the average long-term freeze up period was from December 21 to March 15. So any precipitation events that occurred during these periods were ignored and not included in the, respective, final average rainfall year. It is interesting to note that during the eight-month monitoring period in Livonia that included the winter months, very little snowfall was observed and the typical frozen period did not occur.

The average rainfall year for Livonia, Michigan contains 61 runoff-producing events that occur from February 22 through December 20. These events total 630 mm (24.79 in) of rainfall over a total duration of 387 hours which yields an average rainfall intensity of 1.63 mm/hour (.064 inches/hour). The average event is 10.4 mm (0.41 in) in depth and lasts for approximately 6.35 hours. The average rainfall year for Jackson, Michigan contains 63 runoff producing events that occur from March 16 through December 20. These events total 546 mm (21.51 in) of rainfall over a duration of 271 hours which yields an average intensity of 2.01 mm/hour (.079 in/hr). The average event is 8.6 mm (0.34 in) in depth and lasts for approximately 4.30 hours.

## BMP ANALYSIS

Using the calibrated model parameters from each of the nine land use areas (i.e., the two residential areas in Livonia were combined) and the respective average rainfall year, SIMPTM was used to simulate average annual Total Suspended Solids (TSS) loadings or washoffs on a unit acre basis for a large array of best management practices. The practices that were evaluated included catchbasin cleaning, mechanical street sweeping, tandem sweeping (i.e., vacuum-assisted followed by mechanical), regenerative air sweeping, and high-efficiency sweeping. For a completed discussion on SIMPTM's ability to simulate street sweeping operations and the sweeping model parameter values used for these simulations, please refer to Sutherland and Jelen (1997).

High-efficiency street sweepers utilize strong vacuums and the mechanical action of uniquely designed main and gutter brooms combined with an air filtration system that only returns clean air to the atmosphere (i.e., filters particulates to 2.9 μm). These machines sweep dry and no water is used since they do not emit dust. Schwarze Industries, Inc.'s EV series, which includes the EV-1 and EV-2, are currently the only documented high-efficiency sweepers. High-efficiency sweepers were named by Sutherland for their unique ability to pick up and totally contain a very high portion of the fine, contaminated dirt that accumulates on streets and parking lots. For more information on high-efficiency sweeping, please refer to Sutherland, Jelen and Minton (1998).

## PRODUCTION FUNCTIONS

For the BMP simulations that were used, the frequency of the street sweeping was varied from bimonthly to daily. The frequencies (i.e., days between sweepings) used were 61, 30, 15, 7, 4, 2, and 1. Since the average rainfall years were approximately 9 months in length (due to frozen conditions) and sweeping was not assumed to begin until March 15 in Livonia and March 23 in Jackson, the actual number of sweepings that corresponded to the above frequencies were approximately 5, 9, 19, 40, 69, 140, and 282 times per year, respectively.

For the BMP simulations that were used, the frequency of catchbasin cleaning was assumed to be annual. This means the SIMPTM model began the average year simulation with the catchbasins cleaned and empty. These BMP simulations also included the simulation of no street sweeping and no catchbasin cleaning occurring throughout the year which was used to calculate how effective each of the BMPs were in removing TSS from the washoff (i.e., mass/area/year).

If one plots the relationship between effort and removal, a curve called a production function would be the result. For example, Figure 3 presents the array of production functions developed for single-family residential areas found within the Livonia study area. Similar figures were also developed for the other two test areas in Livonia and the six areas in Jackson. Note that high-efficiency sweeping with annual catchbasin cleaning is the most effective BMP followed closely by regenerative air sweeping with annual catchbasin cleaning.

## TOTAL COST CURVES

The next step in establishing the optimal levels of the various BMPs described earlier is to establish curves that show the relationships between TSS reduction and total cost. In order to establish these relationships, we needed to estimate the cost of street sweeping and the cost of catchbasin cleaning and multiply the production functions by these various costs. Working with cost data provided by the City of Livonia, it was estimated that catchbasin cleaning costs $44.25 per catchbasin and street sweeping costs $123.00 per curb km ($76.90/curb mi) swept. In Jackson, catchbasin cleaning was $28.75 per catchbasin cleaned and street sweeping was $224.00 per curb km ($140/curb mi) swept. These costs include labor, overtime, equipment and overhead associated with each activity.

As part of the analysis we did not factor in potential differences in equipment capital costs and life cycle costs. However, the equipment costs provided to us did contain existing amortized capital equipment costs and existing equipment maintenance-related costs. The intent of the cost analysis was to keep it simple and see approximately how cost effective various BMPs could be in reducing pollutants entering both Livonia and Jackson area waterways.

The BMP production functions discussed earlier were then multiplied by the appropriate unit area costs to create the BMP total cost curves. For example, Figure 4 presents the array of total cost curves developed for single-family residential areas found within the Livonia study area. Similar figures were also developed for the two other test areas in Livonia and the six areas in Jackson.

Note that for any given BMP, the solids removal increases as the total costs increase. Early on, any given BMP will remove a lot of solids for not much cost. As removals increase beyond this point, costs increase at a greater rate. As we move along the curve, the cost increases bring smaller and smaller marginal increases in removal until the costs become prohibitive and no more removal can occur. Economic production theory tells us that if everything else is essentially equal, we should always operate our practices at optimal levels. Optimal levels provide for the most cost-effective removals because they consider the true cost of removing the next kilogram or pound of a given pollutant. Finding these optimal levels is the subject of the next subsection.

## MARGINAL COST CURVES

In order for one to find the optimal level for any given practice, we need to understand the relationship between solids removal and the change in cost of removing those solids. Once the cost of removing a reasonable amount of solids reaches a reasonable marginal cost, the level of effort associated with that point is considered optimum.

To assist us in determining where the optimal level of effort is for any given BMP, we developed BMP marginal cost curves. These curves show the relationship between solids removal and the marginal cost of removing those solids. Figure 5 presents the single-family residential marginal cost curves developed for the Livonia study area. Similar figures were developed for the two other test areas in Livonia and the six areas in Jackson.

Working with the curves in Figure 4, we can conclude that $22 per kg ($10/lb) of solids removed from washoff is a reasonable level of effort in relationship to the amount of solids actually removed. Note that each BMP reaches that $22 per kilogram marginal cost at varying amounts of solids removed. Those BMPs that reach the $22 marginal cost at the lowest removal are the least cost-effective and the ones that reach this level at the highest removal are the most cost-effective. Table 6 presents a listing of the optimal effort levels for the most cost-effective to the least cost-effective BMPs for single-family residential areas in Livonia. Similar tables were generated for the other two test areas in Livonia and the six areas in Jackson.

**Table 6 Optimal Effort Levels of Various BMPs on Single-Family Residential Areas in Livonia, Michigan**

| BMP Description | Optimal Level of Effort in Sweeping Frequency | Marginal Cost $/kg removed ($/lb removed) | Solids Removed from Washoff Annually kg/ha (lb/ac) | % Reduction in Solids Washoff |
|---|---|---|---|---|
| HS & annual CBC | every 15 days | 25.24 (11.36) | 39.9 (35.2) | 84 |
| RS & annual CBC | every 15 days | 28.98 (13.04) | 38.7 (34.1) | 81 |
| HS & no CBC | every 15 days | 14.09 (6.34) | 33.8 (29.8) | 71 |
| TS & annual CBC | every 30 days | 23.53 (10.59) | 34.1 (30.1) | 72 |
| RS & no CBC | every 15 days | 15.87 (7.14) | 31.6 (27.9) | 66 |
| MS & annual CBC | every 30 days | 15.38 (6.92) | 30.0 (26.5) | 63 |
| TS & no CBC | every 30 days | 12.91 (5.81) | 23.4 (20.6) | 49 |
| MS & no CBC | every 15 days | 18.51 (8.33) | 22.2 (19.6) | 47 |

HS – high-efficiency sweeping; RS – regenerative air sweeping; TS – tandem sweeping; MS – mechanical sweeping; CBC – catchbasin cleaning

It should be noted that the optimal levels of effort defined in Table 6 were those levels whose marginal costs were the nearest to the $22 value that was arbitrarily selected. Some of these costs exceeded $22 and one could argue that one should have selected the next lower level of effort. Using this logic one could argue that the actual optimal level of effort on single-family residential areas in Livonia for high-efficiency or regenerative sweeping with annual catchbasin cleaning was approximately once every 21 days or approximately 12 times during Livonia's average sweeping season (i.e., March 15 through December 1). So the assignment of optimal levels of effort is somewhat subjective and could vary from one land use area to the next.

## CONCLUSIONS

The results clearly show that street sweeping in combination with catchbasin cleaning could provide some very significant reductions in TSS loadings with scheduled frequencies of 15 to 30 days. In urbanized areas of southern Michigan, it appears that the most cost-effective maintenance practice involves high-efficiency (i.e., EV) or regenerative air sweeping with annual catchbasin cleaning approximately every 15 to 30 days during the sweeping season depending upon the actual land use. This conclusion was reached for all of the land use areas that were studied. However, implementing these optimum frequencies would represent a large increase in existing sweeping effort and cost since both cities currently sweep single-family residential areas four times a year and does not sweep any parking areas since they are primarily privately owned. The difficult part will be finding the financial resources to pay for these increased costs.

## KEY FINDINGS

- An urban area study design which focuses on the monitoring of contaminated sediment accumulating on upland paved areas and sediment trapping catchbasins (that can be implemented for one fifth to one tenth of the cost of monitoring end-of-the-pie stormwater flow and concentrations) has been offered for TMDL loading analyses that provides:

    - reasonably accurate urban stormwater pollutant washoffs
    - optimal effort levels for street sweeping and catchbasin cleaning practices
    - an understanding of the pollutant load reductions associated with various street sweeping and catchbasin cleaning practices

- In selected southern Michigan urban areas, high-efficiency street sweeping every 15 to 30 days with annual catchbasin cleaning can provide an 80% reduction in annual TSS washoffs which should translate into significant in-stream water quality benefits. A serious re-examination of the actual stormwater quality benefits associated with these maintenance practices is needed throughout the United States and the world.

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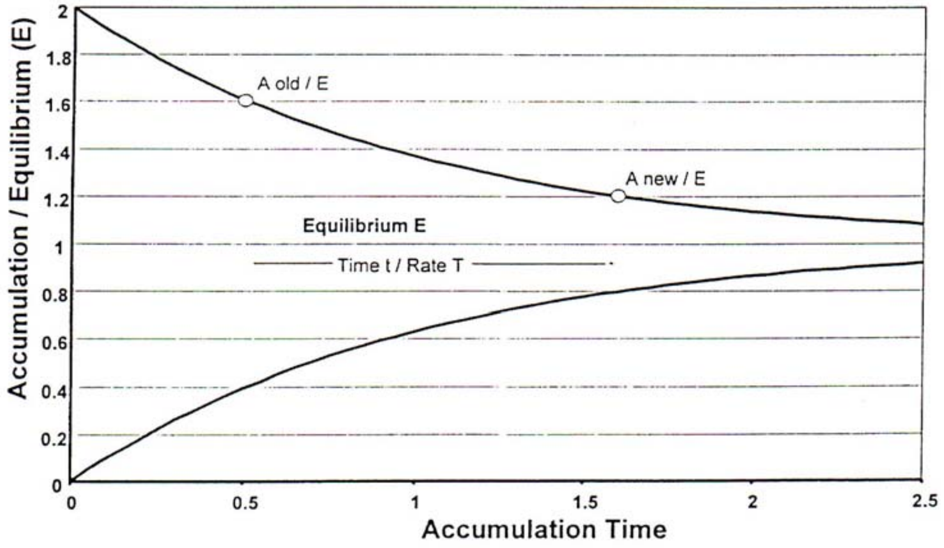
## Figure 1
## Dry Weather Accumulation Function in SIMPTM from Sutherland and Jelen, 1996



$$A_{new} = (A - E)(e^{-t/T} - 1)$$

## Figure 2 - SIMPTM Calibration
## Durand SFR

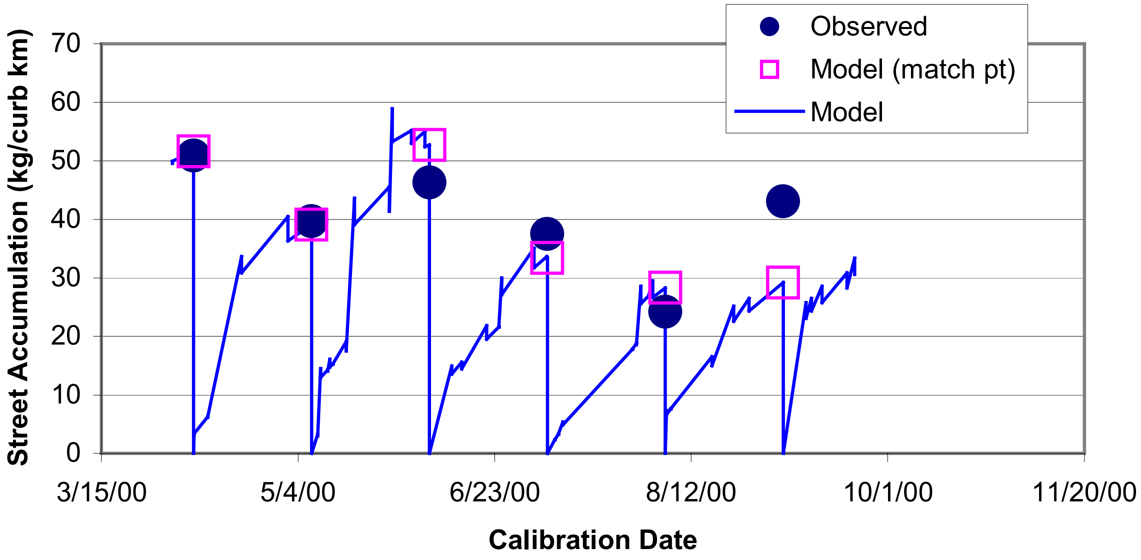


**Figure 3**
**BMP Production Functions - Single Family Residential - Livonia MI**

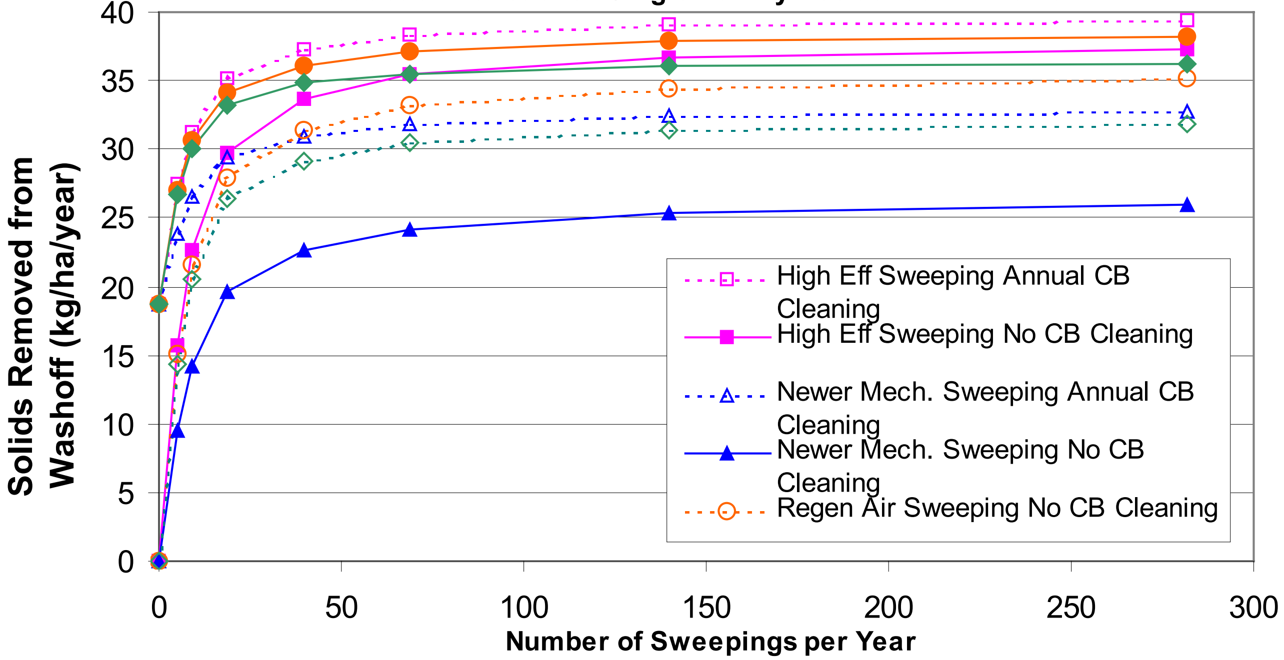


**Figure 4**
**BMP Total Cost Curves - Single Family Residential - Livonia MI**

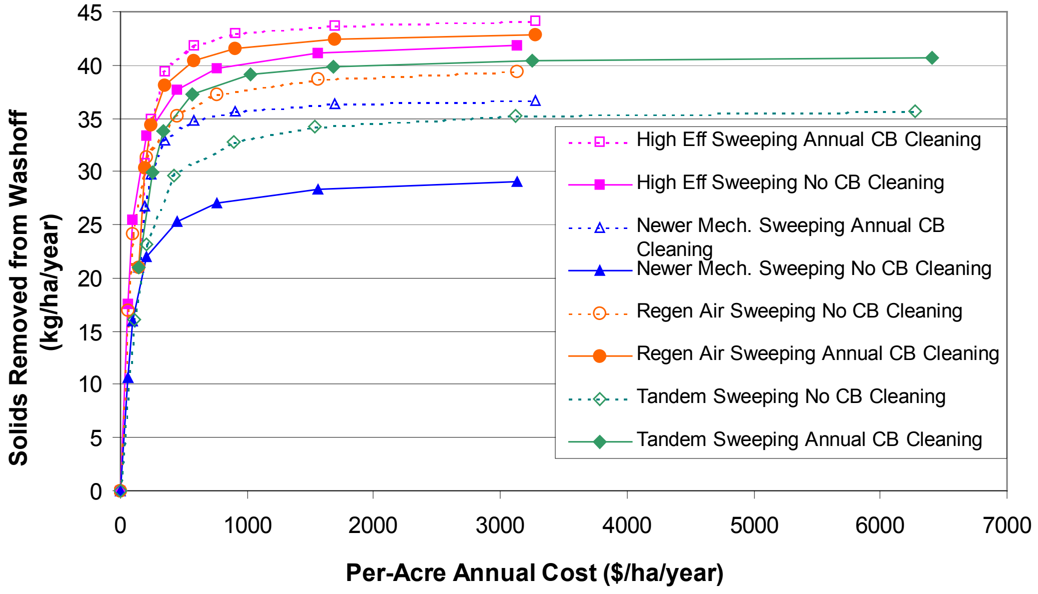


**Figure 5**
**BMP Marginal Cost Curves - Single Family Residential - Livonia MI**