Chapter I

Sophisticated Stormwater Quality Modeling Is Worth the Effort

Roger C. Sutherland and Seth L. Jelen

Annual runoffs and pollutant loads for six homogeneous Nationwide Pollutant Discharge Elimination System (NPDES) stormwater sites in Portland, Oregon, were simulated using SIMPTM, the Simplified Particulate Transport Model, calibrated to local runoff quality data. Results clearly showed that current linear or exponential sediment accumulation models fail to represent the seasonal variation of accumulation and runoff quality without resorting to arbitrary seasonal rates that depend upon the results they would compute. And the calibrated model results suggested that simplified annual pollutant load calculations, of concentration times volume, could overestimate expected loads by up to seven times. In addition, results of a street sweeping testing showed that tandem street sweeping (i.e. mechanical followed by vacuum) was much more effective than previously concluded by the Nationwide Urban Runoff Program (NURP).

I.1 Introduction

Annual runoffs and pollutant loads for six NPDES stormwater sites in Portland, Oregon, were simulated using SIMPTM (Sutherland and Jelen, 1993a). SIMPTM is a continuous stormwater quality model that simulates stormwater pollutant loadings and expected load reductions from best management practices such as street sweeping and using and cleaning water quality inlets and maintenance hatches. Each NPDES site simulated represented a homogeneous residential (R), commercial (C), industrial (I) or transportation (T) land use (WCC 1991).

Sutherland, R. and S.L. Jelen. 1996. "Sophisticated Stormwater Quality Modeling is Worth the Effort." *Journal of Water Management Modeling* R191-01. doi: 10.14796/JWMM.R191-01.

© CHI 1996 www.chijournal.org ISSN: 2292-6062 (Formerly in *Advances in Modeling the Management of Stormwater Impacts*. ISBN: 0-9697422-5-8)

After runoff hydrographs were calibrated to sixteen months of continuous gage records, sediment accumulation and washoff were calibrated to observed event-mean concentrations for seven events plus sampled accumulations measured throughout the year at three residential sites and once at the six NPDES sites. Both field observation and runoff quality suggested that existing popular accumulation functions were not realistic. Accumulations were noticeably higher during the wet season than the dry, while traditional accumulation models compute just the opposite (since their accumulation increases with the number of dry days). Rather than use seasonal values that depend on the results to be simulated, a new accumulation function was developed. Results from the calibrated model also suggested that simplified loads estimated as concentration times volume could be up to seven times too high.

The calibrated model was used to simulate existing annual pollutant loads and reductions associated with various management practices like street sweeping. Expected removals from three different street sweeping methods were quantified by comparing observed accumulations before and after sweeping, and relating them to particle size. Samples were sieved into eight size groups for this analysis. Tandem street sweeping (i.e. mechanical followed by vacuum) was observed to be much more effective than it has been concluded to be by the Nationwide Urban Runoff Program (USEPA 1983).

1.2 Background

The NPDES stormwater permitting process highlights the need to better understand stormwater quality. Urban stormwater pollution results mainly from washoff of contaminated sediment accumulated on streets, roofs, driveways, and parking lots. Contamination from many sources, like bacteria from animal feces, nutrients from rotting vegetation, and oils and grease, heavy metals and chemicals from vehicles, binds to sediment accumulating on pavement or roof surfaces after eroding from adjoining lots or abrading from pavement itself. Left unchecked, the contaminants can enter stream ecosystems and significantly degrade receiving water quality. Pollutant load modeling can help focus potential management strategies on practices providing the greatest expected benefits.

SIMPTM was used to simulate per-acre stormwater runoffs and pollutant loads from six homogeneous sites throughout Portland, Oregon, representing residential, commercial, industrial, and transportation land uses. Event mean concentrations and continually-gaged flows were combined with hourly local rainfall and sample data of street sediment quality at these and three other local sites to form the calibration data set. Once calibrated, expected annual pollutant loads were projected for the entire NPDES-permitted system. Figure 1.1 illustrates the areas studied and the individual data collection sites.

Figure 1.1 Sites for NPDES and street sweeping modeling using SIMPTM.

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 sediment and bound pollutant transport using the Yalin-Einstein and Foster-Meyer equations, to simulate the capacity of the hydrograph to transport available accumulated sediment from paved areas. This has been shown by Ellis and Sutherland (1979) to be much more accurate than the empirically-based exponential washoff used, for example, in 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, inlets, 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.

SIMPTM has been used extensively in the Portland, Oregon area as part of surface water management and water quality management plan development since 1988. It has 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) recently 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).

1.3 Runoff Volumes

Estimating stormwater pollutant loads is virtually impossible without first accurately modeling runoff volume estimates. Between April 1991 through September 1992, runoff flow was recorded from each of the six sites used for this study and Portland's NPDES permit application. Concurrent hourly rainfall data was also recorded at several nearby City gages. In analyzing each record, continuous records were condensed into over 100 events. For each site, resulting observed event runoff volumes related to rainfall event depths by a simple exponential curve involving only a maximum initial rainfall loss (between 0.05 to 0.10 inches (1.27-2.54 mm)) and a slope. For such small urban sites, no significant pervious runoff volumes were observed. Figure 1.2 illustrates how this curve fits observed data points for one site. Similar curves were found for each site (Sutherland and Jelen 1993b).

It is worth noting that while a simple line might seem to fit the data, relative error at small events could be unacceptably high. These smaller events represent a significant fraction of total annual runoff volumes, and an even more significant fraction of transported pollutant loads (Pitt 1987).

Figure 1.2 Example of calibrated event runoff model with observed data.

1.4 Solids Washoff

Modeling solids washoff required calibrating both dry-weather accumulation and wet-weather transport and deposition. Wet-weather data included up to seven sampled event mean concentrations plus gaged flows at each NPDES site (Woodward-Clyde 1992). Dry weather data included accumulations measured once at each NPDES site plus ten times at three residential areas from November 1991 to October 1992. An industrial shop-vac was used to sample areas of paved surfaces, then samples were sieved into eight size groups.

Wet-weather transport was limited by the available supply or the transport capacity of the flow. SIMPTM uses event rainfall statistics to shape event runoff volumes into representative flows into each inlet, which are then related to bed and suspended load capacities at each time step using the Yalin-Einstein and Foster-Meyer equations (respectively). Both depend on hydraulics through the representative number of inlets, channel slope, pavement roughness, and either effective flow width (for parking lots) or side slope (for curb and gutter streets). These model input parameters were either measured or set to previously published values and checked during calibration.

Sediment accumulation clearly varied with rainfall. Pavement deposits visibly increased during most events. Figure 1.3 illustrates how wet-season accumulations (i.e. October through April) were higher overall than in the dry season using recorded street sweeping pick-up from the City of Portland (Condor, 1989). Independent field observation further supported this. However, traditional accumulation models (like SWMM) cannot simulate any wet-weather accumulation so arbitrary seasonal dry-weather accumulation parameters are introduced in an attempt to account for this deficiency. Instead, SIMPTM allows upstream pervious washoff (when it is simulated) to exceed downstream transport capacity and accumulate for later washoff or removal.

Figure 1.3 Recorded street sweeping pick-ups for Portland Oregon.

Figure 1.4 compares the two methods, showing 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 depositions from higher volume 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 like SWMM. Street cleaning and washoff are of course explicitly modeled.

Figure 1.4 SIMPTM dry accumulation model.

Figure 1.5 illustrates for one NPDES site, and for over 100 individual storm events during the sixteen month calibration period, the close match between washoffs computed by SIMPTM and observed, for the seven events sampled. Table 1.1 presents the calibrated runoff and solids washoff parameters for each site.

Figure 1.5 Example of washoffs as observed and modeled using SIMPTM.

Table 1.1 SIMPTM model input parameters calibrated to Portland NPDES data.

Site and Description	Runoff		Solids Accumulation				Solids Washoff		
	EIA*	Loss inch	Accumulation Unit	Curb Ft per Ac.	Equil. Level	Wet Rate*	Flow Type	Inlets per ac.	Width
C1 Shopping Mall	0.87	0.05	Lbs/Paved Acre	—	5	15	Overland	2.09	20
C2 Downtown Comm.	0.90	0.05	Lbs/Paved Acre	—	20	90	Overland	3.42	8
I1 Heavy Industrial	0.63	0.05	Lbs/Paved Acre	—	100	100	Overland	0.57	20
I2 Campus Industrial	0.60	0.05	Lbs/Paved Acre	—	80	20	Overland	0.18	15
R2 Suburban SF Res.	0.19	0.10	Lbs/Curb Mile	350	200	300	Gutter	0.76	—
T1 Major Arterial	0.80	0.05	Lbs/Curb Mile	1400	30	140	Gutter	4.00	—

*EIA is effective impervious area or fraction of the total catchment that is impervious and directly connected to the drainage system.

The *dry accumulation rate* (for exponential model) was calibrated to be 0.02 per day for all sites.

*Wet Rate is the rate of accumulation *during* an event, in accumulation units per inch of rainfall depth.

The *wet accumulation threshold* for wet accumulation to begin was calibrated to be 0.5 inches of rainfall depth during any significant rainfall event.

(Significant rainfall events are those that produce runoff and are generally defined by threshold events as .04, .06 and .10 inches of rainfall within any 1, 3 or 6 hour period, respectively. Significant rainfall events are generally separated from each other whenever any three hour period occurs with rainfall depths less than .02 inches per hour.)

1.5 Washoff of Other Pollutants

Sediment washoff was related to washoff of other pollutants by mass-fractions or potency factors assigned to each of the eight particle size groups of accumulated sediment. These are generally set from observed fractions of accumulated sediment or from observed sediment washed off during sampled events. Potencies from runoff data were preferred since only one accumulation sample was taken per NPDES site. Six accumulated sediment samples taken from three ungaged residential neighborhoods plus one per NPDES site were sieved into the eight groups and composited back to three for chemical analysis (Hilts 1992). The resulting 72 samples were tested for ICP metals (and phosphorus), COD and TKN (AmTest, 1992). Results were provided whenever enough sample was given. Runoff data based potencies were simply ratios of event mean concentrations of pollutant and TSS from Woodward-Clyde runoff data (WCC 1992).

Table 1.2 lists pollutant potencies used in the simulation. Note that potencies were not varied by particle size since the model was not directly calibrated to other pollutant washoffs. Similarities in potencies between the two data sets (i.e. accumulation versus runoff) were from pollutants almost totally suspended, like lead and copper. But many others, such as phosphorus or zinc, were much higher for runoff than for even the finest street dirt size group. For these pollutants, washoff calibration requires that the potency of the finer sediment fractions be set to values higher than observed in the accumulation data; this procedure will account for the dissolved portions of the pollutant mass which were actually attached to those larger particles that are not transported during most events.

Table 1.2 Modeled mass fraction of other pollutants to mass of TSS.

Site	BOD5	COD	TP	TKN	Cd	Cu	Pb
C1	0.19	1.03	3.7E-03	2.2E-02	7.8E-06	4.4E-04	8.3E-04
C2	0.19	1.03	3.7E-03	2.2E-02	7.8E-06	4.4E-04	8.3E-04
I1	0.44	0.88	5.2E-03	1.5E-02	2.9E-05	4.0E-04	3.8E-04
I2	0.44	0.88	5.2E-03	1.5E-02	2.9E-05	4.0E-04	3.8E-04
R2	0.06	0.40	3.3E-03	9.6E-03	2.6E-06	5.4E-05	1.5E-04
T1	0.17	0.66	2.1E-03	1.3E-02	1.6E-05	3.3E-04	3.4E-04

1.6 Performance of Street Cleaning Practices

Three methods of street cleaning were tested seven times each between November 1991 and October 1992 for Portland’s Combined Sewer Overflow (CSO) Abatement Project (HDR,1992). Tested methods were: standard (mechanical or broom with conveyor sweeper), heavy flush (following mechanical sweeper), and tandem (vacuum-assisted following mechanical sweeping). For each size group, SIMPTM computes street cleaning performance as follows:

$$Removed = EFF * (Before - ACC_{minimum})$$

where *EFF* and *ACC_{minimum}* are street sweeping input parameters related to efficiency and accumulation.

Removal was found by measuring accumulations before and after cleaning, then plotting removal against accumulation before cleaning. Values of *EFF* and *ACC_{minimum}* are determined from the straight line that best fits the data points. Figure 1.6 presents results for one of the eight size groups, together with the expected best-fit line. As expected, not all street dirt was removed during cleaning, and finer accumulations were harder to remove. While heavy flush performed slightly better than standard mechanical, both were clearly inferior to tandem sweeping.

Figure 1.6 Street sweeping performance as observed and modeled.

1.7 Expected Loads and Benefits of Street Cleaning

Annual loads were set for varying levels of street cleaning to establish the expected benefit from reduction of pollutant loads to receiving waters compared to the expected existing-condition loads. Rather than model and analyze decades of rainfall-runoff-washoff events, 40 years of rainfall at the Portland Airport (1948 to 1988) and fifteen years from a local gage (PCC-Cascade, 1976 to 1991) were used to form a representative rainfall-year reflecting monthly, seasonal and annual totals, means and variations. After 1.5 inches (38 mm) of non-runoff producing rainfall was excluded, the remaining 35 inches (890 mm) were formed into 152 events, from which about 30 inches (760 mm) runoff was expected (Adderly 1992).

Runoff and TSS and pollutant washoffs were simulated for each site with this representative (or average) year. Per-acre totals (unit loads) were then computed. Table 1.3 compares these unit loads for TSS (total suspended solids) against those published in Portland’s permit application that simply used an overall observed event mean concentration (EMC) times an assumed runoff volume. Modeled effective impervious area (EIA) previously discussed is also shown for information purposes.

Table 1.3 Annual average TSS loads from SIMPTM and EMC x Volume.

Site Description		EIA	SIMPTM	Constant EMC	Load Ratio: EMC/SIMPTM
C1	Shopping Mall	0.87	143	580	4.06
C2	Downtown	0.90	401	580	1.45
I1	Heavy Ind.	0.63	775	814	1.05
I2	Campus Ind.	0.60	320	814	2.54
R2	Sub. Residential	0.19	73	541	7.41
T1	Major Arterial	0.80	1064	843	0.79

Simulated TSS average annual load reductions for alternative street sweeping methods and frequencies are presented for site R2 (Suburban Single Family Residential) in Figure 1.7. Note that for residential areas, the expected 5% TSS washoff reduction from mechanical sweeping 6 times per year was projected to increase to over 18% with tandem sweeping 26 times per year.

The unit TSS loads without any sweeping are projected to be up to *six* times less than those estimated using observed constant concentrations, clearly

supporting the value of using models like SIMPTM over simplified concentration times volume approaches. Sophisticated stormwater quality modeling is definitely worth the effort.

Figure 1.7 Projected fraction of annual load picked up.

1.8 Recommendations

Certainly even more sophistication is possible. Availability of continuous turbidity and conductivity data offers the potential to collect much more runoff quality data than is affordable by lab analysis alone. Work could be done to define relationships between these parameters and TSS washoff concentrations.

In addition, maintenance records of the total amount of street sweeping pick-up (from disposal volume) can provide system-wide accumulation data (by using measured cleaning performance to relate aggregate removals to aggregate accumulations both before and after cleaning occurs). Continuing to collect accumulation and washoff data from diverse regions and sites further establishes the model parameter data set and validates the underlying physical basis of the model.

SWMM currently does not model real sediment accumulation and washoff processes. Adding physically-based scour and deposition algorithms and allowing excess upland washoff to accumulate (i.e. wet-weather accumulation) for later storm washoff or removal by management practices as SIMPTM does could greatly enhance the applicability of SWMM for urban water quality projects.

Acknowledgements

This work was funded under contract to the City of Portland Bureau of Environmental Services (BES) as part of their NPDES Stormwater Permitting Project (BES 1993) for the direct benefit of the Combined Sewer Overflow Abatement Project (CH2M 1993). Special thanks are given to Victor Viets and Eric Strecker of Woodward-Clyde Consultants, Portland, for providing us with the runoff and water quality data.

References

- Adderly, Virgil, 1992. Creation of Average Year Rainfall Series. Prepared by CH2M HILL, Portland, Oregon.
- AmTest, 1992. Chemical Analysis Reports of Street Dirt. Beaverton, Oregon.
- BES, 1993. Part 2 - National Pollutant Discharge Elimination System (NPDES) Municipal Stormwater Permit Application, Volume 3. Submitted by the City of Portland Bureau of Environmental Services (BES) to the Oregon Department of Environmental Quality (DEQ).
- CH2M HILL, Brown & Caldwell, & Associated Firms, 1993. Draft Facilities Plan, Combined Sewer Overflow Management Plan. Prepared for the City of Portland, Bureau of Environmental Services.
- Condor, S., 1989. Street Cleaning Report: 24-City Survey and City of Portland Cost Allocation and Funding Analysis. Prepared for the City of Portland, Bureau of Environmental Services.
- Ellis, F.W., and R.C. Sutherland, 1979. An Approach to Urban Pollutant Washoff Modeling. Proceedings, International Symposium on Urban Storm Runoff, Lexington, Kentucky.
- HDR, 1992. Combined Sewer Overflow SFO Compliance Interim Control Measures Study, Final Report. Prepared For City of Portland, Bureau of Environmental Services.
- Hilts, David E., 1992. Mechanical Analyses of Street Sweepings Laboratory Test Results. Prepared by Fujitani Hilts & Associates, Inc., Portland, Oregon.
- Pitt, Robert, 1987. Small Storm and Particulate Washoff Contributions to Outfall Discharges. Ph.D. Thesis, University of Wisconsin. Madison, Wisconsin.
- Sutherland, Roger C., and Seth L. Jelen, 1993a. SIMPTM Users Manual. Kurahashi & Associates, Inc., Tigard Oregon.
- Sutherland, Roger C., and Seth L. Jelen, 1993b. Technical Memorandum 5.3, CSO and Separate Stormwater Pollutant Loads Estimation. Prepared for CH2M HILL and Brown & Caldwell, Portland, Oregon.
- USEPA 1983. Results of the Nationwide Urban Runoff Program, Volume I - Final Report, Washington DC.
- USGS, 1992. Calibration and Users Guide for the Simplified Particulate Transport Model (SIMPTM), Water Resources Division, Austin, Texas.

- WCC, 1991. Water Quality Monitoring Plan. Prepared by Woodward-Clyde Consultants, Inc., Portland, Oregon, for the City of Portland Bureau of Environmental Services.
- WCC, 1992. Preliminary Stormwater Data Report, February 12th Draft. Submitted by Woodward-Clyde Consultants, Inc., Portland, Oregon, to the City of Portland Bureau of Environmental Services.

Note:

For further information regarding the difficult-to-locate references contact Mr. Roger C. Sutherland at the address listed in the review of authors in the front matter.