Figure 1. Storm grate with leaf accumulation

Quantifying Nutrient Removal by Enhanced Street Sweeping

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In the early 2000s, two major federal programs offered promise of improved water quality within and downstream of cities. First, EPA's stormwater program moved stormwater drainages into the National Pollutant Discharge Elimination System (NPDES), subjecting them to regulation. Most cities with populations greater than 10,000 now have active municipal separate storm sewer system (MS4) programs. Second, EPA's total daily maximum load (TMDL) program compelled states to develop plans to restore impaired surface waters.

So far, there is little evidence that these programs have resulted in widespread improvement of urban water quality, at least with respect to nutrients. As an example, about 140 lakes in the Minneapolis–St. Paul metropolitan region have been designated as "nutrient-impaired," but only one has been delisted as the result of deliberate management. Some of the lack of lake response to changes in management may be due to legacy effects, such as recycling of phosphorus (P) from lake sediments, but there is growing concern that we are not achieving nutrient reduction goals. Moreover, cities have learned that the costs of their stormwater programs have been high, compelling them to think about improving the economic efficiency of stormwater control measures. Hence, a decade into the TMDL and stormwater programs, some cities have taken a new look at a very old street management practice: street sweeping.

Early analysis of the effect of street sweeping conducted during EPA's National Urban Research Program (NURP) concluded that street sweeping was not effective at reducing event mean concentrations of P in stormwater (USEPA 1983). Even today, street sweeping has been relegated to the diminutive category of "housekeeping practices" in MS4 programs, not to be taken too seriously. This attitude is changing. The influence of leaf litter and organic matter on nutrient loads in street sediments has often been noted in recent years (Waschbusch et al. 1999, Seattle Public Utilities 2009, Law et al. 2008, Sansalone and Rooney 2007, Minton and Sutherland 2010). In a way, this is obvious. Surely the leaves collecting above the storm grate (Figure 1) are a source of nutrients!

The Prior Lake Street Sweeping Experiment

In 2009, the city of Prior Lake, MN, a leafy southwestern suburb of the Twin Cities, started an ambitious project to quantify nutrient removal by street sweeping, partnering with the University of Minnesota through an EPA 319 grant. The study had several defining characteristics that made it unique. First, it was conducted as a factorial design, with two treatments: frequency of sweeping (once, twice, and four times per month) versus tree canopy cover (low, medium, and high, although we later evaluated findings based on a continuous gradient of canopy covers). Second, rather than attempt to measure the effects of sweeping on stormwater loadings (as was done in the NURP study) we measured solids, nitrogen (N), and P in swept material, allowing us to estimate sweeping load recoveries directly.

Furthermore, whereas many studies of street sweeping discarded coarse material (e.g., leaves and seeds) that don't pass through a 2-millimeter sieve (e.g., Townsend et al. 2002, Rochfort et al. 2009), we collected coarse organic material trapped *above* the sieve and analyzed it separately. Third, unlike many studies that were of short duration or ceased before autumn leaf fall (e.g., Selbig and Bannerman 2007, Vaze and Chiew 2004), sweeping was conducted from just after snowmelt up until the first snowfall. Finally, we kept detailed records of costs—for labor, equipment maintenance, and fuel—and included capital depreciation for the sweepers.

Sweeping started in August 2010 and continued through July 2012 using a Tymco Model 600 regenerative air sweeper. Three hundred ninety-two sweeping samples were collected and stored frozen until analysis by the research team (Figure 2). Samples were sieved to isolate fines (passing through a 2-millimeter sieve) and coarse material (not passing). The coarse material was then floated in 3 liters of water. Material that floated to the surface was collected and termed *coarse organic matter* (COM). Heavier material that had been attached to the COM settled to the bottom; this

Figure 2. Street sweeping research team. Left to right: Ross Bintner, Chris Buyarksi, Sarah Hobbie, and Paula Kalinosky

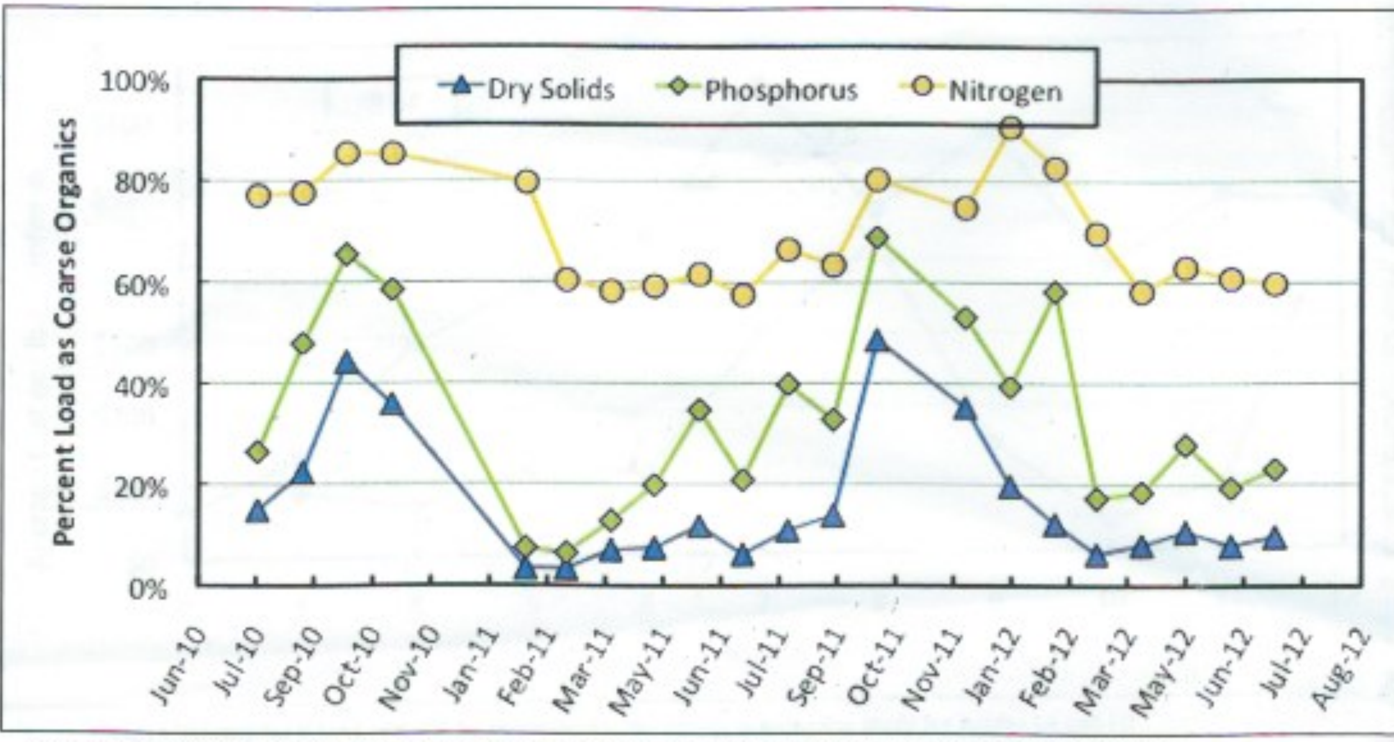

Figure 3. Trend in percent dry solids, N, and P in the COM fraction of sweepings for the two-year sweeping period

material was dried and re-sieved. The fraction that passed through the sieve was added to the original fines fraction, and coarser material (mostly sand and pebbles) was weighed but not analyzed for nutrients. Wet and dry weights of the original samples and components were recorded. The fines and the COM were analyzed for carbon (C), N, and P. The water used for the flotation step was analyzed for nutrients, and the mass of C, N, and P, but nutrients dissolved in the flotation step were only 1 to 2% of the total nutrient mass of swept material. High-resolution land cover for the city of Prior Lake was developed by the University of Vermont Spatial Analysis Laboratory (*www.uvm.edu/rsenr/sal*) using object-based image analysis that combines satellite imagery and LiDAR data (Kilberg et al. 2011). This enabled us to estimate percentage of canopy cover over streets for each sweeping route. Additional methodological details are reported in Kalinosky et al. (in process a).

Street Sweeping has been relegated to the diminutive category of "housekeeping practices" in MS4 programs, not to be taken too seriously. **This attitude is changing.**

Table 1. Composition of COM and Fines as Percent of Dry Weight

	COM	Fines
% organic matter	81.1	8.3
% C	40.4	5.6
% P	0.17	0.07
% N	1.6	0.14

What Did We Find?

The composition of fines and COM was different. As one might expect, the chemical composition of COM was quite different from that of the fine fraction ("street dirt") (Table 1). On average, the percentage of organic matter and the N content was about 10 times higher for COM than for fines; the P content of COM was about 2.4 times that of fines.

The importance of COM in load removal varies seasonally. For the entire study (all routes and sweepings), COM accounted for only 15% of dry solids, but 33% of P and 72% of N. The percentages of solids, P, and N varied by season, with the largest spikes occurring during autumn leaf fall (Figure 3). Smaller spikes occurring in late spring and early summer probably reflect inputs of tree bracts, flowers, and aborted seeds.

As expected, both sweeping frequency and percentage of tree canopy affected load removal of nutrients by sweeping. For P, the smallest annual sweeping load reduc-

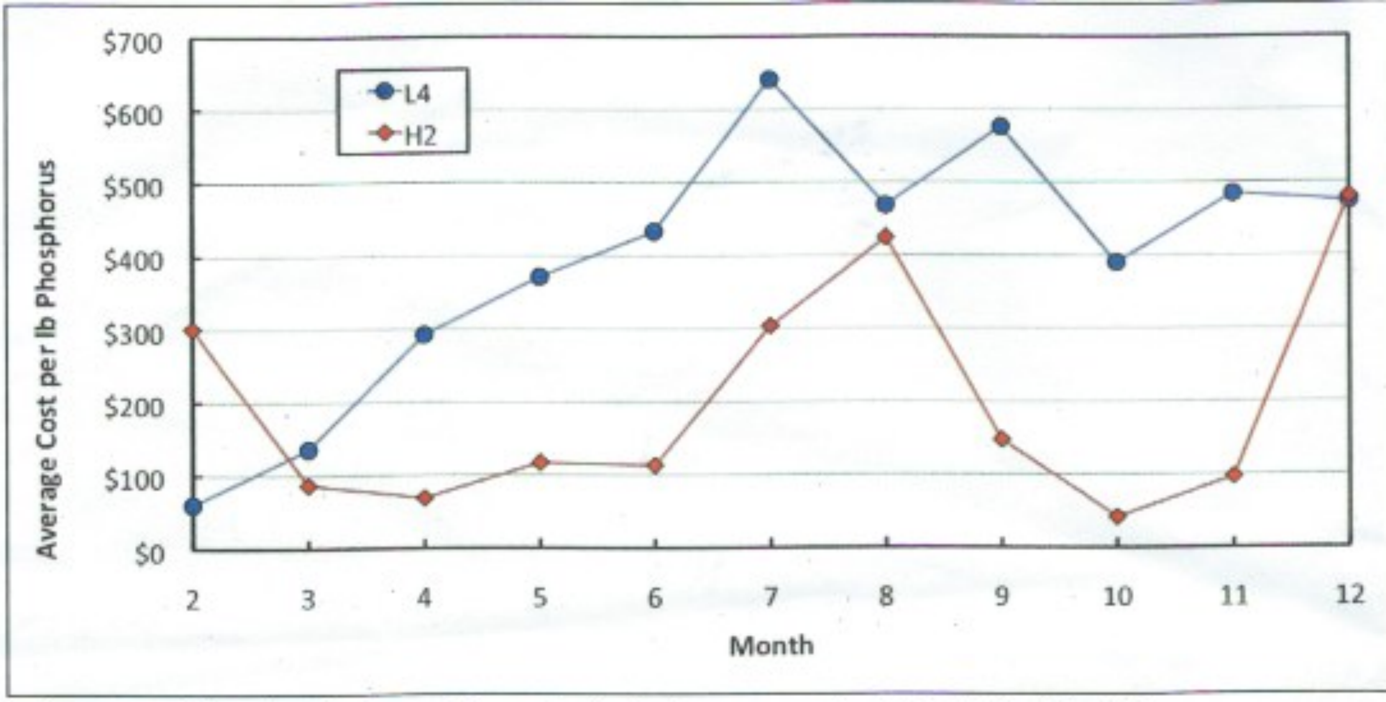

Figure 4. Cost efficiency for P load removal by sweeping for the two-year sweeping study for Routes L4 and H2

tion was 1.4 pounds per curb-mile (for once-per-month sweeping of a route with 0.4% tree canopy cover over the street), and the largest was 6.2 pounds per curb-mile (for a route with 15% canopy swept four times per month).

Reducing P loads by Street Sweeping Can Be Very Cost Efficient. The cost of sweeping, including labor, fuel, maintenance, and amortization of capital, was $23 per curb-mile swept. The cost efficiency of P removal varied depending on season and route (Figure 4). For the worst case (Route L4 with 5% street canopy swept four times per month), cost efficiency rose to $600 per pounds of P in mid-summer. For the most cost-efficient route, Route H2 (15% street canopy, swept twice per month), the cost of P removal dropped to less than $100 per pounds of P during spring and fall.

Tools for Planning and Implementing Enhanced Street Sweeping

Planning Level Tool. Findings from the Prior Lake study were used to develop a spreadsheet planning tool to aid public works and streets departments that want to plan enhanced street sweeping. The spreadsheet tool is based on a multiple regression equation that includes percentage of tree canopy, frequency of sweeping, and time of year (Kalinosky et al. in process b). The spreadsheet tool allows users to enter two types of information: fixed baseline data (average street percent canopy along each route being evaluated, the curb length of each route, and the cost of sweeping per curb mile) and sweeping frequency per route, which can be varied in scenarios. The spreadsheet calculates expected pounds of N, P, and solids removed per route and across all routes, and calculates the cost efficiency for P removal for each month and for the entire year. The user can then vary sweeping frequency along each route to informally optimize sweeping, asking one of two questions: 1) How much P can be removed with a given sweeping budget? or 2) How much would it cost to reduce the P load by a fixed amount? The latter question might be asked in the context of TMDL load reduction goals.

Because the spreadsheet planning tool is based upon findings from Prior Lake, predictions can be made only for cities with similar types of trees (north-temperate deciduous trees that drop leaves in autumn), with over-street percent canopy up to about 20%. We plan to continue sweeping studies in other cities with much higher canopies; as we do so, we will expand the spreadsheet calculator.

Implementation Level Tool. During the implementation of enhanced street sweeping, most cities would want to calculate P load recoveries in their sweeping loads. Our research analytical protocol is more rigorous (and expensive) than most cities would want to adopt, at least for a prolonged period. Hence, we asked the question, What is the least amount of information a city would need to accurately predict sweeping P load recoveries? To answer this question, we used a statistical approach (fivefold cross validation) to compare estimated recoverable P loads with the measured P recoveries (the "true" value) for each route

Table 2. Accuracy of Predicted P Load Removals for Increasing Levels of Information

Measured During Implementation	Value, lb. (% error)
Curb miles swept	494 (-9.4 %)
Fresh (wet) weight of sweepings	505 (±0.0 %)
Dry weight of sweepings	495 (-1.9 %)

Note: The actual measured value for the P load from the study was 505 pounds.