Costs and Infiltration Benefits of the Watershed Augmentation Study Sites.

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INTRODUCTION

Structural devices which infiltrate storm water (Best Management Practices - BMPs) reduce the volume and the pollutant concentrations carried in storm water to receiving waters (Dillaha 1986, Schueler 1987, Pitt 1987, SEWRPC 1991, Duchene et al. 1993, Fujita 1993, EPA 1999). In addition, infiltrated storm water can recharge groundwater basins. Groundwater recharge and decreased runoff can be promoted in an urban setting through the use of small-scale infiltration BMPs that capture and infiltrate runoff from a single parcel. Parcel-level infiltration solutions are attractive because they avoid the expense and difficulty of public land acquisitions for neighborhood or watershed-scale storm water infiltration. However, it is unclear if: 1) parcel-scale solutions generate enough benefits to justify the investment, and; 2) whether parcel-scale solutions should be sized to capture small, medium, or large rainfall events.

There is currently a large interest in parcel-scale infiltration solutions. As a result, five non-residential land uses located throughout Los Angeles County were equipped with infiltration BMPs. The study sites include a commercial building, an industrial metal recycling yard, a recycled materials sorting facility, an elementary school, and a community park. This study aims to estimate the groundwater recharge benefits relative to total costs for each study site's BMP system; it does not however, include an assessment of the BMP pollutant removal effectiveness. In other words, our estimated costs of BMP installation do not include pollutant removal.

Research began with hydrologic modeling of each BMP system to determine the additional volume infiltrated due to the BMPs. Next we used various sources to estimate construction and maintenance costs. Finally, we combined the cost and infiltration benefit estimates to estimate the total cost net of water supply benefits.

The modeling indicated that, for all but one of the five study sites, the BMPs captured nearly all runoff from single large storms as well as smaller storms occurring in sequence over the available hydrologic period. However, the largest storms occur very infrequently, so a large portion of the BMP capacities were rarely needed. Because of this, the costs of BMP construction and maintenance substantially exceeded the groundwater recharge benefits at all but the commercial site. The benefit-cost ratio is largest for the commercial site and, under some scenarios, groundwater recharge benefits might actually exceed BMP costs. The high benefit-cost ratio for the commercial site is probably related to the modestly-sized set of BMPs used. This finding suggests that it may be more cost-effective (in terms of groundwater recharge) for BMPs to be sized according to the typical rain events. Our future research will develop cost curves to estimate the costs of common BMPs at different sizes to determine how parcel size, soil textures, and land use influence the optimal sizing of BMPs for groundwater recharge.

STUDY SITE DESCRIPTIONS

Hillery T. Broadous Elementary School, Pacoima

This 7-acre institutional land use was retrofitted to replace an asphalt playground with grass underlain by a proprietary hydrodynamic separator (or "proprietary device") and a subsurface infiltration leachfield. The BMP drainage area (6.72 acres) excludes the school parking lot but captures runoff from the classroom roofs, paved areas, small landscaped areas and the grassy playground. Storm water runoff flows via surface flow to scattered catch basins that are directly connected to the hydrodynamic separator. Runoff less than the bypass flow of the catch basins is directed to the subsurface hydrodynamic separator designed to trap suspended solids, trash, oil and grease. It measures 9 feet wide, 15 feet long and 8 feet-3 inches deep with 6 inch concrete walls and, according to the device vendor, is designed for a design storm frequency of 10 years, a design storm flow of 20 cubic feet per second (cfs) and a system design flow (i.e. treatment design flow) of 14 cfs (LASGRWC, 2004). We estimate the actual treatment flow rate[2] closer to 1.1 cfs (or 494 gallons per minute-gpm), which is the product of the actual drainage area (6.72 acres), the recommended design storm intensity standard (0.2 inch per hour)[3] and our estimated percent impervious (81.9%).[4]

[2] If 80% removal efficiency of 50 micron total suspended solids is assumed.
[3] See California Regional Water Quality Control Board Order No. 01-182, Part 4, Section D(3)(b).
[4] The percent impervious value of 81.9% was taken from Appendix E of the 1990 Los Angeles County Hydrology Manual (LADPW, 1990) because complete site plans were not available to calculate the actual percentage. This value appears to be consistent with an aerial photo of the site (Google Earth, 34°16'58.18" N, 118°24'29.48" W).

In order to choose the correct model from the vendor, the swirl chamber area necessary for treating the design runoff rate must be calculated. This is done by dividing our estimated treatment flow rate (494 gpm) by the operating rate (13 gpm per ft^2 –provided by vendor) that results in 38 ft^2 of required swirl chamber area. A larger device with a swirl chamber area of approximately 64 ft^2 was used instead. Although using the larger device treats more runoff and removes more pollutants prior to infiltration, the difference in cost between the small and large model is substantial. The present purchase price of the smaller model is approximately $25,300 and the present price of the larger device is approximately $30,500, not including the installation cost estimated at 30% of the purchase price (personal communication, 11/23/05). The maintenance cost can range from $750 to $5,000 per device per cleaning (personal communication, 10/11/05).

Upon exiting the hydrodynamic separator, runoff is conveyed through a 24 inch main pipe to 58 8-inch feeder pipes that slope 2% to distribute water directly to the infiltration leachfield. The infiltration leachfield is composed of plastic perforated chambers assembled into rows. The dimensions, layout and quantity of plastic chambers have yet to be confirmed.[5] According to design drawings, the leachfield has a total footprint of 88 feet by 70 feet and a maximum capacity of 95,200 gallons (LASGRWC, 2004). It is shown to be covered by 6 feet of compacted gravel and underlain by approximately 10 feet of gravel. If the percolation zone is the area directly beneath the chamber footprint, and the design infiltration rate is 8 inches per hour, the chambers could drain the maximum volume of 95,200 gallons in approximately 3 hours.

A geotechnical investigation of the playground soils was undertaken in August of 2001 when one lysimeter and two off-site groundwater monitoring wells were installed (LASGRWC, 2005). On-site soils consist of soils with sandy and gravelly texture to a depth of approximately 40 feet. According to the Los Angeles County Hydrology Manual, onsite native soils consist of Hanford fine sandy loam (Soil Group 005), which is a well-drained soil in Hydrologic Group "B"

[5] It is not certain how many plastic chambers were installed, and what their exact dimensions are. For modeling purposes, 224 chambers were assumed, this number taken from a site plan provided by the project engineer. The vendor has been contacted, but no response.

indicating moderate to low runoff potential and moderate infiltration rates even when thoroughly wetted (Soil Survey, 1971).

Scrap Metal Recycling Yard[6], Los Angeles

This completely impervious outdoor industrial facility was retrofitted to drain a 0.85-acre area to an at-grade concrete settling basin that discharges to a subsurface infiltration leachfield. The settling basin was located based on pre-existing topography so that it would capture most of the site surface runoff. The settling basin measures 12 feet square and 2.5 feet deep with 12 inch thick concrete walls. In the center of the basin is a 2 feet high, 8 inch diameter perforated discharge column ("Top Hat") that conveys runoff to the subsurface infiltration leachfield. Runoff volumes exceeding the volume of the basin bypass the system via surface flow to the street storm drain. The infiltration leachfield consists of two 48-inch diameter perforated corrugated metal pipes (CMP) that are each 90 feet long and surrounded on all sides by 2 feet of clean, washed gravel (LASGRWC, 2004).

Assuming a design rainfall depth of 0.75 inch over the sites' drainage area of 0.85 acre, the design runoff volume is approximately 17,300 gallons. At full capacity with no infiltration loss, the infiltrator pipes are estimated to hold approximately 16,900 gallons. The difference of approximately 400 gallons is assumed to be either en route to the basin, settling within the basin, en route to the infiltrator or within the gravel beneath the infiltrator. The design runoff rate used to size this device was 0.64 cfs (or 286 gpm) based on a design rainfall intensity of 0.75 inch occurring over one hour. Ignoring horizontal seepage, the percolation zone was calculated as the area directly beneath the infiltrator pipes, which is 8 feet wide (two 48-inch pipes) and 90 feet long. If the design infiltration flow rate of the leachfield is 7.5 inches per hour and the percolation zone is 720 ft^2, then the percolation rate is 0.13 cfs (59 gpm). Therefore, the infiltration pipes could drain 17,300 gallons in approximately 5 hours.

Six borings were made throughout the site during a geotechnical investigation that was conducted in August of 2003 (Geomatrix, 2004). Six percolation test results conclude that the soil's average percolation rate is approximately 8.5 inches per hour (at 9 feet below ground

[6] All private business names are withheld for confidentiality.

surface -bgs), which is greater than the BMP's design infiltration flow rate of 7.5 inches per hour. At this rate, the soil could infiltrate 17,300 gallons in approximately 4.6 hours. Generally, on-site soils exhibited textures of silty sand and clayey sand. According to the Los Angeles County Hydrology Manual, onsite soils consist of Hanford fine sandy loam (Soil Group 006), which is a well-drained soil in Hydrologic Group "B" indicating moderate to low runoff potential and moderate infiltration rates even when thoroughly wetted (Soil Survey, 1971). A groundwater monitoring well was also installed on the site, down-gradient from the infiltration leachfield.

Veterans Memorial Park, Long Beach

The BMP system at Veterans Park drains a 0.5-acre area consisting of sidewalks, grass, and a portion of the park's parking lot. Prior to installing the BMP, runoff discharged into the city storm drain system. In order to retain and infiltrate the runoff, two new catch basins were installed in strategic collecting points within the parking lot entrance/exit. The catch basins drain directly into a subsurface concrete settling vault ("proprietary device") via orifices that are 2.1 inches in diameter, which can be easily restricted when trash enters the catch basins (Jensen memo, 12/7/05). A 4 inch conveyance pipe takes the runoff from the catch basins to the proprietary device. The proprietary device drains directly to the single subsurface infiltrator pipe. Runoff bypasses the system and flows to the city storm drain when the runoff rate exceeds the drainage rate of the catch basins.

The proprietary device is a sand-oil interceptor with general dimensions of 8 feet long, 5 feet wide and 7 feet deep. Water flows into a large primary chamber that spills into a small secondary settling chamber. Upon exiting the device, runoff is conveyed by a 4 inch diameter PVC pipe to a 48 inch diameter perforated corrugated metal pipe (CMP) that is 30 feet long and surrounded on all sides by 2 feet of clean, washed gravel (LASGRWC, 2004). The design runoff rate of the site is 0.37 cfs (163 gpm) based on a design storm intensity of 0.75 inch per one hour and total drainage area imperviousness (100%). However, according to vendor materials, the treatment flow rate of the proprietary device is actually 0.33 cfs (147 gpm; Jensen memo, 12/7/05). With a design rainfall depth of 0.75 inch, the site is estimated to generate a design runoff volume of approximately 9,840 gallons. Assuming no infiltration losses however, the full pipe storage volume of the CMP is only 2,800 gallons and the proprietary device can hold a maximum of only 940 gallons for a total of 3,740 gallons. Ignoring horizontal seepage, the percolation zone was calculated as the area directly beneath the CMP, which measures 4 feet wide and 30 feet long. With a design infiltration flow rate of 7.5 inches per hour for the CMP and a percolation zone of 120 ft^2, the percolation rate is 0.02 cfs (9.3 gpm). Therefore, the infiltration pipe could potentially drain 9,840 gallons in approximately 17.5 hours.

Nine percolation tests were performed at the site for an average percolation rate of 4.5 inches per hour (at 8-ft bgs) which is less than the BMP's design infiltration rate. With a soil percolation rate of 4.5 inches per hour, the CMP could potentially drain 9,840 gallons in 29 hours.

Two lysimeters and four monitoring wells were installed onsite in order to monitor pollutant transport through the soil and groundwater (Geomatrix, 2004). A geotechnical investigation was performed in September 2003, which found that within the first 24 feet of soil, textures generally consist of sandy clay and clay with sand. According to the Los Angeles County Hydrology Manual, the onsite soils consist mainly of Tujunga fine sandy loam (Soil Group 015), which is in Hydrologic Group "A" exhibiting low runoff potential and a rapid infiltration rate even when thoroughly wetted (Soil Survey, 1971).

Recycling Facility, Sun Valley

This is an industrial site with a completely impervious BMP drainage area of approximately 2.2 acres. The BMP system collects runoff from a portion of the roof measuring 20,400 ft^2 and a portion of the paved yard measuring 75,000 ft^2. The roof downspouts have been connected directly to the subsurface infiltration leachfield, which is also fed by the at-grade concrete settling basin that captures surface flows from the paved yard. The concrete basin is 11 feet square and 2.5 feet deep with a 2 foot high, 12-inch diameter perforated discharge column ("Top Hat"). The system is bypassed when the basin overflows into the street, though there is no storm drain in Sun Valley. The subsurface infiltration leachfield consists of three 48-inch diameter CMPs that are each 120 feet long and surrounded on all sides by 2 feet of clean, washed gravel (LASGRWC, 2004). The design runoff rate for the roof is approximately 0.35 cfs (156 gpm) and the design runoff rate for the paved yard is 1.3 cfs (575 gpm). Using a design storm depth of

0.75 inch, the design runoff volume of the roof is 9,500 gallons and the design runoff volume of the paved yard is 35,000 gallons for a total of 44,500 gallons. Without infiltration losses, the maximum in-pipe storage of the CMP is approximately 33,600 gallons. Ignoring horizontal percolation, the percolation zone is the area directly beneath the infiltrator pipes, which measures 12 feet wide and 120 feet long. If the design infiltration flow rate of the leachfield is 7.5 inches per hour and the percolation zone is 1,440 ft^2, then the entire capacity of the infiltrator pipes can be drained in approximately 5 hours.

Neither a geotechnical investigation nor percolation tests were conducted at the site but field reconnaissance indicated that soils are primarily coarse-grained sediments (Geomatrix, 2004). According to the Los Angeles County Hydrology Manual, onsite soils consist mainly of Tujunga fine sandy loam (Soil Group 015), which exhibits low runoff potential and rapid infiltration rates.

Commercial Building, Santa Monica

This 3.55-acre facility resembles a tilt-up warehouse surrounded by parking lot and drought-tolerant landscaping. According to plans the site is 88% impervious, which is slightly less than the typical value for commercial warehouses (LADPW, 1990). The BMP was part of the building's design and construction, unlike the other study sites which were retrofitted. The BMP installed at this study site is significantly different than the other study sites in that simple, cheap and minimally intensive changes in the site landscaping and runoff routing were incorporated. This includes discharging roof runoff into small gravel drains and draining parking lot runoff into a recessed planter with a flush curb. Specifically, half of the roof drains to seven gravel drains that are installed in the landscaping. Runoff from most of the parking lot, sidewalks and the other half of the roof flows southerly to a recessed planter with a flush curb. A small area of parking lot and driveway drains to an on-site catch basin that is connected to the storm drain system (LASGRWC, 2004). According to plans, the gravel drains measure 3 feet long, 1.5 feet wide and 2 feet deep (Burton, 1999). Each drain is filled with 6 inches of California gold gravel followed by 1.5 feet of pea gravel with 2 inches of space behind the concrete header. Assuming no infiltration each gravel drain could hold a maximum of 0.75 ft^3 (5.6 gallons) above the gravel and behind the 2 inch concrete header. Running through the pea gravel and extending outward to each side of each drain at a depth of approximately 2.5 feet is a 6 foot long, 4 inch diameter perforated PVC pipe.

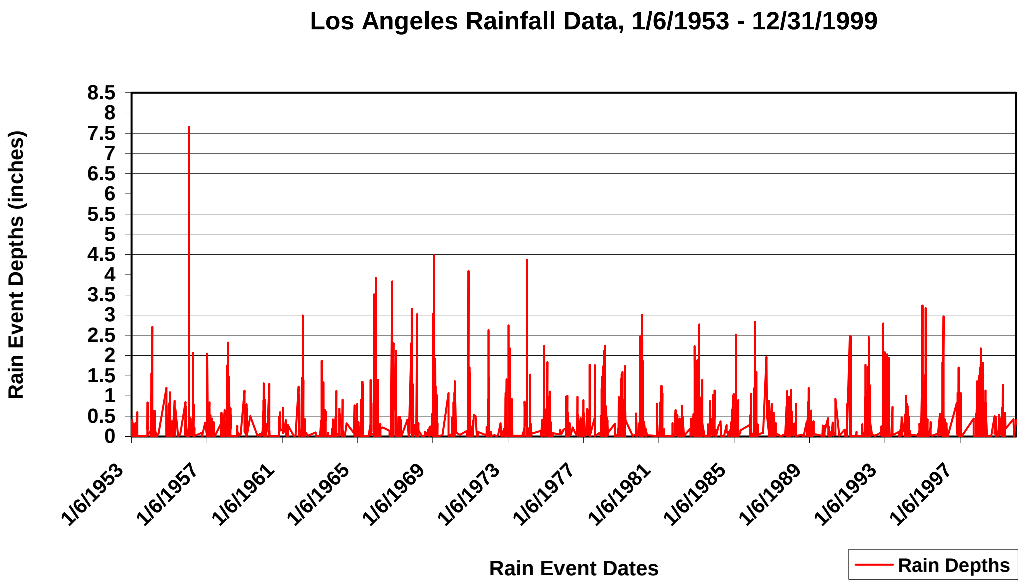
The flush-curb planter is located along the site's frontage street and measures approximately 3 feet wide, 416 feet long with a retaining depth of 0.5 inch along the flush curb and 2 inches along the concrete header. Assuming no infiltration, a maximum volume of 130 ft^3 (966 gallons) could be held in the planter. According to plans, the planter should contain 4 inches of decomposed granite underlain by a weed barrier.

Assuming a design rain depth of 0.75 inch over the impervious drainage area of 3.124 acres (0.88*3.55 acres), the design runoff volume is approximately 63,618 gallons. A design intensity of 0.75 inch per hour generates a design flow rate of 2.343 cfs (1,052 gpm). Notably, this is the largest potential runoff volume and runoff rate of all the study sites. If the gravel drains and recessed planter are assumed to be the percolation zones with an infiltration rate typical of silty clay (0.04 inch per hour), the design runoff volume of 63,618 gallons would drain in 83 days. According to the City of Santa Monica, the project proponent complied successfully with the City's SUSMP regulation by installing an infiltration BMP; however more detailed BMP sizing and design specifications and costs were not recorded.

A geotechnical investigation was undertaken at the site in October of 2001 during installation of two lysimeters and two monitoring wells (LASGRWC, 2005). The report indicates on-site soils consist mainly of clay, silt and silty clay to a depth of approximately 60 feet, which are poor soil textures for infiltration. In comparison, the Los Angeles County Hydrology Manual shows onsite soils consisting mainly of Yolo loam (Soil Group 016), which is well-drained with slow to medium runoff potential and moderate permeability. It is also inclined to be friable, porous and droughty (Soil Survey, 1919).

HISTORICAL LOS ANGELES RAINFALL PATTERNS

The chart below illustrates the recorded rainfall depths taken at the Los Angeles Civic Center monitoring station (COOP ID 045115) from January 6, 1953 through December 31, 1999. The graph shows 2,670 rain events that have an average depth of 0.26 inch and a median depth of 0.07 inch. Each model run used this same rain data file, which was obtained from the National Climatic Data Center (NCDC). The NCDC rain file lists the start date, start time, end date and end time for each recorded rain event.



According to this data, 94% of the events are less than 1.0 inch deep and 85.4% of the events are less than 0.5 inch deep. The average duration of a single rain event was 3.3 hours. Rain events lasting two days occurred 384 times in the dataset; however, rain events lasting three days occurred only four times.[7] The average intensity was 0.057 inch per hour. Therefore, smaller rains with shorter duration occur far more frequently in the Los Angeles basin than larger, runoff-generating rains. Because these small events may occur in close succession, BMP sizing should take into account the potentially large volume of runoff generated by multiple smaller storms. Our chosen rainfall-runoff model, WinSLAMM, contains dynamic modeling suitable for

[7] January 23–25, 1954; January 25-27, 1956; January 6-8, 1974; February 19-21, 1996.

analyzing multiple small events because it accounts for infiltration losses, volume carry-over and decreasing BMP performance with successive storm events.

COMMERCIAL RUNOFF MODEL: WinSLAMM

There are many types of runoff models available and none are without shortcomings. Early runoff models that were intended for flood control design and drainage analysis tend to oversimplify runoff generation from small rain events thereby underestimating their effect in an urban setting. Many current models maintain these same flood control-based methods that are not appropriate for water quality modeling. Runoff model applications range from watershed-scale to water quality, and finally receiving water models. Within these types, there is a range of input and output complexity. WinSLAMM can be grouped within the mid-range of complexity under watershed-scale loading models. SWMM, HSPF, PRMS, and HEC-HMS are considered more complicated in comparison.

SWMM, HEC-HMS, HSPF and PRMS are models that are capable of modeling the infiltration of storm water in an urban environment. WinSLAMM was designed to be simpler than others with the belief that increasing model complexity can produce inaccurate results. The general model of WinSLAMM's programming can be related to both the Horton Infiltration equation and the SCS curve number method. HEC-HMS, PRMS, and SWMM use the Green-Ampt equation, which is not as applicable as the Horton Infiltration equation for compacted, urban soils (Pitt, 1987). SWMM and HEC-HMS can employ the SCS curve number method; however, the method is not an accurate estimator of runoff for rain events less than 0.5-inch, especially for pervious areas. WinSLAMM calculates a runoff coefficient, which varies by rainfall depth, for each rain event. The runoff coefficient is based upon extensive monitoring data and is a function of the runoff source area (eg, pitched rooftops, paved parking, sidewalks, small landscaped areas, etc.). In addition, the model accounts for volume carry-over and decreasing BMP performance between rain events.

Although WinSLAMM does not directly calculate infiltration or consider detailed subsurface conditions, its methods for calculating runoff volume and losses were developed from extensive and published measurements taken throughout the U.S, that were then used to calibrate the model (Pitt 1979, Pitt and Bozeman 1982a, Pitt and Sutherland 1982b, Bannerman et al. 1983, Pitt et al. 1983b, Pitt 1985, Pitt and McLean 1986, Pitt 1987, Pitt and Voorhees 1995, Pitt et al. 1996, Corsi et al. 1999, Roa-Espinosa and Bannerman 1994, Waschbusch 1999, Waschbusch et al. 1994-95). Calibrated results were then verified by independent site measurements (Pitt et al. 2004a, Pitt et al. 2004b, Pitt et al. 2002, Pitt 1997).

WinSLAMM was used in this project to model the effects of BMPs in attenuating runoff, and thereby contributing to infiltration.[8] Another reason WinSLAMM was chosen for this research is that the available input data for each study site was not sufficient for the other models. One of WinSLAMM's most useful attributes is its consideration of BMPs that serve multiple source areas. For example, a BMP device can be designed to serve just one roof or a parking lot (a "source area device"); or, a BMP could serve many source areas draining from one or two parcels (a "land use device"). The largest scale would consist of a BMP serving at an outfall pipe that drained an entire housing tract or an entire watershed (an "outfall device"). Structural BMPs can be designed and instituted manually in other models; however WinSLAMM is designed to accommodate various BMP designs at different scales specifically in urban settings.

The Elementary School, Scrap Metal Yard, Recycling Yard and Community Park were modeled similarly in WinSLAMM. Each site's BMP system begins with a pre-treatment concrete chamber device, be it hydrodynamic, an oil/grit separator, or a settling basin, it is identified in the model as a "land use catch basin" with a bypass option (bypass or "failure" occurs when the runoff rate exceeds the BMP inflow rate). In essence, the vault-like pretreatment device is a large catch basin with an inlet and an outlet placed to allow some settling of heavy pollutants. Each vault is followed by a subsurface infiltration leachfield (perforated pipes – metal or plastic - on gravel bed), which is identified in the model as an "outfall biofilter."[9] For these study sites, the model routes runoff through the land use catch basin to the outfall biofilter and accounts for

[8] The runoff calculations are based on the equation: $F = bit + a(1-e^{-git})$ where (F) is the variable runoff loss, (b) is the rate of variable losses after equilibrium, (i) is the constant rain intensity, (t) is the time at start of runoff, (a) is the intercept of the equilibrium loss line on the accumulative variable loss axis, and (g) is a constant.

[9] According to WinSLAMM documentation, a biofilter or biofiltration device, "replaces the simple calculation methods used for infiltration devices with the full routing calculations associated with pond storage." Outlets of the biofilter include natural soil infiltration, evaporation, surface discharges through overflows via weir or stand-pipe, and rain barrels/cisterns.

hold-over between rain events. Table 1 lists the input requirements for each model run. Since the model continues to route sediment through each BMP even though this research does not include pollutant removal, pollutants such as TKN, copper, and zinc could be modeled simultaneously with volume reduction modeling if desired.

The Commercial study site differs in that it was modeled with a "source area biofilter" device (i.e. the gravel drains) and a "land use biofilter" device (i.e. the flush, recessed curb planter). Model input requirements for the "source area biofilter" and the "land use biofilter" devices are the same as the "outfall biofilter" device shown below in Table 1.

Table 1: Input Requirements for Concrete Chamber, Infiltration Leachfield Combination

Land Use Catch Basin	Outfall Biofiltration Device
1. Area served by device (ac): 2. Number of catch basins:* 3. Sump depth below catch basin outlet invert (ft): 4. Depth of sediment in catch basin sump at beginning of study period (ft):** 5. Outlet pipe diameter (ft): 6. Outlet pipe slope(ft/ft): 7. Catch basin sump surface area (ft^2): 8. Catch basin depth from sump bottom to street level (ft): 9. Manning's n value:*** 10. Leakage rate (in/hr): 11. Inflow hydrograph peak to average flow ratio:**** 12. Critical particle size file:***** 13. Catch basin cleaning frequency:******	1. Top area (ft^2): 2. Bottom area (ft^2): 3. Depth (ft): 4. Depth that is rock-filled (ft): 5. Fraction of rock filled volume as voids (0-1): 6. Engineered soil depth (ft): 7. Fraction of engineered soil as voids (0-1): 8. Seepage rate (in/hr): Seepage rate coefficient of variation: Seepage rate multiplier for side and bottom: 7. Random number generator to account for variability in infiltration rates is turned "on" 8. Number of devices: 9. Emergency broad crested weir outlet dimensions: length, width and height from datum: 10. Inflow hydrograph peak to average flow ratio: 11. Fraction of runoff from outfall routed to outfall biofilters (0-1):

*Number of catch basins assumed to be one, since one vault per site.
**Depth of sediment in catch basin at beginning of study period assumed zero feet for all sites.
***Manning's n value assumed 0.013 for all sites.[10]
****Inflow hydrograph peak to average flow ratio assumed to be 3.8 for all sites.
*****Critical particle size file is from the National Urban Runoff Program (EPA, 1983) for all sites.
******Catch basin cleaning frequency assumed once a year for all sites.

The two primary purposes of WinSLAMM are: (1) to identify sources of urban storm water pollutants, and; (2) evaluate the efficiency of control practices (i.e. BMPs). The model is based on the concept of small storm urban hydrology, which recognizes that most of the pollutants in

[10] Manning's n value of 0.013 is a standard value that corresponds to the roughness of a concrete/clay pipe. See Haan, C.T., Barfield, B.J., Hayes, J.C. *Design Hydrology and Sedimentology for Small Catchments.* 1994.

storm water runoff come from small storms, in contrast to large design storms that are used in other runoff models. The model applies this concept through its seven parameter files: rainfall, runoff coefficient, particulate solids concentration, pollutant probability distribution, street delivery, particulate residue, and critical particle size. In addition, the model incorporates the soil type (sandy, silty or clayey), land use area, rainfall depth, development characteristics and control practices in order to generate the final output.

RESULTS and FINDINGS

As shown in Table 2, each of the five study sites was modeled twice using WinSLAMM: the first being the “No BMP Scenario” and the second being the “With BMP Scenario”. The No BMP Scenario represents each study site as if no BMP installation had taken place.[11] Modeling of the With BMP Scenario was based on best available information including site-specific engineering plans, geotechnical reports and other documentation that are available in public record.

WinSLAMM calculates runoff volumes as the difference between the product of the site area and rainfall depth and the product of the site area and the total losses depth.[12] The depth of total losses is the amount of rainfall that did not run off; therefore, it evaporated, intercepted, infiltrated, or got caught in surface storage depression. Since non-infiltration losses should not increase with use of an infiltration BMP, we can assume the decrease in runoff volume (or the increase in losses) for the With BMP Scenario is solely due to infiltration. Therefore, the volume of storm water infiltrated on each study site was conservatively estimated as the difference between the No BMP Scenario runoff volume and the With BMP Scenario runoff volume.[13] The difference in volumes was converted to acre-feet and divided by 46 years in order to get an annual average according to the years of rainfall data used. The cost per acre-foot was calculated by dividing the cost of the BMP retrofit (including capitalized maintenance costs generated by

[11] The School site “No BMP Scenario” modeled the playground as a pervious field when actually it was a paved yard prior to BMP retrofit.
[12] Rainfall tends to be higher in Sun Valley and Pacoima than downtown Los Angeles, where the rain data was collected. Rainfall variability across the county was not taken into account in this report.
[13] This approach may underestimate infiltration to some degree since runoff storage on pavement is infiltrated at some study sites. The effect of evapotranspiration (ET) on the volume available for infiltration was considered negligible for the study sites since the BMP installations did not change the pervious and impervious areas from the pre-BMP conditions. Other types of BMP installations warrant consideration of ET.

WinSLAMM and the project engineers) by the product of the average annual acre-foot infiltrated and the average lifetime of a BMP device (Table 2). This project assumes the lifetime of a BMP is 25 years and the BMP retrofit costs for each study site are shown in Table 3.

Table 2: Results for Each Study Site using WinSLAMM

Study Site	Scenario	Runoff Volume (ft^3)*	Infiltration Rate Used in Model (inch per hour)	Percent Reduction from No BMP Scenario	Additional Average Annual Volume Infiltrated (acre-feet)**	Cost per Additional Average Annual Volume Infiltrated***	
Elementary School	No BMP Scenario	5,787,099	8 (estimate from available data)	99.9%	n/a	$4,419	$4,131
	With BMP Scenario	277.3			2.888		
Scrap Metal Yard	No BMP Scenario	1,983,843	8.5 (percolation test confirms)	100%	n/a	$6,047	$4,887
	With BMP Scenario	0			0.990		
Veterans Park	No BMP Scenario	1,125,896	4.5 (percolation test confirms)	83.6%	n/a	$9,596	$12,200
	With BMP Scenario	184,269			0.47		
Commercial Building	No BMP Scenario	6,876,000	0.04 (estimate from available data)	14%	n/a	$1,750	$1,093
	With BMP Scenario[14]	5,923,000			0.476		
Recycling Facility	No BMP Scenario	5,289,355	8.5 (inferred from Scrap Metal Yard test)	99.5%	n/a	$5,159	$4,497
	With BMP Scenario	28,329			2.625		

* Runoff volume = (rain depth x site area) – (total loss depth x site area)
** Average annual volume infiltrated = (No BMP scenario runoff volume – with BMP scenario runoff volume) ÷ 46 years
*** Cost per acre-foot = (BMP capital cost in 2005 value + capitalized maintenance cost) ÷ (average annual volume x 25 years) for both maintenance costs (first, WinSLAMM and second, project engineer estimate).

Even with a good infiltration rate, the Veterans Park BMP infiltrates the smallest volume at the highest cost per acre-foot. The Elementary School and Recycling Facility BMPs both show large volumes infiltrated at similar costs per acre-foot. Notably, even with the worst soil

[14] There are discrepancies between the site "as-built" and the site as depicted on development plans ("as-planned"). Results for the Commercial site are presented in the "as-planned" scenario throughout this document.

infiltration rate the Commercial site has the least cost per acre-foot. Also, at five-times the cost of the Commercial site, the Veterans Park BMP infiltrates the same estimated volume from an area less than half the size of the Commercial site.

The Commercial site has been observed to drain better than expected from the at-depth soil textures would indicate (personal communication, 4/6/06). In addition, water content reflectometer sensor logs indicate high infiltration rates to depths up to 20 feet bgs (LASGRWC, 2004). Therefore, in order to better represent the uncertainty over the appropriate infiltration rates, WinSLAMM was used to model the Commercial site with a BMP infiltration rate of 1.0 inch per hour. As expected, the model results indicate more runoff infiltrating at a lower cost (Table 3).

Table 3: Results from Increasing Infiltration Rate at Commercial Site

Scenario	**Runoff Volume After BMP (ft^3)**	**Percent Reduction from No BMP Scenario**	**Additional Average Annual Volume Infiltrated (ac-ft)**	**Cost per Additional Average Annual Volume Infiltrated**	
No BMP Scenario	6,876,000	n/a	n/a	n/a	
With BMP Scenario	4,116,000	40%	1.377	$604*	$377**

*Using capitalized WinSLAMM-generated maintenance cost estimate.
**Using capitalized alternative maintenance cost.

The City of Santa Monica has actively collected BMP installation data in their Urban Runoff Database since 1992 in accordance with Chapter 7.10 of the City Municipal Code (Urban Runoff Pollution), which is a requirement of the countywide National Pollutant Discharge Elimination System (NPDES) Municipal Permit. We used the database to obtain a development cost attributable to BMP/storm water compliance for the Commercial study site, since none was available and the site is in Santa Monica. We inferred a BMP cost from commercial facilities that installed an infiltration BMP as the product of the average BMP capacity cost ($3.24 per gallon) [15] and the study site's BMP capacity (1,595 gallons). The cost per average annual acre-foot infiltrated for the Commercial site in Table 2 reflects using this BMP cost. Table 4 lists the BMP costs obtained for each study site.

[15] The average cost per gallon was calculated from 22 commercial sites with infiltration BMPs of capacities greater than 500 gallons but less than 4,000 gallons.

Table 4: Study Site BMP Costs

Study Site	Purchase Year	Total Cost in Purchase Year	Total Cost in 2005 Value*
Elementary School	2001	$217,996[16]	$248,365
Scrap Metal Yard	2003	$85,900[17]	$93,906
Veterans Park	2003	$64,430[18]	$70,435
Commercial Building	1999	$4,284	$5,168
Recycling Facility	2003	$259,670[19]	$283,871

*Construction cost indices obtained from Engineering News Record, enr.com.

Each study site BMP has a different capacity for capturing runoff, which is related to the BMP cost in Table 4 and the costs per acre-foot in Table 2. BMP capacity can also be related to a site's impervious area in a ratio that could be applied to similar sites to find a typical capacity for a typical area of imperviousness. The amount of impervious area at a site is one of the largest factors that increase runoff (for a given storm event). This ratio could also help relate capacity to expected BMP cost. Table 5 lists the percent impervious area, BMP capacity, impervious area and the BMP capacity to impervious area ratio for each study site.

[16] This cost number includes infiltrator chambers, 1 hydrodynamic separator, installation, catch basins, rock, filter fabric.
[17] Cost includes labor for design and construction oversight, construction sub-contractors, and other services. Total price inferred using percentage of site's construction sub-contractor cost to total construction sub-contractor cost and multiplied by the construction oversight and "other services" total costs.
[18] Cost contains same services described for Scrap Metal Yard.
[19] Cost contains same services described for Scrap Metal Yard.

Table 5: BMP Capacities and Impervious Areas

Study Site	Percent Impervious	BMP Capacity (gallons)*	Impervious Area (ft^2)**	Capacity per Impervious Area Ratio (gallons per ft^2)
Elementary School	81.9%	98,229	223,686 (5.1 acres)	0.439
Scrap Metal Yard	100%	16,920[20]	37,026 (0.85 acre)	0.457
Veterans Park	100%	3,760	21,780 (0.5 acre)	0.173
Commercial Building	88%	1,595	136,081 (3.1 acres)	0.012
Recycling Facility	100%	33,841	95,832 (2.2 acres)	0.353

*BMP Capacity does not include capacity of gravel, engineered soil, conveyance pipes, or catch basins.
**Impervious Area is the drainage area of the BMP.

As shown in Table 5, a high ratio value represents a BMP that has a comparatively large capacity to the impervious area that drains to it; in contrast, a low ratio value indicates a BMP with a small capacity for runoff compared to its impervious drainage area. Notably, the Commercial study site has the lowest ratio of BMP capacity to impervious area by an order of magnitude, and the Scrap Metal Yard has the highest ratio. Since the commercial site also has the lowest cost per acre foot of infiltration, this data supports the idea that BMPs sized for average or smaller sized storms are likely to be more cost-effective for infiltration.

We were able to gather construction costs for four of the five sites, but observed BMP maintenance costs specific to any of the sites were unavailable. Fortunately, WinSLAMM contains a module that can generate maintenance costs for detention ponds, porous pavement, street cleaning, biofiltration devices, catch basin cleaning and grass swales. The pre-determined module values are based on a commonly cited source of Wisconsin cost data.[21] The model

[20] The concrete settling basins and vertical stand pipes that collect at both the Scrap Metal Yard and the Recycling Facility has relatively negligible capacity (a holding depth of approximately 3 inches in a 12x12-foot and 11x11-foot box, respectively. Therefore, capacity for these sites only considers the volume of the subsurface infiltrator pipes.
[21] See *Costs of Urban Nonpoint Source Water Pollution Control Measures, Technical Report Number 31* published by the Southeastern Wisconsin Regional Planning Commission (SEWRPC, 1991). This report includes findings from Schueler (1987). This report does not give costs for "biofilter" devices specifically, but their technical similarity to infiltration trenches was grounds enough to equate the costs of infiltration trenches to "biofilters" in WinSLAMM.

adjusts these values according to a Los Angeles cost index of 1.13, which is the quotient of a city cost index of 8232.32 and a baseline national cost index of 7314.74. In addition, the model uses a crushed stone fill value of $31.65 per cubic yard and a catch basin cleaning cost of $57.00 per cleaning.

Table 6 lists the study site maintenance costs estimated by WinSLAMM, the items assumed to require maintenance and other assumptions used in the cost-estimation process. The model-generated maintenance costs were based on "catch basins" and "biofilters" since they were used in the modeling to represent vaults and infiltration galleries.

Table 6: WinSLAMM-Generated Annual Maintenance Costs

Study Site	Annual Maintenance Cost*	Maintained Components
Elementary School	$5,016	Hydrodynamic separator, underground plastic infiltrator pipes
Scrap Metal Yard	$3,957	Concrete sedimentation basin, two underground metal infiltrator pipes
Veterans Park	$3,001	1,000-gallon sand/oil interceptor, underground metal infiltrator pipe
Commercial Building	$1,110	Landscaping, gravel
Recycling Facility	$3,885	Concrete sedimentation basin, three underground metal infiltrator pipes

*Assumed annual BMP cleaning and property value was considered $0.

The present value of a stream of future costs or benefits is an essential calculation to estimate whether the project will produce future results that are negative or positive to the entity who undertook the expenditure. The present value of costs was calculated for each study site by assuming constant annual maintenance costs over 25 years at an interest rate of 5% summed with the cost of installing/purchasing the BMP, which was adjusted to 2005 dollars. The present value of benefits was calculated similarly by multiplying the volume of infiltrated storm water in acre-feet (Table 2) by an estimate of one acre-foot of groundwater ($820[22] and $449[23]), over 25 years with an interest rate of 5%. The traditional cost-benefit evaluation criteria is the *net* present value (NPV) which is the difference between present value of benefits and present value of costs. A positive NPV, in this case, indicates that the recharge benefits of the BMP alone

[22] Cutter, B. "Valuing Groundwater in an Urban Context." Forthcoming, *Land Economcs*.
[23] Acevedo, Mario. Personal communication, RE: WAS TAC minutes - next meeting 8/31/05. 8-18-2005.

justify the project. In this case, none of the projects has a positive NPV on water supply benefits alone.

Table 7 presents the net cost of the BMPs, which is the amount of costs not covered by recharge benefits (present value of costs less present value of water supply benefits). In other words, the net cost is the value of other benefits the project would have to generate to reach zero NPV. We present net cost rather than net benefit because our analysis does not include values of all benefits from BMP installation. The high cost of treating storm water or managing runoff at the watershed scale[24] suggests that non-water-supply benefits could be substantial[25] so it would be misleading to call any value an NPV that did not include these benefits.

Table 7: Cost and Benefit Analysis Using WinSLAMM-Generated Maintenance Costs

Study Site	Present Value of Costs		$820 per acre-foot		$449 per acre-foot	
	BMP Cost (in 2005 Value from Table 4)	**Maintenance Cost** (over 25 years, 5% rate)	**Present Value of Benefits***	**Net Cost**	**Present Value of Benefits**	**Net Cost**
Elementary School	$248,365	$70,695	$33,365	$285,695	$18,270	$300,791
Scrap Metal Yard	$93,906	$55,770	$11,442	$138,234	$6,265	$143,411
Veterans Park	$70,435	$42,296	$5,432	$107,299	$2,974	$109,756
Commercial Building** .04"/Hour	$5,168	$15,644	$5,495	$15,317	$3,009	$17,803
1"/Hour	$5,168	$15,644	$15,833	$4,979	$8,670	$12,143
Paper Recycler	$283,871	$54,755	$30,337	$308,288	$16,612	$322,014

***Present Value = (cost per acre-foot infiltrated x value of 1 acre-foot of infiltrated storm water)
**Results are presented for two different infiltration rates because of the uncertainty about the correct infiltration rate (Table 3).

[24] See Gordon, P., Kuprenas, J., Lee, J., More, J., Richardson, H.,Williamson, C. *An Economic Impact Evaluation of Proposed Storm Water Treatment for Los Angeles County*. University of Southern California. November 2002.
[25] See Braden, J.B., Johnston, D.M. *Downstream Economic Benefits from Storm Water Management.* ASCE Journal of Water Resources Planning and Management. November/December 2004.

According to both values of infiltration benefit ($820 per acre-foot and $449 per acre-foot), all sites show significant net costs. This result indicates that benefits other than groundwater recharge would have to be substantial to justify the projects.

A cautionary note on the cost and net cost estimates presented in Table 7: The present value of maintenance costs is a large proportion of overall costs. For example, the maintenance cost for the Commercial site is almost 75% of the total. Therefore, if WinSLAMM's estimates of maintenance costs are too low, then the NPV is even less attractive. If WinSLAMM's maintenance cost estimates are too high, then some of the BMPs may actually have a positive NPV based on infiltration benefit alone. This uncertainty underlines the importance of collecting accurate maintenance cost information on any future BMP projects.

A different set of maintenance costs were collected by way of estimates prepared by the engineering firms that designed the BMP systems (except the Commercial Building; MWH no date, Geomatrix 2005a, Geomatrix 2005b, Geomatrix 2005c). These are presented in Table 8 and note how they differ from the maintenance costs generated by WinSLAMM in Table 6.

Table 8: Maintenance Costs Estimated by Project Engineers

Study Site	Annual Maintenance	Annual Inspection	Subtotal	Contingency (%)	Total Annual Cost	Total Biannual Cost
Elementary School	$2,590*	$360	$2,950	20	$3,540	n/a
Scrap Metal Yard	$1,420**	$180	$1,600	20	$1,920	$2,790
Veterans Park	$3,950	$360	$4,310	20	$5,172	n/a
Commercial Building	n/a	n/a	n/a	n/a	$555***	n/a
Paper Recycler	$1,140**	$180	$1,320	20	$1,584	$2,454

* Does not include $1500 every two years to remove oil and grit from sedimentation chamber.
** Does not include $725 every two years to clean infiltration pipes.
***Since the estimates for the other study sites in Table 8 are approximately half of the estimates in Table 6, half of the WinSLAMM-generated value for the Commercial Building was used.

The same cost and benefit analysis presented in Table 7 was repeated in Table 9 using the total annual maintenance cost estimates in Table 8.

Table 9: Cost and Benefit Analysis Using Engineer's Maintenance Cost Estimates

Study Site	Present Value of Costs		$820 per acre-foot		$449 per acre-foot	
	BMP Cost (in 2005 Value from Table 4)	**Maintenance Cost** (over 25 years, 5% rate)	**Present Value of Benefits**	**Net Cost**	**Present Value of Benefits**	**Net Cost**
Elementary School	$248,365	$49,893	$33,365	$264,893	$18,270	$279,988
Scrap Metal Yard	$93,906	$27,060	$11,442	$109,525	$6,265	$114,701
Veterans Park	$70,435	$72,894	$5,432	$137,897	$2,974	$140,354
Commercial Building* .04"/Hour	$5,168	$7,822	$5,495	$7,495	$3,009	$9,981
1"/Hour	$5,168	$7,822	$15,833	($2,843)**	$8,670	$4,320
Paper Recycler	$283,871	$22,325	$30,337	$275,858	$16,612	$289,584

* We present results for two different infiltration rates because of the uncertainty about the correct infiltration rate (Table 3).
**The net benefit in this scenario is a positive $2,843 (or, a net cost of zero), indicating that no further benefit other than groundwater recharge would be necessary to justify the project.

Under both recharge-value scenarios, the Commercial Building has the lowest net cost indicating the least value of benefit necessary, other than groundwater recharge, to justify the project. Similar to Table 6, each study site has significant net costs that require significant non-recharge benefit to justify the project.

Table 10 presents the value (or monetary benefit) of one acre-foot of infiltrated runoff such that NPV equals zero for each study site, according to the WinSLAMM-generated maintenance cost and the project engineer-generated maintenance cost estimates. This is the value that infiltrated runoff would need to be for costs to equal recharge benefits (i.e., the minimum acre-foot value that would justify building the project on recharge benefits alone).

Table 10: Infiltration Benefit Break-Even Values[26]

Study Sites	Using WinSLAMM-Generated Maintenance Cost Estimates ($ per acre-foot)		Using Engineer-Generated Maintenance Cost Estimates ($ per acre-foot)	
Elementary School	$7,841		$7,330	
Scrap Metal Yard	$10,727		$8,670	
Veterans Park	$17,018		$21,637	
Commercial Building*	$3,106	*$1,078*	$1,938	*$673*
Paper Recycler	$9,153		$8,276	

*Values in italics represent results based on the increased infiltration rate of 1.0 inch per hour (Table 3).

As expected, the least-cost BMP installation requires the lowest value of infiltrated runoff for recharge benefits to equal costs, or NPV equal to zero. If the benefits of pollution reduction were included, these break-even values would be less.

An alternate understanding of the capitalized benefits and costs is shown in Table 11. The ratios (or percentages) are the quotient of present value of benefits and present value of costs, which provides the fraction of benefit attributable to the BMP expenditure.

[26] The values are the same for both the $820 and $449 per acre-foot scenarios.

Table 11: Ratio of Present Value of Benefit and Present Value of Costs*

Study Sites	Ratio based on $449 per acre-foot		Ratio based on $820 per acre-foot	
	WinSLAMM*	**Estimate****	**WinSLAMM***	**Estimate****
Elementary School	0.0573 (6%)	0.0613 (6%)	0.105 (11%)	0.112 (11%)
Scrap Metal Yard	0.0419 (4%)	0.0518 (5%)	0.0764 (8%)	0.0946 (10%)
Veterans Park	0.0264 (3%)	0.0208 (2%)	0.0481 (5%)	0.0379 (4%)
Commercial Building***				
.04"/Hour	0.145 (15%)	0.232 (23%)	0.264 (26%)	0.42 (42%)
1"/Hour	0.416 (42%)	0.667 (67%)	0.761 (76%)	1.218 (122%)
Paper Recycler	0.0491 (5%)	0.0543 (5%)	0.0896 (9%)	0.0991 (10%)

*Present value of costs includes the capitalized maintenance costs generated by WinSLAMM.
**Present value of costs includes the capitalized maintenance costs estimated by project engineers.
***Results are presented for two different infiltration rates because of the uncertainty about the correct infiltration rate (see Table 3).

The percentage of groundwater recharge benefit is highest for the Commercial study site, especially when the infiltration rate is increased from 0.04 inch per hour to 1.0 inch per hour. Percentages are considerably lower for the other study sites. It appears that study sites with large BMP capacities have groundwater recharge from infiltration valued as a small percentage of total costs, while groundwater recharge from infiltration is valued as a large percentage of total benefit for the smallest capacity BMP.

CONCLUSIONS

The findings discussed above indicate there is only one site where the recharge benefits alone might justify the entire BMP cost. For the other four sites, additional pollution reduction benefits provided by the BMP devices would need to be substantial to justify their installation and maintenance expenses.[27] In addition, the fraction of total costs covered by groundwater

[27] See Landphair, H.C. et al. *Design Methods, Selection and Cost-Effectiveness of Stormwater Quality Structures*. Report No. FHWA/TX-01/1837-1, Texas Transportation Institute. November 2000 for quantified pollution reduction benefit from various BMPs.

recharge benefit varies widely. Notably, the most modestly-scaled urban, parcel-level BMP in our study has the highest recharge benefit to cost ratio. It also has the lowest cost per acre foot of recharge. It is possible that the study site BMPs could be cost-effective for groundwater recharge in different physical settings or redesigned as smaller or cheaper devices that still met the physical constraints of the study sites. Our results suggest that treatment capacity sufficient to treat almost all runoff from a parcel is too costly for the typical rainfall patterns of Los Angeles.

FURTHER RESEARCH

The next stage of this research will estimate cost-capacity curves for several common infiltration BMPs so we can estimate construction and maintenance costs at various sizing levels. We will then use an optimization model to determine the most cost-effective sizing of parcel-level BMPs for groundwater recharge according to different soil types, parcel-size and other land-use factors. This research will enable us to make policy recommendations about whether urban, parcel-scale BMPs are cost-effective methods for recharging groundwater using storm water runoff and, if so, how they should be implemented.

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