Storm Water Low-Impact Development, Conventional Structural, and Manufactured Treatment Strategies for Parking Lot Runoff

Performance Evaluations Under Varied Mass Loading Conditions

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Eleven storm water treatment strategies were evaluated for water quality performance and storm volume reduction during rainfall–runoff events between September 2004 and August 2005. Evaluated treatment strategies included structural best management practices (BMPs) (swales, retention ponds), low-impact development (LID) designs (treatment wetland, filtration and infiltration designs), and manufactured BMPs (filtration, infiltration, and hydrodynamic separators). Contaminant event mean concentration, performance efficiency, and mass-based first flush were evaluated for storms with varying rainfall–runoff characteristics. Previous research demonstrated that treatment performance of storm water control measures varies widely in response to site-specific contaminant loading functions. For that reason, the devices were tested in parallel, with a single influent source providing uniform loading to all devices. Treatment strategies were uniformly sized to target a rainfall–runoff depth equivalent to 90% of the annual volume of rainfall. Under the parallel and uniformly sized configuration, a normalized performance evaluation is possible because treatment strategies of the same scale receive runoff from events of the same duration, intensity, peak flow, volume, antecedent dry period, and watershed loading. Runoff constituent analyses included total suspended solids (TSS), total petroleum hydrocarbons-diesel, dissolved inorganic nitrogen, and total zinc. Several water quality parameters (temperature, dissolved oxygen, pH, conductivity) were monitored as real-time data. Performance evaluations indicate that several LID designs have removal efficiencies of 80% to 100%. In contrast, conventional structural BMPs perform poorly for most measures except for the pond with TSS. The manufactured systems tended to vary widely and were dependent on the design and contaminant of interest.

Recent implementation of National Pollution Discharge Elimination System Phase II rules under the Clean Water Act requires the design and implementation of local storm water management plans, and many communities are curious about different treatment strategies. Many factors influence engineers, planners, resource managers, and others in the selection of treatment strategies. The state of the practice currently focuses predominantly on storm volume and peak flow reduction, with some attention also paid to sediment issues. This is evident by the widespread dominance of storm water ponds as treatment measures and swales as conveyance means. These systems continue to dominate the storm water landscape despite volumes of quality research indicating that there are more effective treatment systems as well as the inclusion of these alternate designs in more recent storm water design manuals. A wide range of research on contaminant-specific removal strategies exists for sand filters (*1–3*), bioretention systems (*4–7*), and gravel wetlands (*8, 9*). For manufactured storm water devices, people are left largely to manufacturer claims for product efficiency. Maintenance demands for the range of treatment strategies have an important role in treatment selection.

In New Hampshire the poor performance of current storm water management is demonstrated by the fact that storm water runoff is ranked as the number one pollution source of 14 identified nonpoint sources (*10*). Shellfish beds in New Hampshire (Hampton, Rye, and Little Harbors; Great and Little Bays, and tributaries) are subject to regular closure after a 0.5 in. of precipitation. Runoff from impervious surfaces in urban areas contains significant amounts of hazardous contaminants, many of which are not removed with conventional best management practices (BMPs). The 21-km^2 Great Bay Estuary is fed by a 2,400-km^2 watershed. Investigations by Ballestero et al. (*11*) found that the performance of traditional storm water control systems (retention pond, detention pond, grassed swale) had a high degree of failure for at least one type of contaminant. Failure was defined as effluent concentrations exceeding influent concentrations during the first flush. In addition, for a wide range of contaminants, there was no clear trend of positive performance.

There is a growing body of data that indicate that wet storm water control systems, catch basins, and storm water pipes may be increasing microbial and dissolved contamination problems (*12, 13*). These studies indicate that wet control systems are inconsistently effective for reducing nutrients. Even those systems found to be effective for

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treating urban runoff in national studies (primarily for treating nutrients) may not be effective for all contaminants of concern and may be ineffective for much of the year in New Hampshire and other cold regions. Progress is needed on these questions to provide a scientifically sound basis for decisions on resource allocation relative to reducing contamination in surface water.

RESEARCH OBJECTIVES

The main research objective was to evaluate three classes of storm water treatment strategies—manufactured BMPs, conventional structural BMPs, and low-impact development (LID) designs—in a normalized fashion by using a parallel treatment configuration.

The study was performed at the University of New Hampshire (UNH) Stormwater Center field facility between August 2004 and April 2005. The center is located on the perimeter of a 3.6-ha commuter parking lot at UNH in Durham. The parking lot is standard dense-mix asphalt, installed in 1996, and is used near capacity throughout the academic year. The subcatchment area is large enough to generate substantial runoff, which is gravity fed to the parallel treatment processes. The lot is curbed and entirely impervious. Activity involves a combination of passenger vehicles and routine bus traffic. The runoff time of concentration for the lot is 22 min, with slopes ranging from 1.5% to 2.5%. The area is subject to frequent plowing, salting, and sanding during the winter months. Literature reviews indicate that contaminant concentrations are above or equal to national norms for parking lot runoff.

The climatology of the area is characterized as a coastal, cool temperate forest. Average annual precipitation is 122 cm uniformly distributed throughout the year, with average monthly precipitation of 10.2 cm ± 1.3. The mean annual temperature is 9°C, with the average low in January at –9°C and the average high in July at 28°C.

METHODOLOGY

Site Design

The site was designed to function as numerous uniformly sized, isolated, parallel treatment systems. The site as a whole was designed to get "dirty storm water" to each device, without significant impacts, such as sedimentation, from the distribution system. Rainfall runoff is evenly divided at the head of the facility in a distribution box, designed with the floor slightly higher than the outlet invert elevations to allow for scour across the floor and into the pipe network. Subsurface infiltration–filtration systems have gravel subdrains installed below to capture effluent. Finally, effluent from all systems is piped into a central sampling gallery, where system sampling and flow monitoring is centralized. The parallel configuration normalizes the treatment processes for event and watershed-loading variations. Site design began in 2002, and construction was completed in June 2004.

Site surficial geology is almost entirely marine clays, which allow for strict mass balance controls of influent and effluent. Within the systems, there are virtually no losses or additions from groundwater, leaving changes in mass to "within-system" losses.

The field facility currently contains 12 treatment strategies. There are two conventional BMPs (a rip-rap swale and retention pond), three LID devices (surface sand filter, bioretention system, and subsurface gravel wetland), and six manufactured devices (four vortex separators, a storm filter, and a subsurface infiltration device). Eight devices are discussed here: bioretention system, gravel wetland, sand filter, subsurface infiltration unit, manufactured filter device, hydrodynamic separator, rip rap swale, and retention pond. A bioretention system is the most common LID design in practice that treats storm water by filtration through a vegetated filter media made up of a soil mixture optimized for infiltration. A gravel wetland is a horizontal flow, multicell system designed to be continuously saturated, to promote water quality treatment conditions. The sand filter is a shallow surface sand filter with an extremely permeable filter bed. The manufactured subsurface infiltration unit is a treatment train comprising a pretreatment system followed by a large subsurface infiltration system made up of a series of perforated pipes. The hydrodynamic separators, sometimes referred to as manhole retrofits, are small structures designed to treat storm water through vortex settling. The rip-rap swale is a stone-lined unvegetated channel. This rip rap swale represents the common condition of passively vegetated storm water conveyance channels during the first few years before vegetation is well established. The retention pond is a wet pond designed to retain a standing pool at all times. The treatment strategies are all sized uniformly to treat the same peak flows and treatment volumes and to convey large flows. Design criteria were based on a rainfall frequency analysis to determine a rainfall depth corresponding to 90% of total runoff volume. For Durham, New Hampshire, a 2.5-cm rainfall depth is equivalent to 92% of the annual rainfall volume, based on 76 years of record. For much of the northeast it ranges from 2.0 to 3.3 cm. These criteria were selected because of their increasingly widespread use and the economical sizing and because water quality treatment will account for more than 90% of the annual runoff volume. The veracity of this sizing concept was to be evaluated. Design specifications for each device are included in Table 1 and include appropriate items such as maximum velocities, slope, residence times, as per the design manuals.

Treatment unit designs and selection were based primarily on manuals from New York State (*14*), New Hampshire (*15*), Brown (*16*), and FHWA (*17*). There are two sets of manufactured devices that are in series. The first is a water quality unit followed by a subsurface infiltration device. The other is a hydrodynamic separator followed by a filtration system. All of the manufactured BMPs except the subsurface infiltration unit are small-volume nonstorage units, so they typically do not affect peak flows but rather are limited to water quality treatment.

Sample Monitoring and Data Network

Detailed sample monitoring of the rainfall events occurred between August 2004 and April 2005. Sample analysis involved many discrete

TABLE 1 Storm Water Treatment Device Sizing and Design Criteria

Design Specification	Value
Rainfall–runoff depth	25.4 mm (1 in.)
Catchment area	0.4 hectares (1 acre)
Treatment peak flow	2,450 m^3/day (1 cfs)
10-year peak storm flows	8,570 m^3/day (3.5 cfs)
Treatment volume	92 m^3 (3,264 ft^3)
Treatment volume drain time	24–48 h

samples taken through the rising and falling limb of the hydrograph to determine entire-event mass balances.

Sample monitoring occurred at two primary locations, the distribution box and the sampling gallery. Influent samples are taken at a single location in the pipe leading to the distribution box. Effluent samples are taken at a centralized location for each of the 12 treatment devices, located at the sampling gallery. The effluent piping for each device is plumbed to the sampling gallery, which is a subsurface vault.

Effluent sampling is performed using automated 6712SR ISCO samplers. Each sampler is fitted with a water quality sonde and flow meter. All but one device use a bubbler flow meter combined with a Thelmar composite weir. The samplers are located in a shed above the sampling gallery. Sampling lines are fed through the floor of the shed into the sampling gallery vault below. Each sampling port for the individual treatment device is monitored by a YSI Model 600XL multiparameter sonde, recording pH, temperature, dissolved oxygen (DO), and conductivity at regular intervals. An on-site rain gauge provides rainfall frequency, duration, and depth.

Automated sampling is triggered on the basis of preset flow conditions. The sampling program for each device is based on analyses of multiple and varied effluent hydrographs. For the nonstorage devices, the effluent hydrograph is nearly equivalent to the influent hydrograph because of minimal peak flow attenuation. For both influent and effluent sampling, programs are designed to take five samples in the time of concentration and then spread out the remaining samples over the rest of the hydrograph. Typical influent sampling would be at 4-min intervals for the duration of the event, or until flow trigger conditions cease. For the large storage units, effluent sampling is at 60-min intervals for a total of five up to the time of concentration, and afterward at 140-min intervals or until flow trigger conditions cease. For the storage, filtration, and infiltration devices, effluent hydrographs are substantially altered and take 24 to 48 h to drain completely, as designed.

Runoff constituent analyses routinely include total suspended solids (TSS), total petroleum hydrocarbons-diesel (TPH-D), dissolved inorganic nitrogen (DIN) (composed of nitrate, nitrite, and ammonia), and zinc (Zn). Selection of constituents for routine analysis was based on an initial constituent characterization that included a wide range of petroleum hydrocarbons (gasoline range organics, lube oils, oil, and grease), total and dissolved metals (cadmium, copper, iron, lead, mercury), and nutrients (DIN, phosphate, total phosphorus). Although such analyses are performed, analyses of bacterial pathogens are not included in this discussion. Samples are stored at 4°C or frozen until analyzed. No acid sample preservation is performed because of cold storage and because of the wide range of analyses, some requiring preservation, others not. All sample analyses are performed by a state-certified laboratory for drinking water and wastewater.

RESULTS AND DISCUSSION

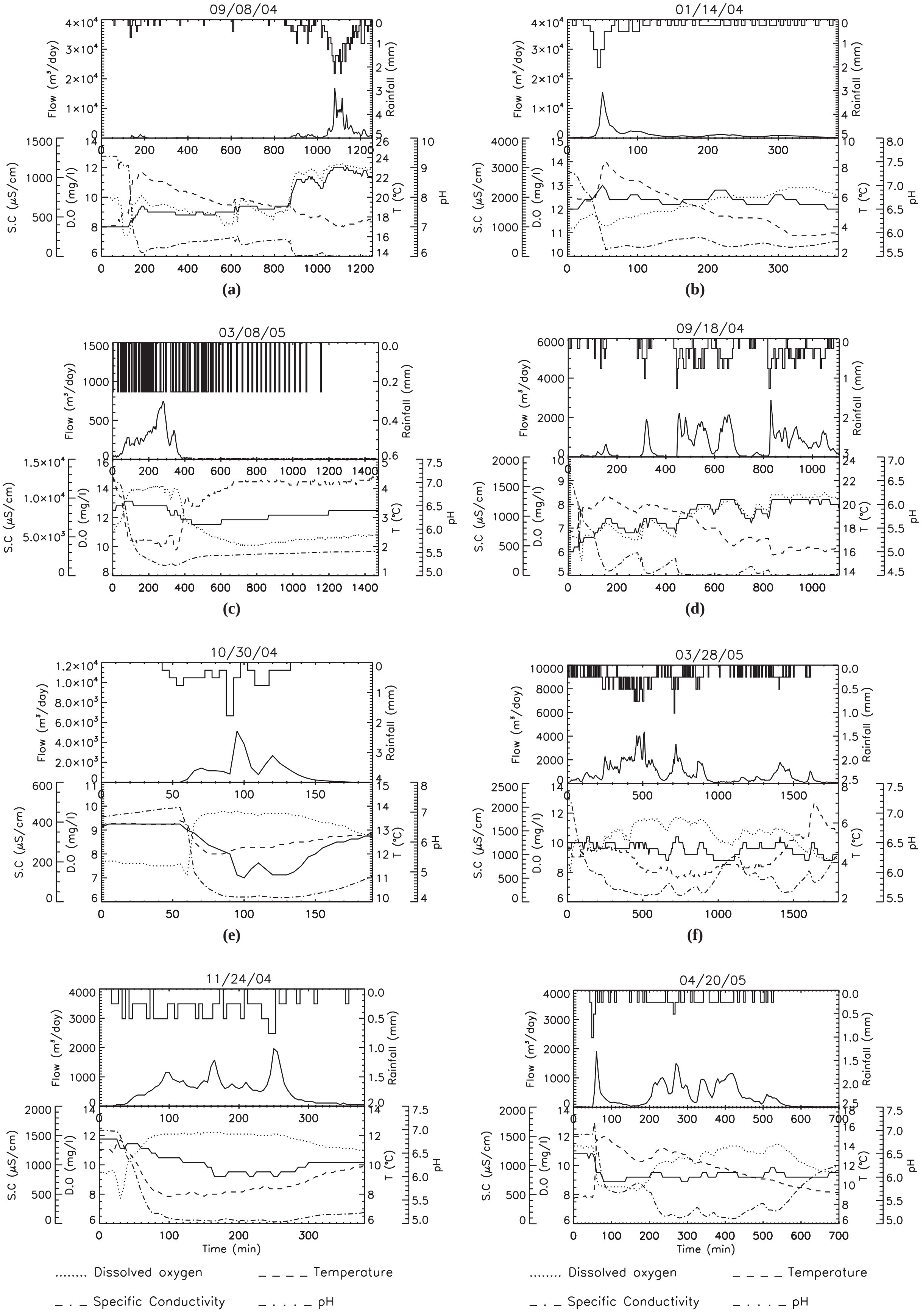
Variations in storm characteristics and whether a storm is either mass-limited or flow-limited would be expected to affect treatment strategies differently. This variability determines the contaminant wash-off rate. Antecedent dry periods average 5.6 days for each storm. All of the systems are designed to treat the first inch of runoff. For the nonstorage units, there is no retention time, but rather a water quality treatment only.

Hydrologic Data and Basic Water Quality

The hydrologic data for the monitored storm events are presented in Figure 1. These influent hydrographs reveal a wide range of storm characteristics for the monitored events. The range of storms includes variations in duration, intensity, total volume, peak flow, antecedent dry period, and a range of seasons. Each of these parameters can influence system performance. The short-duration storms might be expected to be flow-limited events and thus important to assess for first-flush characteristics. Other longer-duration storms might be mass-limited storms, and thus the bulk of the mass of the storms could be expected to be weighted toward the front of the storm. With short antecedent dry periods a lighter contaminant mass load might be expected, and thus lower influent concentrations and lower removal efficiencies. With seasonal variations, changes in nutrient trends would be expected. The storm characteristics presented in Table 2 demonstrate markedly different storms, and thus part of the challenge of storm water treatment. The first two storms were remnants of Hurricanes Frances (9/8/2004) and Ivan (9/18/2004), both large events, but Ivan was substantially longer and of lower intensity. Four storm events exceeded the design criteria for total rainfall depth. The 10/30/04 event exceeded the design criteria for peak flow only, but did not for volume or total depth. The 3/28/05 event exceeded the design criteria for total rainfall depth and volume, but not for peak flow. Only the 3/28/05 storm experienced system bypass, and that mass was monitored and included in the performance evaluations. Often, these variations are due to discrepancies between the typical design storm hydrograph (SCS Type III rainfall distribution) and the actual storm.

Real-time water quality parameters are presented for select systems (Figure 2): bioretention systems, surface sand filter, retention pond, gravel wetland, manufactured BMP subsurface infiltration unit (MD infiltration), manufactured BMP hydrodynamic separator (MD HS), manufactured BMP filter media (MD filter), and a rip rap swale. Real-time water quality monitoring of influent and the range of storm water devices enabled an assessment of water quality effects. Before runoff, background conditions dominate with the low flows, likely derived from groundwater. Background conditions are moderate low flows typically less than 25 m^3/day, temperatures ranging from 13°C to 18°C, specific conductance (SC) about 1,300 µS/cm, DO ranging from 5 to 8 mg/L, and pH near 6.7. Once runoff begins, these basic parameters change quickly for the duration of the event, as is evident in Figure 2. The background conditions return slowly in the next few days depending on the parameter and magnitude of the event.

The distinct variations in routing effects for the 390-min storm are evident with the bioretention system, surface sand filter, retention pond, and the gravel wetland. The same systems have the largest dampening effect on basic water quality parameters such as temperature. The lack of routing in hydrodynamic separators (MD HS), BMP filter media (MD filter), and rip rap swale is also evident and displayed in the water quality parameters. Influent water quality changes at the initiation of a runoff event as SC drops dramatically to <100 µS/cm. The temperature and DO are elevated as a result of warming from the asphalt parking lot and aeration in the distribution system. Runoff water becomes highly aerated, typically >10 mg/L. Water quality values for pH show common pH spikes between 5 and 6. Water quality responses in the treatment systems reflect the system flow retention capacity and the dominant treatment processes such as physical settling and physical–chemical filtration. Nonstorage



(a) (b) (c) (d) (e) (f) (g) (h)

FIGURE 1 Influent hyetographs, runoff hydrographs, and real-time parameters for eight storm events.

TABLE 2 Rainfall–Runoff Event Characteristics for 11 Storm Events, Durham

Rainfall Event m/d/y	Peak Intensity (mm/h)	Duration (min)	Total Depth (mm)	Peak Flow (m^3/day)	Volume (m^3)	Antecedent Rainfall (days)	Season
9/8/2004	27	390[a] 1,135[b]	56	1,884	78	7.0	Fall
9/18/2004	15	1,030	51	321	48	7.0	Fall
10/30/2004	21	130	12	569	11	13.0	Fall
11/24/2004	9	345	18	218	16	3.5	Fall
1/14/2005	24	380	17	1,726	39	1.3	Winter
2/10/2005	6	675	18	224	22	3.6	Winter
3/8/2005	3	445	22	85	8	5.7	Winter
3/28/2005	12	1,685	60	468	127	3.4	Winter
4/20/2005	12	490	15	212	21	5.9	Spring
6/22/2005	15	110	8	611	11	4	Summer
8/13/2005	24	835	13	1,466	21	10	Summer

[a] Denotes measurable runoff duration.
[b] Intermittent rainfall duration.

units (rip rap swale and hydrodynamic separators) have limited basic water quality influences on flow, temperature, DO, SC, and pH. Storage units (bioretention system, subsurface infiltration units, gravel wetland) have substantial effects on the basic water quality. Flows are reduced and delayed over several days, and pH and temperature are very stable. The storage systems dampen, but have less impact on, the decrease of SC and the increase of DO, which react inversely.

Contaminant Water Quality

Similar trends are observed among each respective class of storage and nonstorage systems for contaminant removal. Most manufactured devices (with the notable exception of the filters) do not claim contaminant removal for anything other than solids. It can be seen that there is removal for others that is likely due to surface complexation with solids (*18*). Systems with biological activity perform distinctly for nutrients and TPH-D. Figures 3 through 6 illustrate individual probability plots of influent versus effluent event mean concentrations (EMCs) for BMPs studied here. These probability plots illustrate the unit process response with respect to influent concentration. There is a clear trend of increasing removal efficiency with increasing influent concentration for all contaminants. The top performers are the infiltration–filtration systems (subsurface infiltration unit, bioretention, gravel wetland), with the exception of the surface sand filter. It is possible that there is an in-system source of TSS loading in the sand filter, which may explain the poorer than normal performance. This point is being investigated. The TSS plots show a relatively uniform removal efficiency performance for the hydrodynamic separator. Observable trends suggest that for most devices (except the sand filter) some level of solids removal is occurring. The swale, retention pond, and hydrodynamic separator do fail on occasion. It is hypothesized that the overall poor performance of the surface sand filter may be due to the exceptionally high hydraulic conductivity and small filter bed. This hypothesis is supported by the high level of removal observed in the subsurface infiltration unit that has an identical filter-bed material, but rather a larger filter bed area. It is also possible that the repeated TSS failure for the sand filter is an installation and maintenance issue. The issue is presumably fixed and will be verified for the following 2005–2006 monitoring season. The DIN performance is quite varied and depends largely on the season. The gravel wetland and bioretention systems are the top performers. It can be seen that TPH-D is easily removable, and except for the rip rap swale, it is removed by all systems to some degree. Zn is removed similarly, with the added exception of the hydrodynamic separator.

Effluent probability plots display a statistical comparison of each device for the 11 storms (Figure 7). For TSS the class of filtration–infiltration systems, except the sand filter (i.e., bioretention, gravel wetland, subsurface infiltration device), is very effective for the range of concentrations and routinely achieves removal to detection limits. The large variation in the hydrodynamic separators may suggest sediment resuspension. The retention pond achieves nearly 80% removal, and the rip rap swale and hydrodynamic separator are similar. The LID systems with biological activity (bioretention system and gravel wetland) had almost complete removal for TSS, NO_3, TPH-D, and Zn. In contrast, the swale performs poorly for TSS, NO_3, and TPH-D and has moderate removal for Zn. The rip rap swale will be compared with a vegetated swale in the 2005–2006 monitoring season. The large-volume manufactured BMP removed TSS, TPH-D, and Zn, with minimal effect on NO_3, most likely because of the absence of vegetation. The large-volume manufactured BMP took several months to wash out the fines in the sand filter media. During that time, there was a net export of TSS.

Mass-Based First Flush

Mass wash-off characteristics were examined for the range of storm events and are presented in Figure 8. In general DIN has the fastest wash-off rate; TSS, TPH-D, and Zn vary depending on the storm. None of the events meet first-flush as defined by Stahre and Urbonas (*19*) as 80% of the mass in the first 20% of cumulative volume, but the data are consistent with other reported observations (*20*). First-

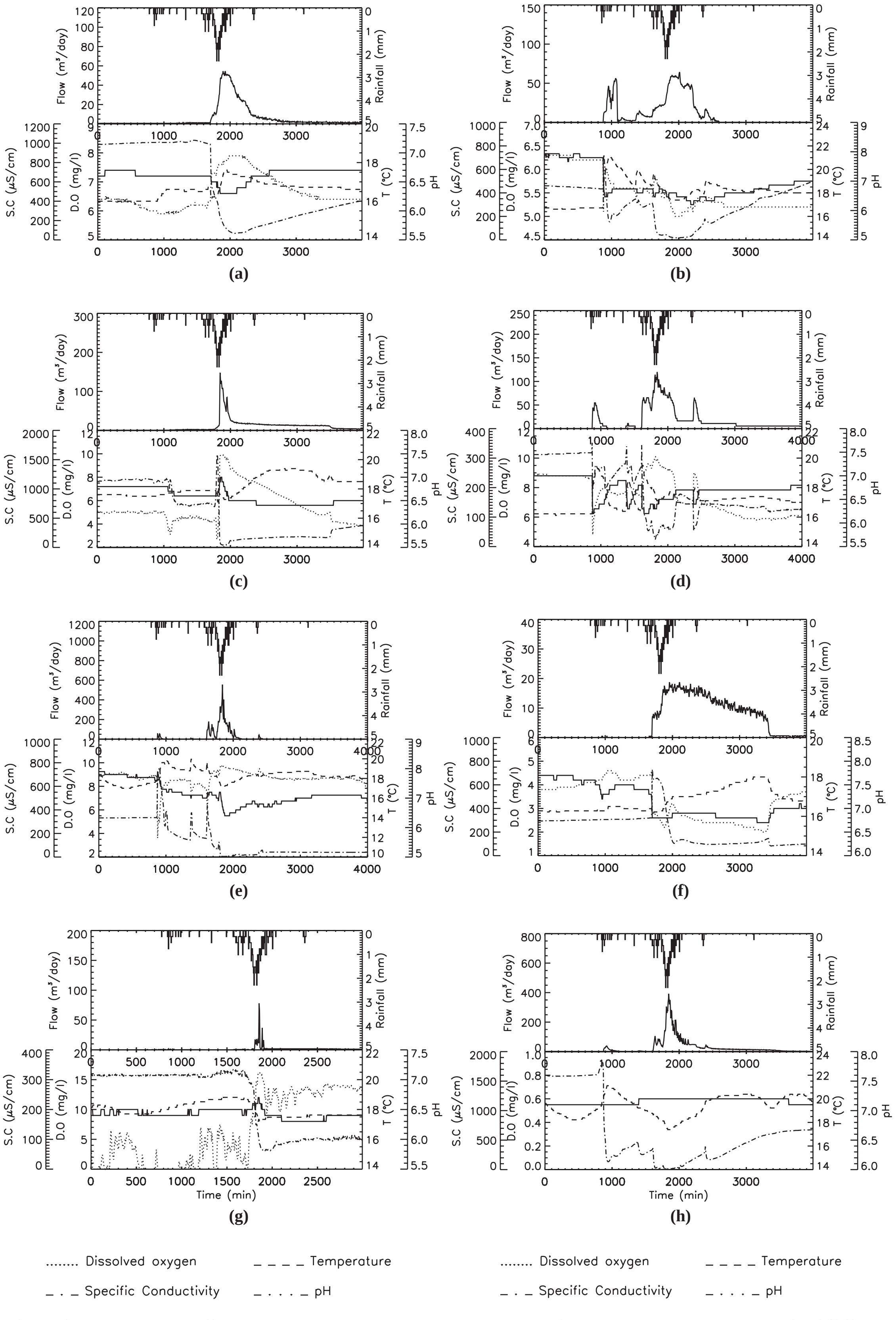


FIGURE 2 Hyetographs, effluent hydrographs, and real-time parameters for eight treatment strategies for 9/8/04 storm event: (*a*) subsurface infiltration, (*b*) sand filter, (*c*) bioretention, (*d*) manufactured filtration system, (*e*) hydrodynamic separator, (*f*) gravel wetland, (*g*) retention pond, and (*h*) rip-rap swale.

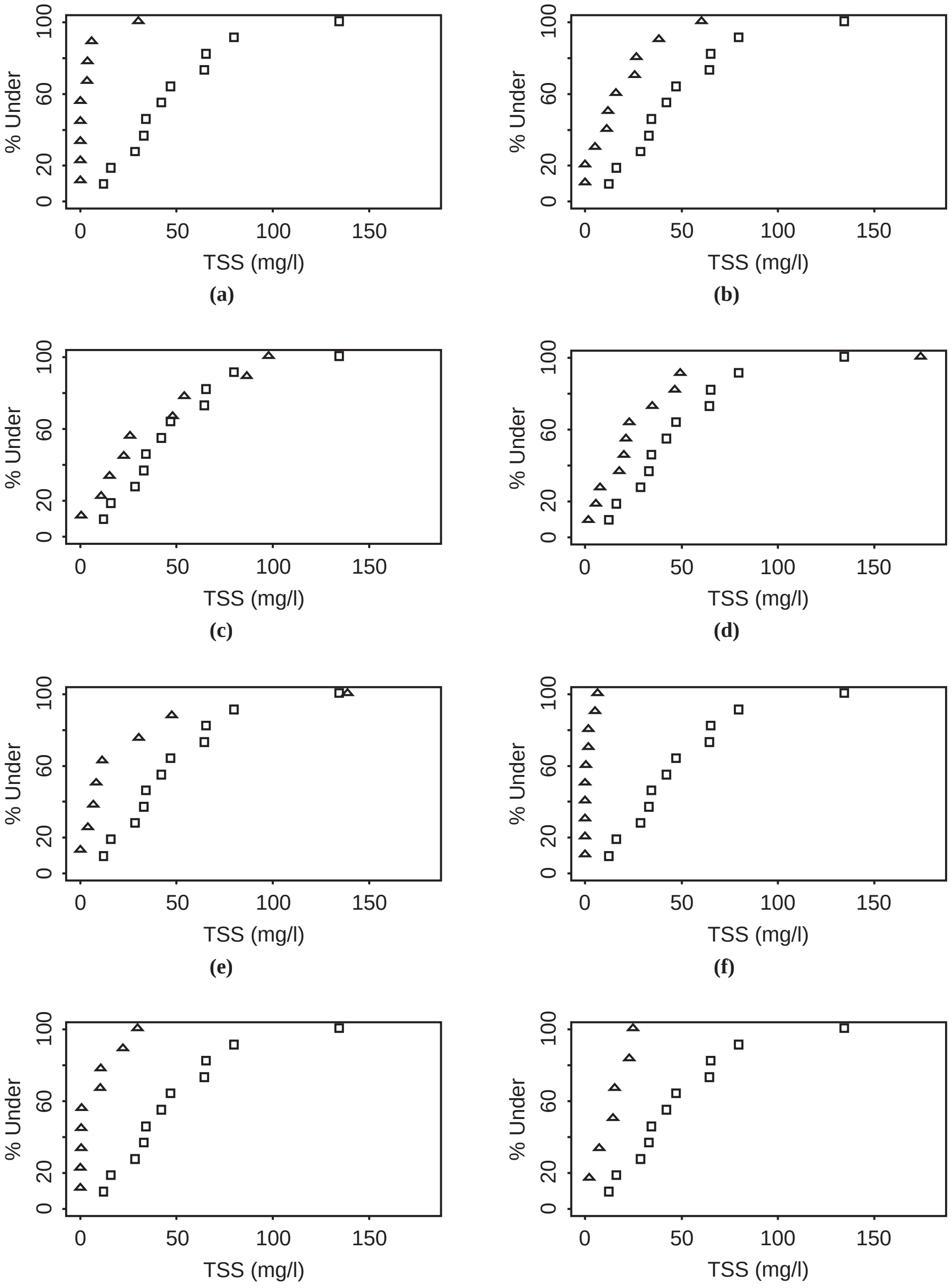


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FIGURE 3 Effluent probability plots for TSS for range of storm water treatment strategies: (*a*) manufactured infiltration, (*b*) manufactured filter, (*c*) sand filter, (*d*) hydrodynamic separator, (*e*) retention pond, (*f*) gravel wetland, (*g*) bioretention, and (*h*) rip-rap swale.

flush characteristics were observed over a range of storms with a predominance of mass in the beginning of the storm and approximate exponential decay of mass-transfer. In addition, three of the eight storms exhibited uniform mass wash-off throughout the storm event. However, peak flow, duration, intensity, and storm volume were not reliable predictors of first-flush tendencies. These storm characteristics varied both for storms that were distinctly first-flush weighted and for storms that had uniform wash-off. Even some of the smaller storms (4/20/05) showed more than 50% of the mass in the first 15% of cumulative volume.

CONCLUSIONS

One of the distinct challenges of assessing performance efficiencies is the process of normalizing performance data to account for variations in watershed and storm characteristics. The larger the data set, the easier the process of normalization; however, challenges still exist. The experimental design presented here inherently normalizes variations in loading and hydrology.

The storm events monitored include a range of storms that exceed one or more design criteria based on a water quality volume (WQV)

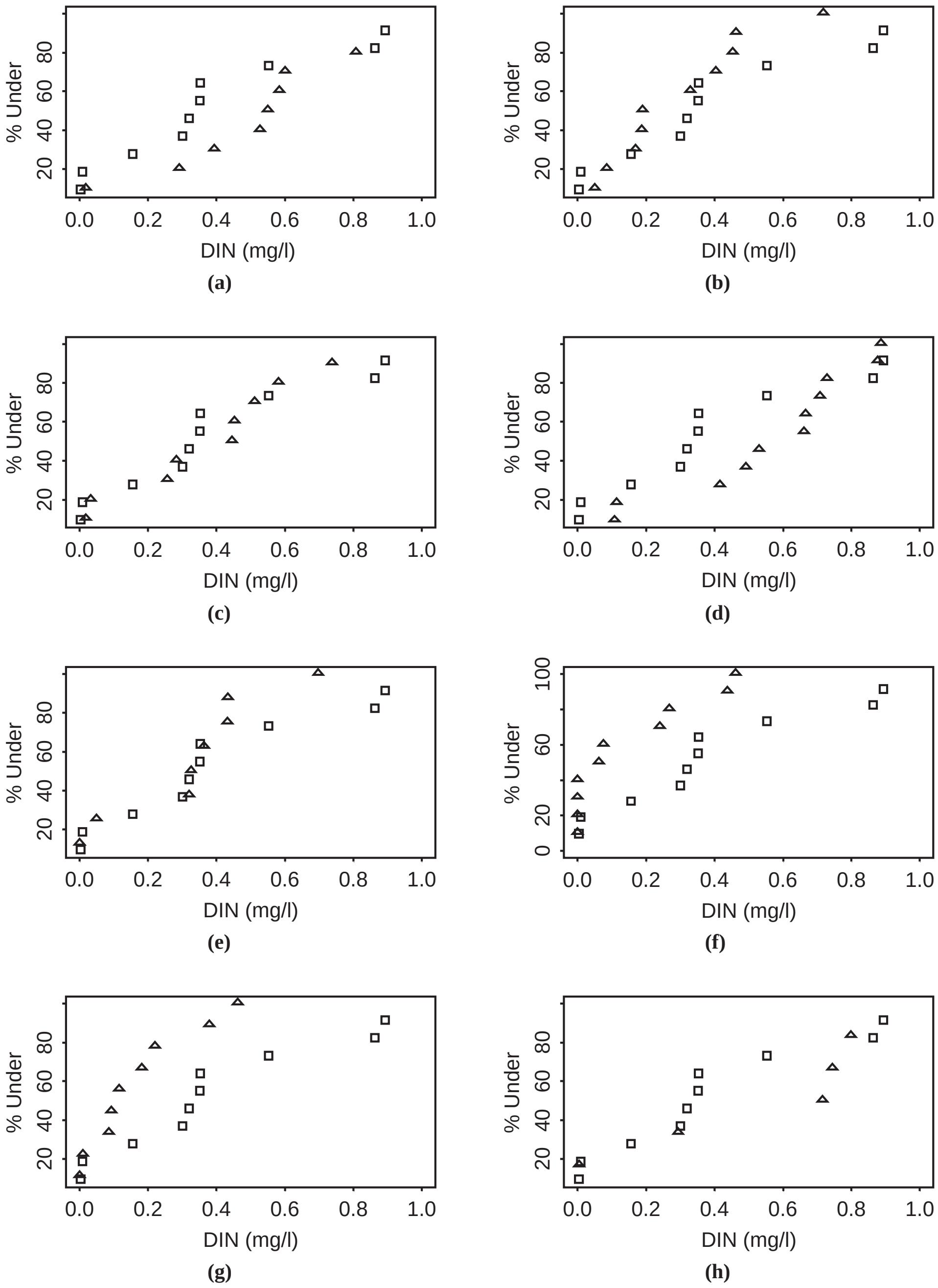

FIGURE 4 Effluent probability plots for DIN for range of storm water treatment strategies: (*a*) manufactured infiltration, (*b*) manufactured filter, (*c*) sand filter, (*d*) hydrodynamic separator, (*e*) retention pond, (*f*) gravel wetland, (*g*) bioretention, and (*h*) rip-rap swale.

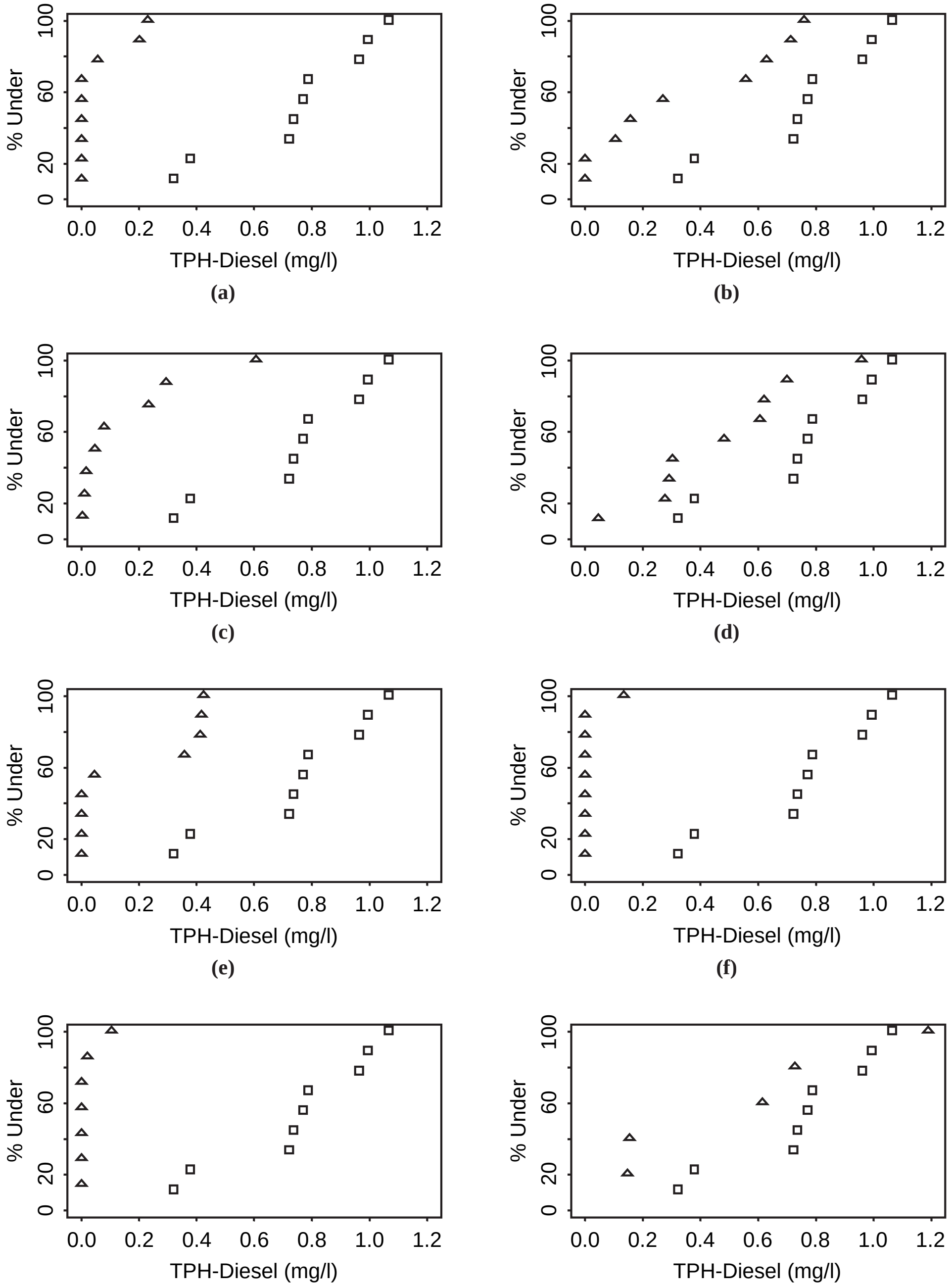

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FIGURE 5 **Effluent probability plots for TPH-D for range of storm water treatment strategies: (*a*) manufactured infiltration, (*b*) manufactured filter, (*c*) sand filter, (*d*) hydrodynamic separator, (*e*) retention pond, (*f*) gravel wetland, (*g*) bioretention, and (*h*) rip-rap swale.**

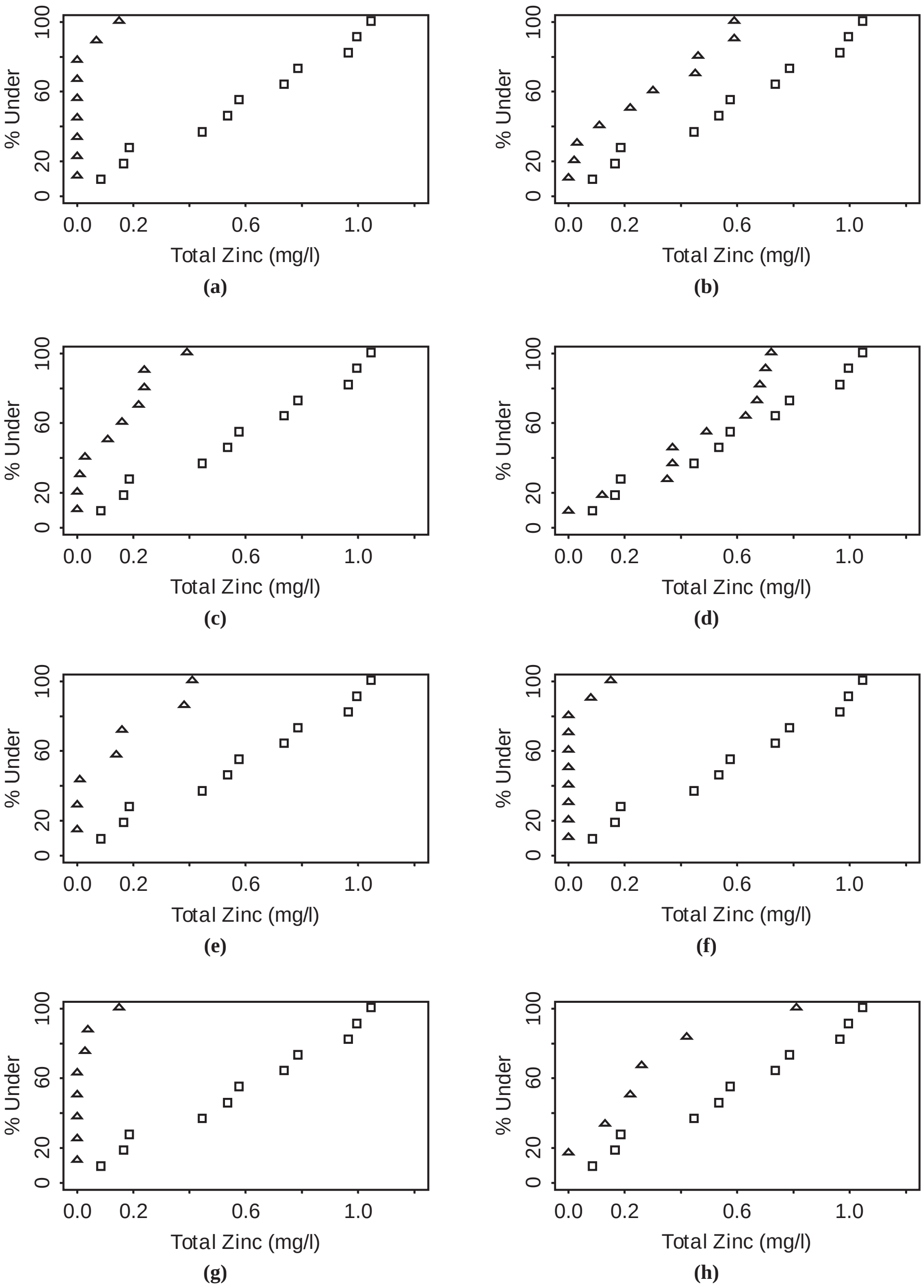

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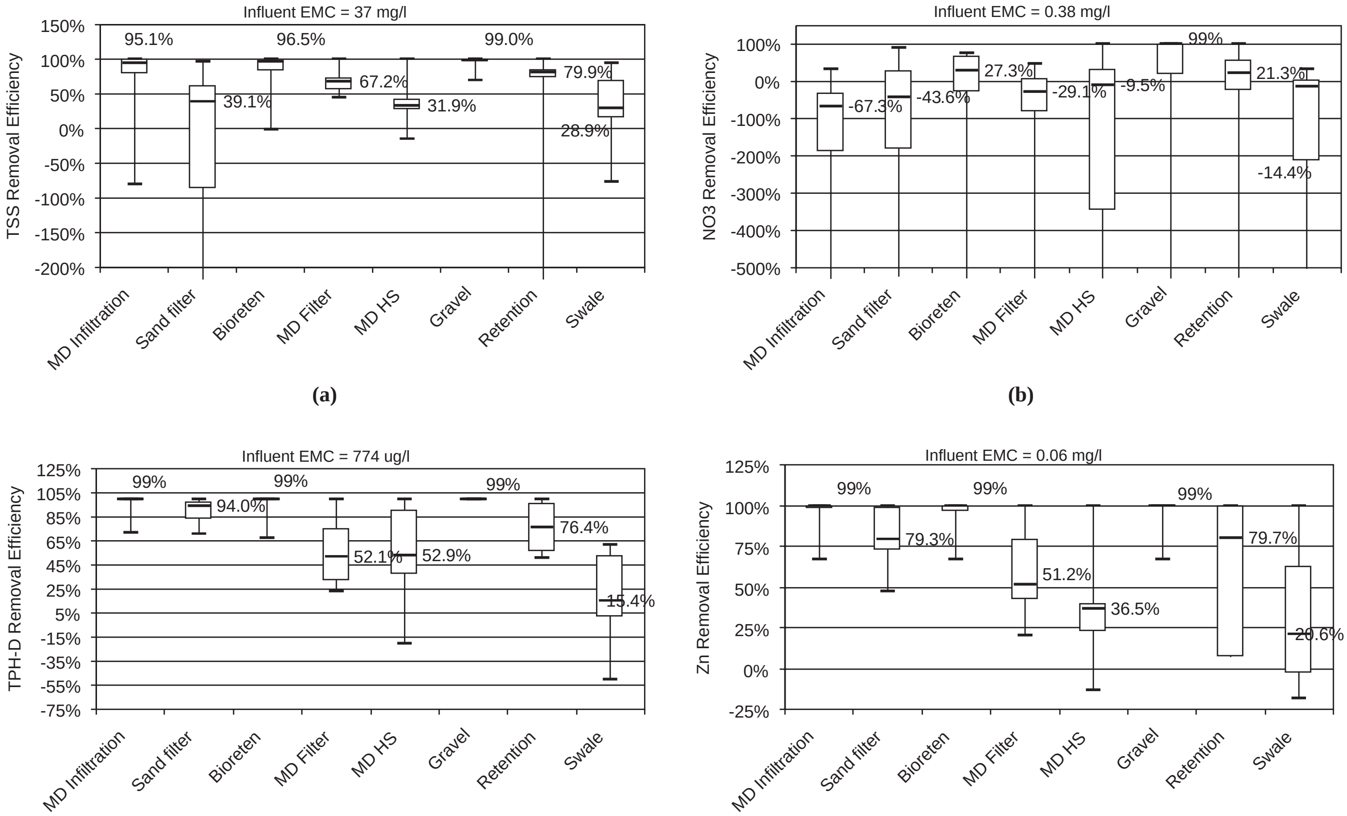
FIGURE 6 Effluent probability plots for total Zn for range of storm water treatment strategies: (*a*) manufactured infiltration, (*b*) manufactured filter, (*c*) sand filter, (*d*) hydrodynamic separator, (*e*) retention pond, (*f*) gravel wetland, (*g*) bioretention, and (*h*) rip-rap swale.



(a) (b)

(c) (d)

FIGURE 7 Removal efficiencies (normalized efficiency ratios) for TSS, DIN, TPH, and total zinc EMCs for eight treatment strategies: bioretention systems, surface sand filter, retention pond, gravel wetland, manufactured subsurface infiltration unit (MD infiltration), manufactured BMP hydrodynamic separator (MD HS), manufactured filter system (MD filter), and rip rap swale.

corresponding to 90% of the total annual rainfall, or 1 in. in 24 h. It appears that on the basis of the WQV sizing criteria, the system performance for the LID systems is very strong.

A wide range of performance efficiencies exist for the three classes of storm water treatment strategies tested for this study. The LID designs clearly had the highest removal efficiencies, and the rip rap swale the lowest. Retention ponds performed at or near the 80% removal efficiency for solids and others. As a standard of practice, it can be seen that widespread use of swales is doing little to improve storm water quality. Rip rap swales would be expected to be representative of the first few years of installation in a passively vegetated site. Among the LID devices, the sand filter performed poorly, possibly because of installation and maintenance issues, which are being examined. The gravel wetland and bioretention systems were consistently the top performers, routinely achieving greater than 95% removal efficiency.

The class of manufactured devices varied widely. The subsurface infiltration device was a top performer for all but nitrogen removal, which is to be expected for a nonvegetated device. These systems, which can be used in lieu of retention ponds, are increasingly being used for “big box stores,” which need large parking lots. That bodes well for the runoff quality for these sites. The hydrodynamic separator was routinely one of the poorest performers. The filter unit, an all-around midrange performer, was the best performer of the nonstorage systems, which have very distinct site constraints (below roadways, limited footprint). An advantage of these systems is that the filter media can be selected on the basis of specific contaminant removal needs.

Maintenance practices are not discussed in detail here; however, many of the LID practices have the added maintenance requirements of the filter media beyond that of conventional structural BMPs (ponds and swales). This is a big concern for owners because of the rise of legally binding maintenance requirements and for municipalities that are facing budget cuts. Yet the maintenance schedule is similar to the annual or biannual catch basin cleaning that is common with Phase I and II “good housekeeping” requirements and to the maintenance regimens necessary for manufactured systems. LID systems maintenance regimens vary from low to moderate. The widely varying site constraints (footprint, head loss, etc.) are typically some of the largest factors influencing selection of a storm water unit process. Long-term maintenance and effluent discharge requirements also factor in heavily in the selection process.

Substantial storm water quality improvements were achieved using a variety of infiltration and filtration practices common in LID practices. Many of the obstacles that exist preventing the widespread adoption of LID techniques are associated with the maintenance issues; however, the maintenance burden associated may be greater still for manufactured systems. It would appear that to reliably achieve higher removal efficiencies, managers must be willing to accept that the maintenance associated with these systems is not substantial when viewed in the context of routine maintenance for landscaping. The data presented here suggest that infiltration and fil-

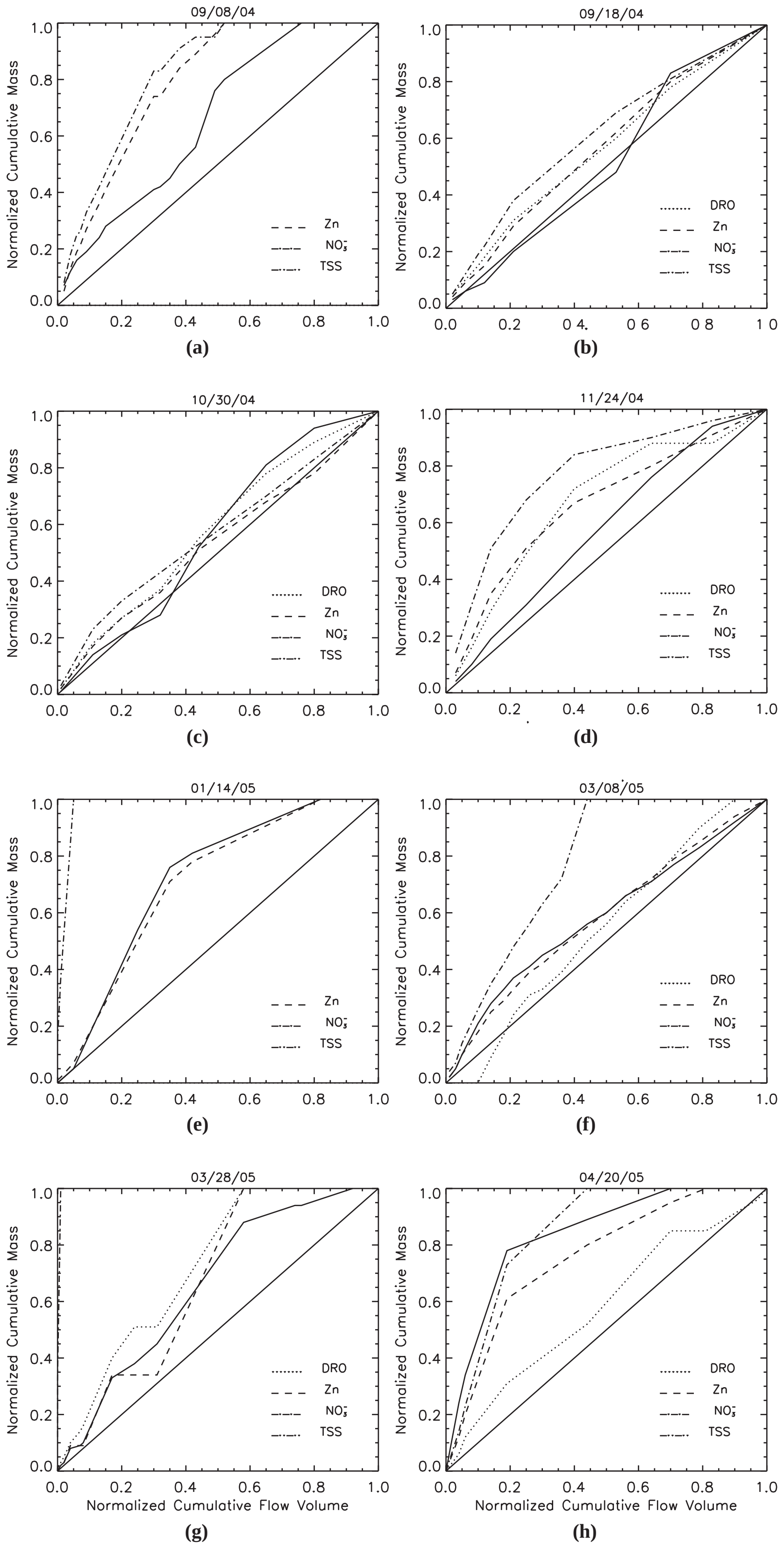


FIGURE 8 Mass-based first-flush load graphs for zinc, DIN, phosphorus, chloride, and TSS for eight sample storm events.

tration treatment strategies have the greatest all-around performance characteristics. It can be presumed that the combined effects of storage volume and physical–chemical filtration are the dominant factors contributing to their performance.

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