Laboratory Media Test Comparisons to Long-Term Performance of Biofilter and Media Filter Treatment-Train Stormwater Controls

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Abstract: Stormwater biofilters and bioretention controls have been extensively studied and are commonly encouraged as effective stormwater controls. Most of these controls incorporate media to enhance pollutant removal. There is much published research describing laboratory tests on the performance and selection of different media, and many field tests on media treatment of stormwater, but complementary long-term, full-scale field tests compared to prior laboratory tests are not as common. The purpose of this paper is to compare the laboratory evaluations of treatment media targeting a broad range of constituents of concern, to the results of long-term monitoring of full-scale stormwater controls using the selected media. The laboratory evaluations identified which media blend would reduce concentrations of constituents of concern to help meet National Pollutant Discharge Elimination System (NPDES) permit discharge limits and benchmarks, given site specific influent concentrations, when deployed in the field. Besides pollutant reductions, treatment flow rates and maintenance requirements were also of a consideration when selecting the media blend, especially determining the useful life of the media before clogging and/or pollutant breakthrough. Statistical comparison tests of the laboratory results with the full-scale field results resulted in similar effluent quality for most measured constituents (especially for lead and the critical form of dioxin), at all field treatment locations. Therefore, the laboratory observations were confirmed by the long-term, full-scale, stormwater control monitoring activities. The selected media has resulted in reductions in concentrations of the constituents of concern, over long periods of use. **DOI: 10.1061/JSWBAY.0000956.** *© 2021 American Society of Civil Engineers.*

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Introduction

There are many publications describing investigations of the performance of stormwater controls, with much recent interest focusing on biofilter (treatment with underdrains)/bioretention (treatment encouraging infiltration) systems. These biofilter/bioretention installations can incorporate some type of treatment media to capture constituents of concern. This paper compares initial laboratory test results to long-term field monitored data from a set of 10 stormwater controls located at the Santa Susana Field Laboratory (SSFL) in Ventura County, California, an industrial and open-space area with historic aerospace and energy research. An early phase of the stormwater control activities at SSFL involved research to identify and test stormwater treatment media having low effluent concentrations and low clogging risks that could be incorporated in the SSFL stormwater treatment systems. Media selection involved consideration of a wide range of constituents, including heavy metals, radiological constituents, and industrial organic compounds. Detailed descriptions of these tests and results are presented by Pitt and Clark (2010). The purpose of the comparisons described in this

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paper is to determine how well laboratory tests can predict full-scale stormwater control effluent concentrations and their ability to meet stormwater permit numeric effluent limits (NELs).

Stormwater discharges at SSFL are regulated by the Los Angeles Regional Water Quality Control Board through an individual industrial National Pollutant Discharge Elimination System (NPDES) permit that includes NELs for many constituents. As part of the stormwater control strategy, many locations throughout the site are routinely sampled to appropriately locate distributed stormwater controls. This process has been ongoing for almost 10 years.

Performance monitoring data for 10 stormwater controls constructed at the locations identified by the site selection process were grouped into four types of controls. These groups are "culvert modifications" (which are media filters installed at road crossings of drainages), detention bioswales (having large subsurface storage), a large sedimentation pond/biofilter treatment train, and a sedimentation tank/media filter treatment train. Most of these controls incorporated the selected treatment media, and their monitored performance was compared to these previous laboratory test results in this paper. Data are available for up to 9 years of monitoring at these full-scale stormwater controls.

Initial Laboratory Tests to Select and Test Stormwater Media for Use at SSFL

As part of the initial stormwater control design activities, Boeing partnered with the University of Alabama and Penn State Harrisburg to conduct laboratory performance studies to identify and evaluate stormwater treatment media mixtures (Pitt and Clark 2010). Bench-scale tests using actual stormwater investigated clogging, breakthrough, and removal; contact time and media depth; media capacity and kinetics; and aerobic/anaerobic effects on pollutant retention. Results indicated that of the 10 media alternatives evaluated, a mixture of rhyolite sand (volcanic origin having silica-rich composition), surface modified zeolite (SMZ) where quaternary amine is sorbed on to the zeolite substrate, and granular activated carbon (GAC) was a top-ranked performer for the removal of a broad range of the contaminants of concern at reasonable flow rates and with minimal clogging or chemical breakthrough (long filtering life before needed replacement). This media mix was implemented at most of the stormwater control systems constructed at SSFL. The following is a brief summary of the findings from those previous laboratory tests. Refer to the full media testing report [Pitt and Clark (2010) available at the Boeing SSFL surface water reports website] for complete descriptions and results of these laboratory tests.

The laboratory column tests involved intermittent stormwater loading of the filter columns (on a Monday, Wednesday, Friday schedule) for 10 weeks (to approximately 60–80 m of volumetric loading, depending on the flow rate through the media). The intermittent loading schedule was designed to accelerate the loadings but still allow for porewater chemical changes in the filter columns during dry periods between rains.

Ten media columns were constructed to test the media mixtures and individual components. At the start of each testing day, 200 L of stored stormwater from the 4,500-L storage tank were transferred to the day tank after the storage tank was mixed for at least 20 min. Selected metal salts were added to the day tank to create increased concentrations for some constituents that would otherwise likely be nondetected, in order to determine the media's ability to reduce elevated concentrations to levels below the NELs. After the media was saturated with stormwater each day and a steady flow was achieved, the flow rate was measured.

Samples for analyses were collected on the first day, and then periodically throughout the 10 weeks of column testing. Seven or eight sample pairs were collected for most analyses (metals and major cations, major anions, bacteria, solids, pH, turbidity, conductivity, oxidation-reduction potential, chemical oxygen demand, and ammonia), and three sample pairs were collected for the outside lab analyses (dioxin, oil and grease, mercury, and radioactive components) from each of the 10 columns.

Besides contaminant removal, clogging and treatment flow rates were also critical in the selection of the media mixture for use at SSFL. Table 1 shows the median particle sizes and the uniformity coefficients for the tested media. The treatment flow rate was about 15 m/day for the selected Rhyolite sand, surface modified zeolite, granular activated carbon (R-SMZ-GAC) media mixture, with a cumulative maximum sediment loading before clogging of about 10–50 kg/m^2. This corresponds to a sediment depth of about 0.6–3 cm (assuming 1.6 g/cc density), most of which would accumulate within the media voids. Column maintenance by scraping the surface layers of the media was only partially effective at restoring the treatment flow rates, with improved flow rates lasting for only short durations. In all cases, after about 2 or 3 scraping maintenance intervals, the scraping ceased being effective. The lack of substantial flow rate recovery indicated that penetration of solids is occurring below the media surface to depths where surface maintenance practices do not extend.

Pitt and Clark (2010) found that the treatment capacities of the media mixtures examined had longer run times before breakthrough for most of the constituents than would be indicated by particulate clogging. The goal was to have excess chemical capacity remaining when particulate clogging occurs, since measuring physical clogging through visual inspections of surface ponding and infiltration rate evaluations is substantially easier and more rapid compared to chemical breakthrough monitoring. If a large excess of chemical

Table 1. Descriptions of tested media

Media	Manufacture's description	Median particle size (D_{50}) (mm)[a]	Uniformity coefficient (D_{60}/D_{10})[b]
Granular activated carbon (GAC)	VCC 8X30 Virgin coconut shell activated carbon (Baker Corp.)	1.45	2.13
Rhyolite sand	D1 biofilter media sand (rhyolite topdressing sand) from Golf Sand, Inc., North Las Vegas, Nevada	0.39	1.79
Site zeolite	Z-200 modified zeolite (Baker Corp.)	2.9	1.55
Surface modified zeolite	14-40 Saint Cloud zeolite with 325 μm modified zeolite (modified with quaternary amine sorbed on to the zeolite substrate) at 3% Vol:Vol	0.73	2.35
Sphagnum peat moss	Purchased from nursery in Elizabethtown, Pennsylvania	0.60	7.31
Site filter sand	Fine textured silica sand from source local to project site	0.95	2.3

[a]Measured in lab.
[b]Measured in lab; uniformity coefficient <5 indicates a very uniform material; 5 is moderate uniformity; and >5 indicates a well-graded and nonuniform material.

capacity was expected after clogging, better pretreatment to remove the fines that cause clogging can be used to extend the run times.

As shown in the laboratory report (Pitt and Clark 2010), statistically significant removals were found for all particulates larger than 3 μm, total cadmium (Cd), total copper (Cu), total lead (Pb), total mercury (Hg), dioxin, oil and grease, and gross alpha radioactivity, plus many others. Dioxin and Pb are the most critical constituents based on site monitoring and the R-SMZ-GAC mixture was selected to have good treatment flow rates, long run times, and good effluent quality for these critical constituents to below the permit limits. The laboratory column performance for the selected media mixture is further summarized in additional information in Appendix D and in Appendix E (specifically Table E-2) available at the SSFL stormwater website, found in Pitt (2020).

During the column tests, some constituent effluent concentrations were greater than the influent concentrations, indicating media leaching of contaminants. The column results indicated a potential for pollutant export, likely due to ion exchange processes involving magnesium, potassium, and chlorine. Batch kinetic tests also indicated increased concentrations for some constituents in the filtrate water compared to the blank/no media chambers. During the batch kinetic tests, Cu was found to be leached during extended interevent periods when GAC or peat were used in the media mixture at large fractions.

Media depth is a design parameter affecting contact time. Longer contact times (deeper media beds or slower flow rates with concurrent larger surface areas) resulted in improved effluent quality for some constituents, but not all. The column tests were conducted at relatively slow to moderate flow rates (about 15 m/day) providing 10–40 min contact times of the stormwater with the media. The flow rates for the full-scale field installations, subsequently described, were about 5 to about 20 m/day (some flows were controlled using outlet restrictions or pumps).

Santa Susana Field Laboratory Site Description

The stormwater controls investigated in this paper are located at the SSFL site in Southern California. The SSFL is a 1,120 ha (2,800 acre) former federal government rocket engine testing and energy research facility located in the Santa Susana Mountains of eastern Ventura County that is currently owned by The Boeing Company and the US government. Activities at the site are now limited to demolition, remediation, and restoration. Stormwater discharges from the site are regulated by the Los Angeles Regional Water Quality Control Board (LARWQCB) through an individual industrial NPDES permit that includes Water Quality Based Effluent Limits (WQBELs) for many constituents, including metals, organic solvents, dioxins, and radionuclides, at multiple outfalls. Fig. 1 is a map of part of the site showing the watershed areas above Outfalls 008 and 009, along with monitoring locations. This map was created using ArcGIS software by Esri. (ArcGIS and ArcMap are the intellectual property of Esri and are used herein under license. Copyright Esri. All rights reserved). Only the outfall monitoring locations are regulated by the NPDES permit, while the internal monitoring locations are used in a site selection process to identify critical subareas where distributed treatment would be beneficial.

Each NPDES regulated SSFL outfall is monitored for up to 44 separate constituents during every storm that produces runoff. In addition, over 250 constituents are analyzed at least once annually at each of these regulated outfalls. The 27 constituents routinely monitored and reported to the regulatory agency at Outfall 009 (the watershed where the controls discussed in this paper are located) for every runoff producing rain include: acute toxicity, antimony, boron, Cd, chloride (Cl), chronic toxicity, Cu, cyanide, fluoride, gross alpha, gross beta, Pb, Hg, nickel, nitrate + nitrite as nitrogen (N), oil and grease, perchlorate, strontium-90, sulfate, dioxin (referring to the specific TCDD TEQ NoDNQ compound), temperature, thallium, total combined radium-226 and radium 228, total dissolved solids, tritium, and pH. TCDD TEQ NoDNQ refers to Tetrachlorodibenzo-*p*-dioxin, toxicity equivalence, but with detected but not quantifiable values excluded, as defined by the regulatory agency. Dioxin SSFL site stormwater measurements in this paper refer to this specific compound.

Description of Distributed SSFL Stormwater Controls and Monitoring Efforts

This paper discusses distributed stormwater controls in the Outfall 009 watershed for comparison with previous laboratory test results. Large outfall stormwater controls are not feasible at the Outfall 009 compliance monitoring location (natural drainage outlet located near the property boundary) due to severe site constraints, including steep slopes with minimal flat areas and poor access. Therefore, a watershed-based, distributed stormwater control approach was implemented, with numerous applications of treatment trains incorporating sedimentation and flow equalization followed by flow-through media filters (or "biofilters" when vegetated).

As part of the evaluation of the distributed stormwater control approach, numerous locations were monitored during all runoff-producing rains at SSFL. Fig. 1 shows 68 monitoring locations at potential stormwater control locations downstream of historical industrial activities, known impacted surface soils, and/or significant developed areas (such as buildings and/or paved surfaces), along with 16 background monitoring locations (in areas not having known industrial or other development activities) and two NPDES outfall monitoring locations (008 and 009). Performance monitoring was also conducted at selected constructed stormwater controls. Therefore, the SSFL has a very high density of monitoring locations and much information available to direct the stormwater management program.

Every year, the source area monitoring data are evaluated, and the locations ranked according to procedures described by Otto et al. (2013) and Costa et al. (2016), focusing on concentrations above the NPDES benchmarks and/or limits and considering the number of samples available. The locations are ranked according to their fractions of the observed concentrations above the benchmarks and/or limits, modified by the power associated with the number of observations available. Those having the greatest fractions above these critical values are then examined in detail and suitable stormwater controls evaluated, designed, and constructed. This ranking process is conducted every year considering the additional data from the current rain year and previous data. Performance monitoring is also conducted at selected stormwater controls to verify their performance. These performance data were evaluated in this paper in comparison to the prior laboratory results. Numerous stormwater controls have been installed at the SSFL. Detailed site descriptions, historical activities, and annual reports (including the monitoring data and evaluations) are publicly available on the SSFL website and are submitted annually to the regional water quality control board. Additional information concerning sources of metals and dioxins are described in the SSFL stormwater expert panel reports (2009 and 2010), also available on the SSFL website.

Table 2 describes the stormwater controls examined in this paper, showing the types of controls at the SSFL and their associated drainage area characteristics. As noted, these controls are all in the Outfall 009 watershed. Distributed stormwater controls in the

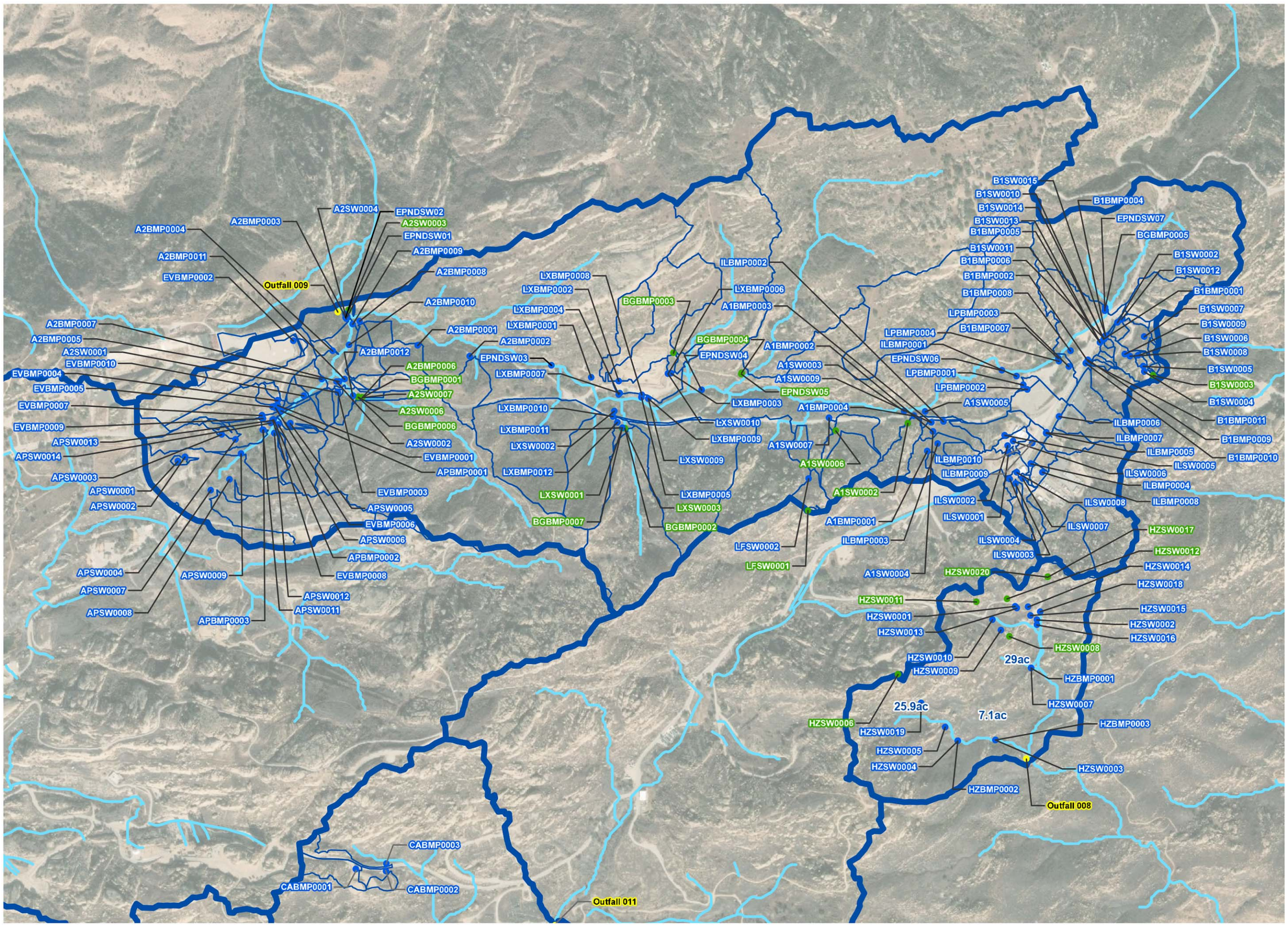

Fig. 1. Source area monitoring locations (68 at potential stormwater control monitoring locations, 16 at background monitoring locations, and at two NPDES outfall monitoring locations (Outfalls 008 and 009). (Base map source: Esri, World Imagery Map, Scale Not Given.)

Outfall 008 watershed focused on erosion controls, soil removal, dirt road stabilization, and channel protection. It should be noted that there is no design storm defined in the NPDES permit at SSFL for compliance purposes, implying that compliance is required for all events. The design team sized these controls to hydraulically handle the 1-year, 24-h rain, which is 6.4 cm (2.5 in.) in depth (the peak flow rates depend on the drainage areas and associated times of concentration), although the percentage of the annual flow treated varies, as indicated in Table 2.

The performances of the stormwater controls are dependent on many site and design factors. Generally, the best performance is expected for large stormwater controls and small drainage areas, resulting in potentially longer contact times with the treatment media, and large fractions of the annual flows treated by the stormwater control (with the excess flows bypassing complete treatment). Also, the effluent quality is better when the influent quality is better, while the percentage reductions are generally better if the influent concentrations are high. Since compliance with the NPDES permit effluent limit or benchmark concentrations is the main stormwater control objective, effluent quality is of the greatest interest when evaluating the controls, and not percentage concentration reductions.

The site controls all incorporate a treatment-train concept, with sedimentation before media treatment. The media was placed on top of gravel storage and underdrains. The first few culvert modification control installations (the first distributed controls installed as they could be constructed quickly) incorporated filter fabric separating the media from the gravel storage. However, the filter fabric geotextile quickly silted causing premature failure, leading to these initial installations being rebuilt (and future control designs) without the use of filter fabrics. Similarly, Boving et al. (2008) found that a geotextile fabric layer restricted vertical percolation of infiltrating stormwater at a porous pavement test site.

The contact time of the stormwater with the treatment media is dependent on the surface infiltration rate of the stormwater entering the media (from 5 to about 20 m/day), the thickness of the media bed (about 0.5 m) and the porosity of the media (about 0.35–0.5 for the selected media), and the use of outlet controls or other flow controlling mechanisms (such as pumping). This results in media contact times of about 10–30 min. If the media bed is larger and the effluent flow rate is restricted with outlet controls, the contact time can be increased, while still treating the same volume of stormwater during the same time. Using controlled pumping rates from the diversion sump, the large lower lot sediment pond and biofilter system has an approximate media contact time of about 2 h. The large detention bioswales, with outlet controls, have up to 72 h of detention time in the storage chambers and gravel bed, which enhances the capture of small stormwater particles by sedimentation. The culvert modifications have media contact times of about

Table 2. Characteristics of selected stormwater controls at SSFL examined in this paper

Stormwater control	Footprint of stormwater control	Drainage area [ha (acres)]	Approximate impervious cover in drainage area (pavement, roofs, and massive rock outcrops) (%)	Percentage of annual flow treated (%), based on site calibrated SWMM models	Treatment area (media filter alone, or sedimentation plus media filter) to drainage area ratio [m^2/ha (%)]
CM-1	Media filter area: 3 m^2	17–21 (43–53)	6.5–22	29	0.14–0.17 (0.001–0.002)
CM-8; background location (no known historical industrial activity)	Media filter area: 3 m^2	1 (2.6)	36	N/A[a]	3 (0.03)
CM-9	Media filter area: 3 m^2	4.1 (10.2)	48	33	0.73 (0.007)
CM-11; background location (no known historical industrial activity)	Media filter area: 3 m^2	2.3 (5.7)	26	N/A	1.3 (0.013)
B-1 media filter	Biofilter area: 19 m^2	1.8 (4.4) (varied due to diversions)	53	51	10.6 (0.1)
ELV treatment train	Sediment tank area: 42 m^2; Media filter area: 21 m^2	2.6–6.2 (6.6–15.6)	26–37	96	10.2–24.2 (0.1–0.2)
Northern detention bioswale	Top of ponding = ~330 m^2 and bottom of ponding = ~150 m^2	1.0 (2.6)	50	91	150 (1.5)
Southern detention bioswale	Top of ponding = ~740 m^2 and bottom of ponding = ~450 m^2	5.7 (14.2)	50	91	130 (1.3)
Lower lot biofilter	Sedimentation area: 300 m^2; Biofilter area: 300 m^2	12 (29.9)	53	79	50 (0.5)
Upper lot media filter	Media filter area: 35 m^2	2.0 (5.1)	35	N/A	17.5 (0.18)

[a]Calibrated SWMM models needed to calculate bypass flow quantities are not available for these locations.

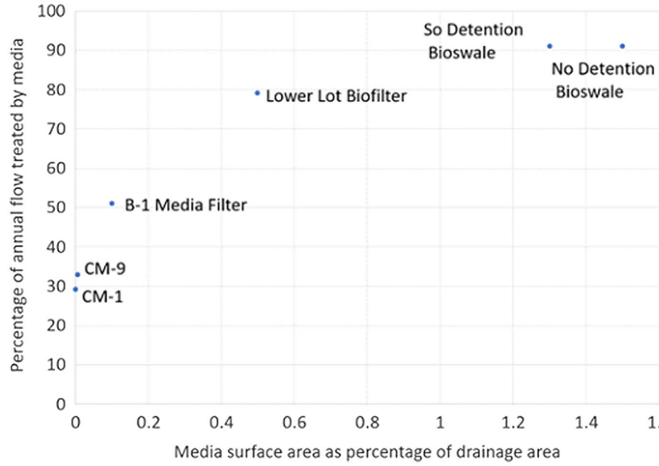

Fig. 2. Percentage of annual flow treated versus media surface area as a percentage of drainage area for SSFL control locations.

10–30 min. These different contact times generally result in different levels of performance of the stormwater controls, as shown in section 4 of the laboratory media test report (Pitt and Clark 2010).

The percentage of the total annual flow treated (with the remaining flows bypassing media treatment) increases as the size of the treatment area increases, relative to the drainage area. Fig. 2 compares these values for the controls shown in Table 2 [except the Expendable Launch Vehicle (ELV) treatment train that is more efficient with a smaller footprint due to the use of tube settlers in the sedimentation tanks] for these SSFL drainage area conditions and rains. Media footprints of about 0.1% of the drainage area results in about half of the annual flows fully treated, while about 0.4% is needed to provide full treatment of about 75% of the annual flows, and >1% is necessary to fully treat about 90% of the annual flows. The remaining flows bypass the media treatment but do receive some partial treatment associated with the sedimentation/ponding components of the treatment systems before overflowing the media components.

Besides the stormwater controls listed in Table 2, many other distributed controls are located at SSFL. The culvert modifications treat about half of the site area in the Outfall 009 watershed, while erosion controls have also been established on much of the site. The main drainage (the Northern Drainage) has constantly undergone restoration and stabilization. Many minor controls are also on the site, including some inlet filters and flow diversions. At the Helipad large paved area, berms are established and much of the flow from that area is pumped to the Silvernale pond and stormwater treatment system, which uses chemical controls, in an adjacent SSFL watershed area. In addition, Interim Source Remediation Action (ISRA) excavations have been conducted to remove contaminated soil from hotspots. A clay pigeon shooting range also was on the site and special soil excavation and stormwater controls have been used to remove Pb and other contaminating material [such as polycyclic aromatic hydrocarbons (PAHs) from the clay pigeons] from that area. Finally, demolition and removal of buildings and asphalt, and other site industrial structures have helped restore the natural hydrological response of the site. Final site restoration, including removal of additional soil contaminated by the site rocket testing and energy research activities, is still in regulatory agency review. The stormwater and erosion controls established on the site will be kept in operation and maintained through the demolition period. The following describe the stormwater controls that are evaluated in this paper.

B1 Media Filter and Detention Basin

A media filter with sediment forebays was installed in 2012 to capture stormwater from the hillside and roadway upstream of the existing B-1 culvert. The media filter consists of a 10-cm layer of gravel on the surface, underlaid by a 45-cm layer of filter media (sand, GAC, zeolite), which are on top of a 10-cm perforated pipe set in gravel. The perforated underdrain conveys the treated stormwater to a riser overflow structure where it is discharged to the Northern Drainage. Additional curb cuts along Facility Road were installed to direct roadway stormwater to a series of check dams and riprap, which ultimately drain to the forebay and media filter. Finally, a detention basin was installed upstream to provide additional settling and pretreatment of hillside flows prior to entering the media bed.

Detention Bioswales

Two detention bioswales were built in 2014 and consist of vegetated swales having surface growth media (a 10-cm layer topsoil/compost vegetative support layer) with underlying storage chambers (Contech ChamberMaxx), surrounded by 2-cm stone bedding. No treatment media are used at these facilities. These detention bioswales detain the drainage water for treatment in the lower lot biofilter after the initial lower lot flows are treated. Excess water that cannot be further treated by the biofilter (during periods of high flows and when the treatment system capacity is full) is directly discharged to the Northern Drainage. Each detention bioswale drains through an outlet pipe, controlled by two orifices sized to drain the system within 72 h.

Lower Lot Sediment Pond and Biofilter

The lower lot sediment pond and biofilter system was construction in 2013. A collection trench drain conveys stormwater from the lower paved lot to an 85-m^3 cistern, where it is then pumped to a 650-m^3 dry sediment basin. The sediment basin drains to a biofilter, which discharges to the Northern Drainage. The sediment basin includes an orifice plate designed to drain half the volume in 12 h and the remaining volume in 28 h. The biofilter includes an outlet structure with orifices sized to slow the flow through the media, resulting in a minimum contact time of 2.1 h. The biofilter cross section includes a 10-cm layer topsoil/compost vegetative support layer, a 46-cm layer of treatment media (fine filter sand, GAC, zeolite), and a 30-cm gravel layer with 150-cm PVC well screen laterals that drain through a 200-cm underdrain.

A pilot planting program was performed to better understand which native species are best suited to the growing conditions on the biofilter (alternating being submerged with long-duration dry periods). Results showed that three species, Sedge (*Carex praegracilis*), salt grass (*Distichlis spicata*), and common rush (*Juncus patens*) were best suited to the conditions in the biofilter. Three additional species, mugwort (*Artemisia douglasiana*), California fuchsia (*Epilobium canum*), and bricklebush (*Brickelia californica*) were expected to perform only moderately well but have the additional beneficial characteristics of being more drought tolerant than the first three species and providing habitat for pollinators. Therefore, a mixture of these six species were planted in the biofilter basin, with an emphasis on the grasses.

NASA ELV Stormwater Treatment Train

The ELV (historic NASA launch vehicle research area) treatment train was constructed in 2013. It is mostly an aboveground installation per the site owner (NASA). The system includes a swale lined with erosion control blankets and check dams to capture runoff from a slope. The swale drains to a small concrete sump with a sump pump. The water is pumped across the road to a flat area to three Baker tanks. The water flow is split and enters the two outside tanks for sedimentation treatment (containing floating inclined tube settlers with orifice control for the designated surface overflow rate). The effluent from the sediment tanks then drains to the central tank that contains a 45-cm layer of treatment media. The media bed is on top of a gravel layer and underdrain (also with orifice control for desired residence time). The effluent from the media tank is then sent back to the drainage downstream from the initial sump where it flows down a steep ravine to where Outfall 009 is located.

Culvert Modifications

"Culvert modifications" (CMs) were installed early in the process in 2009 and 2010, because these could be installed quickly and at relatively low cost. The CMs are retrofits of the existing culverts and include fiber-reinforced plastic headwalls with removable weir boards that span the entrance to each culvert. Twelve culvert modifications were initially installed at SSFL. The stormwater ponds in front of the weir boards and is then directed through a 60-cm (minimum) mound of filter media (GAC, zeolite, sand) where it is collected by underdrains. The weir boards have been wrapped with filter fabric to minimize short-circuiting seepage between the boards.

Sampling Effort and Rainfall

Samples are manually collected at the stormwater controls at the influent and effluent locations. The paired influent and effluent stormwater concentrations for each of these controls are then compared to evaluate treatment performance. The ELV treatment train and lower lot biofilter system also have intermediate sampling locations to represent the different treatment components for those controls. The paired manual grab samples at these controls are collected once per event after flows are well-established at the influent and effluent sampling locations. The average annual rainfall during the sampling period was 33.3 cm (13.1 in.), compared to the long-term average rainfall of 42.7 cm (16.8 in.). Overall, more than 450 samples were collected at the stormwater control locations and evaluated for this paper.

Discussions of Analyses and Findings

The purpose of these evaluations was to determine if the laboratory results could be used to predict the effluent concentrations at full-scale stormwater controls, especially considering compliance with the NPDES NEL and benchmark values, and the cumulative solids load until clogging. The clogging data are further discussed in the trend analyses that are included in a related paper (R. Pitt, "Changes in performance during long-term monitoring of full-scale stormwater controls at an industrial site," submitted, J. Sustainable Water Built Environ., ASCE, Reston, Virginia).

The ongoing performance monitoring at the stormwater control locations evaluated in this paper have a shorter list of constituents than at the regulated outfalls. These include total suspended solids (TSS), dioxin, total and filtered Cu, total and filtered Pb, total and filtered Cd, total and filtered Hg, particle size distribution, conductivity, pH, temperature, and turbidity. These samples are analyzed using the same analytical methods by the same state-certified laboratories that analyze the NPDES outfall samples.

The regulated NPDES outfalls on the SSFL site are monitored for many constituents for each flow-producing event. In recent years, the Outfall 009 stormwater water quality has improved (lower concentrations and associated fewer violations of numeric effluent benchmarks and limits), due to the use of the distributed treatment controls and other on-site efforts. However, periodic exceedances have occurred for dioxin and total Pb, hence their emphasis in these data comparisons.

J. Sustainable Water Built Environ., 2021, 7(4): 04021015

The data analyses used for the comparison of the laboratory tests with the field data (conducted using Microsoft Excel, SigmaPlot version 14, and Minitab version 18) as described in this paper includes the following:

- Basic statistical summaries of influent and effluent concentrations, concentration reductions, filterable fraction of the metals, and particulate strengths of the metals and dioxin, by control measure category.
- Line plots illustrating concentration trends between unit processes in treatment systems and between events.
- Comparisons of paired influent versus effluent concentrations using the nonparametric Wilcoxon Signed Rank test to identify which constituents and control types resulted in significant differences between influent and effluent concentrations.
- Analyses of paired influent and effluent concentrations (for those having statistically significant differences) to identify significant regression coefficients and equations (using ANOVA) to calculate effluent concentrations for given influent concentrations.
- Calculations were also made using the significant regression equations to predict effluent concentrations at the different stormwater controls comparing the laboratory column equations with the performance equations developed from the full-scale site monitoring data.
- Comparisons of influent and effluent concentrations and percentage reductions at the field locations with the laboratory column studies, using nonparametric Kruskal–Wallis and Tukey statistical tests, and grouped box and whisker plots.

The detailed results of these listed statistical tests and graphical analyses are in additional appendixes available at the SSFL stormwater website, found in Pitt (2020). These appendixes are:

- Appendix A. Stormwater characteristics and treatment performance
- Appendix B. Line performance plots
- Appendix C. Influent and effluent concentration probability plots
- Appendix D. Influent and effluent concentration results of laboratory column tests compared to full-scale field monitoring results
- Appendix E. Performance regression equations from laboratory column tests and full-scale stormwater treatment facilities
- Appendix F. Influent and effluent concentration trends with time
- Appendix G. Particulate strength trends with time for Santa Susana Field Lab stormwater controls

Stormwater Characteristics

Table 3 summarizes influent concentrations for the 10 stormwater controls combined for an overall indication of the untreated water quality at the SSFL locations where source area stormwater controls have been located. Industrial stormwater data contained in the National Stormwater Quality Database (NSQD 2018), version 4.02 are generally for light and medium industrial activity (mostly storage yards and warehousing). Even so, the NSQD median stormwater concentrations are about 2–5 times greater than the SSFL influent concentrations for TSS, total and filtered Cu, and total Pb. The total Cd values for both sets of data are mostly nondetected, while the SSFL pH median values are about 1 pH unit less than the NSQD pH values. Industrial stormwater concentrations from medium to heavy industrial sites were summarized by the NAS (2019) committee report on improving the industrial permit process. Those data are from mostly shipyard repair facilities, metal scrapyards, and public works yards, along with selected industrial area data from the International BMP Database (2018). The medium and heavy industry stormwater median concentrations are all much greater than the SSFL concentrations (about 4 times for TSS, about 9 times for Cu, and about 20 times for Pb, while the filtered metal concentrations are closer). Because the influent concentrations were less for the SSFL locations, their corresponding effluent concentrations after treatment are also lower than for the medium and heavy industrial stormwater treatment effluent values summarized in the NAS (2019) report. In contrast, the percentage reductions in concentrations are greater for the medium and heavy industrial area stormwater controls than for the SSFL locations. SSFL constituents that were mostly not detected (52%–95% not detected) included filtered Pb, total and filtered Cd, and total and filtered Hg.

Appendix A [(as part of the additional information posted on the SSFL website found in Pitt (2020))] contains influent and effluent concentration (and % reduction) summaries for each of the stormwater control groups, along with the background CM-8 and CM-11 control locations, for all of the monitored constituents. As shown in this appendix, the number of observations available for each of these stormwater control types varied. At the time of the data analyses for this paper, the background culvert modifications were monitored for one year with 22 samples, the nonbackground area culvert modifications plus basic biofilters were monitored for 9 years with 126 samples, the detention bioswales were monitored for 3 years

Table 3. SSFL influent stormwater concentrations at control locations

Constituent and units	SSFL influent sample counts	SSFL % nondetects	SSFL minimum	SSFL maximum	SSFL median	SSFL COV
Sample date	225	—	12/11/2009	3/22/2018	—	—
TSS influent (mg/L)	199	6.0	<1	1,800	16	3.0
Dioxin influent (μg/L)	183	18.6	$<1.00 \times 10^{-12}$	3.60×10^{-4}	5.60×10^{-8}	11.6
Total Cu influent (μg/L)	158	1.9	<0.1	44.9	6.9	0.8
Filtered Cu influent (μg/L)	148	0.0	0.7	164	4.2	2.1
Total Pb influent (μg/L)	187	8.0	<0.1	55.0	2.8	1.7
Filtered Pb influent (μg/L)	148	52.0	<0.1	26.4	<0.5	2.5
Total Cd influent (μg/L)	161	62.1	<0.10	6.21	<0.25	1.5
Filtered Cd influent (μg/L)	148	80.4	<0.10	4.94	<0.25	1.6
Total Hg influent (μg/L)	162	95.1	<0.05	0.98	<0.10	0.7
Filtered Hg influent (μg/L)	145	97.2	<0.05	0.49	<0.10	0.5
Conductivity influent (mS)	178	0.0	0.005	1.80	0.075	1.5
Grain size influent (μm)	42	0.0	1	347	17	1.42
pH influent	181	0.0	3.83	7.98	6.61	0.1
Temperature influent (°C)	171	0.0	6.5	21.3	11.6	0.2
Turbidity influent NTU	175	0.0	0.2	900	36	1.6

with 38 samples, the lower lot biofilter was monitored for 5 years with 25 samples, and the treatment train located at the ELV location was monitored for 4 years with 13 samples. As expected, the influent samples at the background culvert modification sites had the largest fraction of nondetected concentrations. Monitoring of the culvert modifications at the background locations were suspended after 1 year of monitoring. The effluent samples for all controls also had larger fractions of nondetected concentrations compared to influent samples.

Comparison of Laboratory Column Test Results to Full-Scale Field Stormwater Control Results

This paper summarizes comparisons between the laboratory study and the full-scale field results. The statistical tests and graphical presentations result in a weight-of-evidence supporting these comparisons.

- Appendix D contains box and whisker plots, with Tukey Groups, comparing influent and effluent concentrations for the five full-scale treatment categories and the laboratory columns. These data are also summarized in tables with additional information, including count, minimum, maximum, median, mean, standard deviation, Kruskal–Wallis p-values for the group, and the Tukey group designation. The Tukey groups designate which of the site controls have similar characteristics as the laboratory data. The effluent concentrations are of the greatest interest in the comparisons. The box plots show typically large variations for stormwater. The statistical tests consider these variations, along with the amounts of available data, when calculating the significance of the differences. Fig. 3 is an example of the box and whisker plots and Table 4 is an example of the summary table for the specified dioxin. Table 5 is a summary table showing the Tukey groups for the effluents of the stormwater controls and the column tests.
- Appendix E shows the resulting regression equations used to predict effluent concentrations using site influent concentrations. Table E-2 shows the regression equations for the laboratory column tests. Table 6 shows the calculated effluent concentrations using the stormwater control groups and the laboratory column regression equations, for median site concentration values.

The findings from these evaluations are subsequently described. The comparisons of field results with the laboratory results indicate the usefulness of using laboratory experiments to predict full-scale field performance. The uncertainty associated with the large variability associated with stormwater characteristics is considered in the statistical evaluations. Test water characteristics affect media treatment performance, so, as described by Pitt and Clark (2010), the laboratory tests used stormwater, with some adjustments for a few of the metals to reflect expected SSFL conditions or to increase influent concentrations above nondetectable levels to be able to detect concentration reductions with use of the tested media. The use of actual stormwater for these tests is important due to the partitioning of the pollutants to a wide range of fine particle sizes, the chemical forms of the filtered pollutants, concentrations similar to the expected field conditions, and the presence of major ions that interfere (such as competing for treatment capacity) with the pollutant removal processes. "Simulated" stormwater made using domestic or lab water and a selection of chemicals lacks most of these features, therefore media test results not using stormwater may be misleading, but may be useful for some initial evaluations.

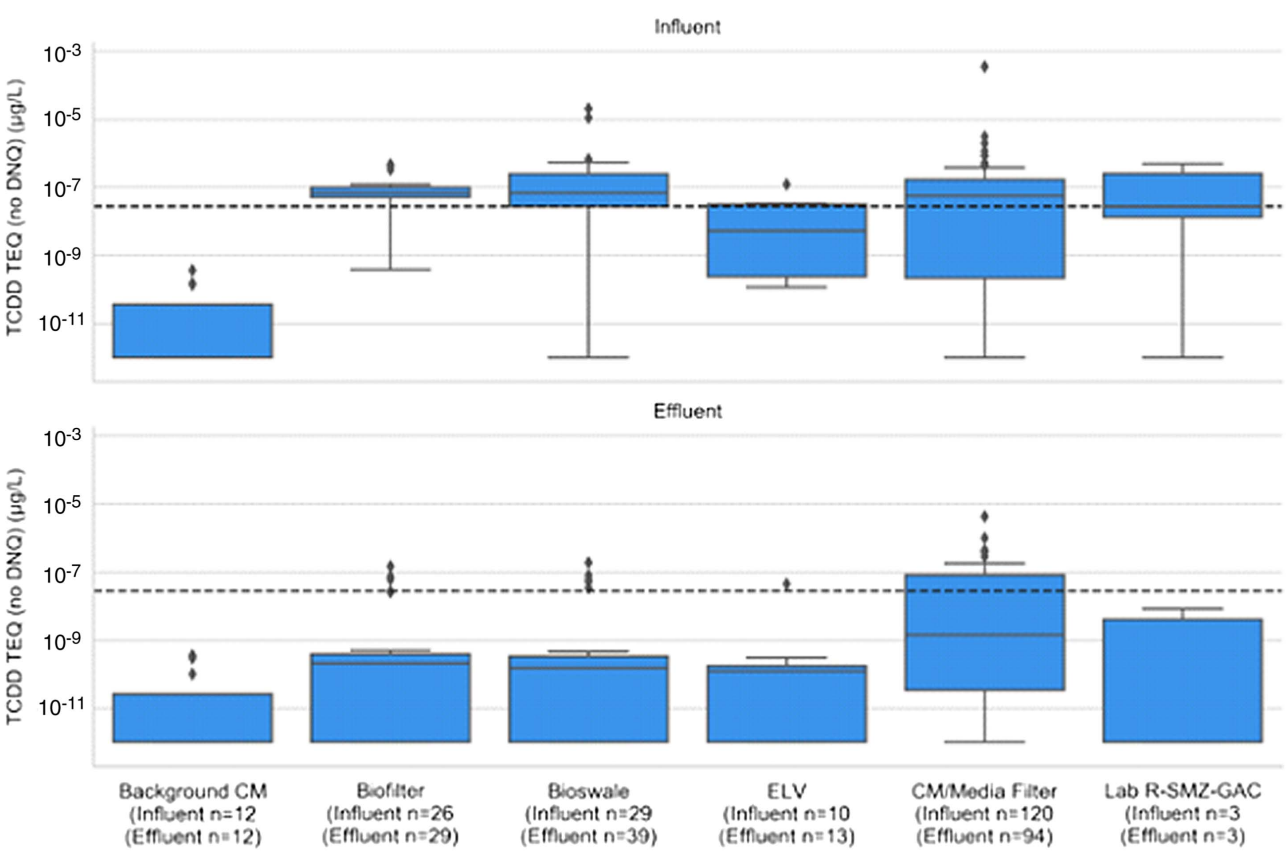

Fig. 3. Comparisons of influent and effluent TCDD TEQ (no DNQ) concentrations for field and laboratory performance tests.

Table 4. Dioxin [TCDD TEQ (no DNQ)] field performance data compared to laboratory column test data

Sample type	Group	Units	Count	Median	Standard deviation	Kruskal–Wallis p-value	Tukey group
Influent	Background CM	μg/L	12	1.00×10^{-12}	1.14×10^{-10}	2.67×10^{-5}	A
	Biofilter	μg/L	26	6.89×10^{-8}	1.19×10^{-7}		A
	Bioswale	μg/L	29	6.84×10^{-8}	4.27×10^{-6}		A
	ELV	μg/L	10	5.27×10^{-9}	3.79×10^{-8}		A
	CM/media filter	μg/L	120	5.59×10^{-8}	3.29×10^{-5}		A
	Lab R-SMZ-GAC[a]	μg/L	3	2.72×10^{-8}	2.75×10^{-7}		A
Effluent	Background CM	μg/L	12	1.00×10^{-12}	1.26×10^{-10}	3.43×10^{-5}	A
	Biofilter	μg/L	29	2.10×10^{-10}	3.16×10^{-8}		A
	Bioswale	μg/L	39	1.50×10^{-10}	3.43×10^{-8}		A
	ELV	μg/L	13	1.22×10^{-10}	1.23×10^{-8}		A
	CM/media filter	μg/L	94	1.43×10^{-9}	4.58×10^{-7}		A
	Lab R-SMZ-GAC	μg/L	3	1.00×10^{-12}	4.76×10^{-9}		A
Percent reduction	Background CM	μg/L	11	0.00	9,207	5.29×10^{-7}	B
	Biofilter	μg/L	26	99.6	35.8		A
	Bioswale	μg/L	27	99.7	1,845		AB
	ELV	μg/L	10	99.2	45.3		AB
	CM/media filter	μg/L	80	48.6	3,028		AB
	Lab R-SMZ-GAC	μg/L	3	69.7	51.3		AB

[a]Lab R-SMZ-GAC designates the laboratory full-column test data using the media used at the full-scale field installations.

Laboratory and Field Concentration and Removal Comparisons

Appendix D of the additional material posted on the SSFL website found in Pitt (2020) contains grouped box and whisker plots and summary tables comparing influent and effluent concentrations (percent reduction values are also summarized in the tables) for TSS, dioxin, total and filtered Cu, total and filtered Pb, Cd, and chromium (Cr).

Table 4 and Fig. 3 show these results for dioxin, a constituent periodically having exceedances at the SSFL Outfall 009 compliance monitoring location. The summary tables show that the Kruskal–Wallis test statistics and the Tukey groups indicate similar performance of these treatment categories. Low p-values (generally < 0.05) indicate at least one treatment category is significantly different from the others, while the Tukey groups indicate how the data groups are related. For the dioxin example, the Tukey groups for the effluent concentrations (the most important performance measure) indicate that all groups are similar, although the p-values indicate potential differences (as an example, A may be different from B, and B may be different from C but A and C may not be significantly different). These plots show that the laboratory column dioxin effluent values are similar to the other locations, while the culvert modification effluent concentrations are higher than at the other locations. The most important finding is that the effluents for the columns and from the different stormwater control groups were almost all below the NEL, with the exception of some of the CM sites which had small footprints compared to the drainage areas and therefore not as effective as the other controls. In contrast, the influent data had substantial numbers of observations above the NEL, with the exception of the background CMs that had overall good water quality.

Table 5 summarizes the Tukey groups for the pollutants for each treatment category. This table designates the significant groupings with separate letters. For an example, suspended solids show "A"s in all columns designating similar groupings of control practice TSS effluents with the laboratory column effluent TSS concentrations. Therefore, the effluent concentrations for all of the sites, including the laboratory column tests, had similar concentrations. Some constituents show different letters in the columns, indicating different significant groupings. The laboratory column test effluents were similar to all of the other locations for TSS, dioxin, and Pb. Total Cu effluent indicates separate A, B, and C groups, while the laboratory column effluent has a BC designation, indicating it is grouped with both B and C groups, but not the A group (the detention bioswales). The Cd laboratory column effluent results were similar to the other categories, except for the detention bioswales, while the

Table 5. Tukey groups for effluent sample categories

Constituent	Background CMs	Lower lot biofilter	Detention bioswales	ELV treatment train	Other CMs	Laboratory column
Total suspended solids	A[a]	A	A	A	A	A
Dioxin [TCDD TEQ (no DNQ)]	A	A	A	A	A	A
Total Cu	N/A[b]	B	A	C	C	BC
Filtered Cu	N/A	B	A	B	B	AB
Total Pb	A	A	A	A	A	A
Filtered Pb	N/A	BC	B	C	C	A
Cd	N/A	BC	B	C	C	C
Cr	N/A	BC	B	C	C	A

[a]Effluent sample categories (capital letters) indicate statistically significant groupings of effluent concentrations for each constituent between field monitoring locations and laboratory column results.
[b]N/A is not available; too few data for analyses.

J. Sustainable Water Built Environ., 2021, 7(4): 04021015

filtered Pb and total Cr effluent results did not indicate any other similar groups with the laboratory column tests.

Effluent Concentration Equations

Additional information from Appendix E Table E-1, found in Pitt (2020), summarizes the results of the statistical analyses examining the relationships between the influent and effluent concentrations at the field locations. Three types of observations were noted, as described here:

1. The constituents having statistically significant removals based on the Wilcoxon Signed Rank Test ($p < 0.05$) were further examined using regression analyses (first-order polynomials), with ANOVA and residual analyses (using combinations of Microsoft Excel, Minitab version 18 and SigmaPlot version 14). The resulting equation coefficients were examined by ANOVA to determine the significance of the coefficients and the overall equation. If the intercept term was not significant ($p > 0.05$), it was removed from the equation which was then reevaluated, forcing the regression through the plot's origin. In this case, the percentage concentration reduction is the same for all influent concentrations. When a significant positive intercept term is included in the equation, low influent concentrations have a corresponding lower percentage removal compared to high influent concentrations. The final significant equations were verified by examining the residual behaviors, desiring an even distribution of the independent variable over the range of concentrations, an overall random distribution of the residual values, random distribution of residuals versus time order, and random distribution of residuals versus calculated effluent concentrations.
2. The second scenario is when the influent versus effluent scatterplot indicates a relatively constant effluent concentration [also confirmed by the grouped probability plots in Appendix C of the additional information found in Pitt (2020)], and if the paired Wilcoxon Signed Rank test indicated significant differences between influent and effluent concentrations ($p < 0.05$). This scenario occurred when the slope coefficient and overall equation were not significant using ANOVA. Under this condition, the effluent concentrations are assumed to be the medians of all observed effluent concentrations, with no change associated with influent concentrations [but with uncertainty described by the coefficients of variation (COV)].
3. The third scenario is when the Wilcoxon Signed Rank test had a large p-value ($p > 0.05$) indicating that the differences between the influent and effluent concentrations could not be distinguished based on the number of data observations available. In these cases, it is assumed that the effluent concentrations were the same as the influent concentrations, with no change with treatment.

As an example, the detention bioswale equations are all in the second category, with the median and COV values shown in the additional information in Appendix A, found in Pitt (2020), except for temperature. If the COV is large, the variation of the resulting effluent concentration is also large. The dioxin results have the largest COV values, while the pH values have the smallest COV values (if present, as most of the pH relationships did not indicate any significant differences between the influent and effluent pH values).

Table 6 compares calculated effluent concentrations using the regression equations from the influent and effluent relationships for the laboratory column and for the site control data pairs, using the median site influent concentrations (from Table 3). The predicted effluent quality using the lab equations are similar to the results from the equations from the stormwater control categories, especially for the critical constituents of concern (TSS, dioxin, and Pb). The lower lot biofilter and ELV controls are treatment trains that include sedimentation pretreatment before the media filters, while the laboratory equations only consider the media filter treatment.

Weight of Evidence Summary for Effluent Concentrations and Compliance with Numeric Effluent Limits

The following is a summary of the major findings from the statistical analyses that support conclusions pertaining to the laboratory column's ability to predict the full-scale stormwater controls and their ability to meet the stormwater permit NELs.

Appendix D of the additional information found in Pitt (2020) shows the box and whisker plots, Tukey groups, and Kruskal–Wallis analyses. As shown on Table 5 (summary of Appendix D), the column effluent concentrations were similar to field effluent concentration Tukey groups: all locations are in the same Tukey group for TSS, dioxin, filtered Cu, and total Pb. Total Cu at detention bioswales, filtered Pb at all locations, Cd at detention bioswales, and Cr at all locations, had effluent concentration Tukey groups different from the laboratory column effluent concentrations. All Kruskal–Wallis p-values are small, indicating that at least one sample category is significantly different from the others. Box plots indicate the following categories having effluent concentrations that are different from the others, likely causing the significant Kruskal–Wallis p-values:

Table 6. Calculated effluent concentrations comparing laboratory column equations and full-scale field performance equations

Constituent and units	SSFL median influent concentrations	Lab equations predicted effluent concentrations	B1, CM1, CM9, ULBF, CM8, and CM11 combined predicted effluent concentrations	South and North Detention Bioswales combined predicted effluent concentrations	Lower Lot Biofilter predicted effluent concentrations	ELV Treatment train predicted effluent concentrations
TSS (mg/L)	16	10.2	8.9	9	16	7.9
Dioxin (μg/L)	5.60×10^{-8}	9.4×10^{-9}	1.07×10^{-7}	1.15×10^{-8}	1.11×10^{-8}	3.51×10^{-9}
Total Cu (μg/L)	6.9	16	4.9	18	6.9	2.9
Filtered Cu (μg/L)	4.2	13	3.3	16	4.8	2.3
Total Pb (μg/L)	2.8	<4	1.3	1,4	2.8	1.3
Filtered Pb (μg/L)	<0.5	<4	0.4	1.0	<0.5	0.4
Total Cd (μg/L)	<0.25	<3	0.19	0.32	<0.25	<0.25
Filtered Cd (μg/L)	<0.25	<3	<LOD	0.47	<0.25	<0.25
Conductivity (mS/cm)	0.075	0.075	0.065	0.29	1.01	0.17
pH	6.61	6.61	6.61	6.5	6.61	6.61
Temperature (°C)	11.6	N/A	11.6	12.3	11.6	11.6
Turbidity NTU	36	N/A	36	36	63	36

- TSS: background culvert modifications had lower effluent concentrations than others. Laboratory column effluents similar to all categories.
- Dioxin: other culvert modifications group had higher effluent concentrations than others. Laboratory column effluents similar to all categories.
- Total Cu: Bioswale effluent concentrations higher than others. Laboratory column effluents similar to others.
- Filtered Cu: Bioswale effluent concentration higher than others. Laboratory column effluents similar to all categories.
- Total Pb: background culvert modifications had lower effluent concentrations than others. Laboratory column effluents similar to all categories.

All box plots indicate typically wide variations, as expected for stormwater, but show similar relationships as indicated by the Tukey groups.

- TSS (no NEL for TSS). All effluent values generally overlap, with background culvert modification influent and effluent concentrations lower than others.
- TCDD TEQ (no DNQ) (2.8×10^{-8} μg/L NEL). Very few effluent concentrations were greater than the NEL. The culvert modifications had less control reductions and more effluent concentrations that were higher than the NEL. The laboratory column effluent concentrations were all less than the NEL, similar to the site control locations. All effluent concentrations had large variations.
- Total Cu (13 μg/L NEL). Most laboratory column effluent concentrations were below the NEL, as were most other locations. Bioswale effluent concentrations were greater than the influent concentrations, with many higher than the NEL. Filtered Cu concentrations had a similar pattern.
- Total Pb (5.2 μg/L NEL). Laboratory column effluent concentrations, along with effluent concentrations at the other locations, were mostly less than the NEL. The culvert modification effluent concentrations were reduced, but many were still greater than the NEL.

As shown on Table 6, the effluent calculations using median influent concentrations and the column regression equations all compared well to site control regressions (except for conductivity).

Conclusions

Statistical tests comparing the laboratory data to the full-scale field data resulted in similar effluent quality for most measured constituents (especially for critical dioxin and total Pb constituents), at all field treatment locations. Therefore, the laboratory observations were confirmed by the long-term, full-scale, stormwater control monitoring activities. The selected media has resulted in reductions in concentrations and NEL exceedances of the constituents of concern at the NPDES regulated outfalls, over long periods of use, according to the annual monitoring reports submitted to the regulatory agency.

Basic summaries of influent and effluent concentrations and removals are shown in this paper, along with statistical comparisons and exploratory data analyses plots. The SSFL untreated influent stormwater concentrations at the controls were much less than typically seen at medium to heavy industrial sites as reported in the literature for many constituents. Low concentrations in influent water results in low concentrations in effluent water, but the percentage reductions are relatively small.

As expected, the controls having the longest contact times and treating the largest fraction of the flows without bypassing generally had the best overall performance. The culvert modifications are all quite small compared to the drainage areas but performed better than initially expected, but with large bypasses (about 30%–50% of the annual flows are treated by each culvert modification). The culvert modifications treating water from undeveloped areas (background sites) did not provide statistically significant reductions in water quality based on the Kruskal–Wallis test. The detention bioswales have large gravel storage areas and provided good treatment, likely because they were quite large compared to the drainage areas and pollutant removals were likely associated with silt settling in the gravel bed.

The following lists the major findings for the selected media during the laboratory tests, along with the long-term field performance monitoring results:

1. The laboratory tests found that the treatment flow rates were about 15 m/day for the selected R-SMZ-GAC media.
   - Field observations confirmed this treatment flow rate at the stormwater controls not having outlet flow controls. Outlet controls at the lower lot biofilter and the ELV treatment train significantly increased the contact times with much smaller treatment flow rates.
2. The selected media was found to have a cumulative maximum sediment load capacity before clogging of up to about 50 kg/m^2. The expected media life before clogging or chemical breakthrough was expected to be at least 10 years before required replacement.
   - As further discussed in an associated paper (R. Pitt, "Changes in performance during long-term monitoring of full-scale stormwater controls at an industrial site," submitted, J. Sustainable Water Built Environ., ASCE, Reston, Virginia), the field observations at the CM-1 location indicated a total sediment load of about 25 kg/m^2 at the time of clogging, showing a useful life of about 10 years. CM-9 is expected to reach this critical sediment load soon, while the other stormwater controls are well below this critical sediment load.
3. During the laboratory tests, statistically significant removals using the selected media were found for a broad range of contaminants, including particulates, total Cd, total Cu, total Pb, total Hg, dioxin, oil and grease, and gross alpha radioactivity.
   - The culvert modifications located at background sites (CM-8 and CM-11) did not have any significant removals due to low influent concentrations, while the culvert modifications at prior industrial locations (BM-1, CM-1, CM-9 and ULBF) had significant reductions of TSS, dioxin, total and filtered Cu, total and filtered Pb, and conductivity. Median particle size, pH, temperature, and turbidity did not indicate significant removals for the numbers of observations available. Cd and Hg had too few detectable observations, and oil and grease and gross alpha radioactivity were not monitored at the stormwater controls. The other control categories had significant removals of dioxin and filtered Cu, and the detention bioswales and ELV treatment train had significant decreases in total Pb.
4. The laboratory tests identified potential export of Mg, K, and Cl (generally greater than 25% increases), likely due to ion exchange processes in the media. During the batch tests, Cu was also found to be leached during extended interevent periods when GAC or peat were used in the media mixture at large fractions.
   - The monitoring programs at the stormwater controls did not include Mg, K, and Cl, but total and filtered Cu were observed to be significantly increased in the detention bioswales (which have long contact times), possibly associated with leaching from the growth media or the gravel storage material (no GAC or peat were used in the detention bioswales, only growth media above gravel storage layers).

The ability of the laboratory tests to predict full-scale stormwater control performance (especially effluent concentrations and their ability to meet NELs) is an important conclusion. However, it is critical that the laboratory tests be conducted correctly. The Pitt and Clark (2010) report describes the tests and procedures used during that study. The most important factors for successful laboratory tests are to use real stormwater for the tests that is similar in quality to that being considered for treatment, to conduct the tests using reasonable flow rates and durations (mimicking actual events), and to collect sufficient data. The test columns should be as large as possible and made of noncontaminating materials. Different physical sizes of the laboratory tests can be used to examine performance issues associated with scaling up the laboratory results (short circuiting, anoxic conditions, clogging differences, etc.), such as starting with 50–150-mm-diameter columns for initial tests and expanding up to pilot-scales of 0.5–1.0 m in diameter. Different tests can be designed focusing on pollutant retention and capacity (breakthrough) and flow rates (clogging). Particle size analyses of the particulates along with total and filtered chemical analyses result in the most useful data, although some useful information can be obtained focusing on simpler monitoring constituents (especially for initial screening tests).

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies. The analyses of the performance data and graphical analyses used in this paper are in supporting appendixes available in Pitt (2020).

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