Performance Changes during Long-Term Monitoring of Full-Scale Media Filter Stormwater Controls at an Industrial Site

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Abstract: Although biofilters and bioretention controls have been extensively studied and are encouraged as effective stormwater controls, there is remaining uncertainty concerning their long-term performance and required maintenance. Most full-scale monitoring efforts have been of short duration, with no clogging or breakthrough observed. This paper describes the long-term monitoring results of media-based stormwater controls located at the Santa Susana Field Laboratory (SSFL) in Ventura County, California, an industrial site with historic aerospace and energy research. The 10 stormwater controls examined in this paper were grouped into four types (referred to as culvert modifications, which are media filters installed at drainage road crossings, detention bioswales having large subsurface storage, a large sedimentation pond/biofilter treatment train, and a sedimentation tank/media filter treatment train). Data were available for about 6–9 years of monitoring. This paper examines the trends in performance and usage until major maintenance is required. In almost all cases, the effluent concentrations tracked the influent concentrations, with no significant performance or effluent concentration differences with time. Silt clogging at one facility occurred as predicted based on initial laboratory tests, and the media in that control was replaced on schedule. **DOI: 10.1061/JSWBAY.0000965.**

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Introduction

There have been many monitoring projects that have investigated the performance of stormwater controls, with much recent interest focusing on biofilters and bioretention green infrastructure systems. Most of these investigations have only been conducted for relatively short (1 or 2 years) periods of time, with minimal data available addressing long-term performance and maintenance issues, which is of great interest to stormwater managers and owners/operators of green infrastructure systems. The objectives of most of the field studies were documenting pollutant removal performance, with some also examining clogging induced failure, while chemical breakthrough has mostly been addressed during laboratory studies. In most cases, with proper design, construction, and maintenance, it is expected that clogging and breakthrough would not be observed during short-term studies.

Maintenance of bioretention stormwater controls is needed to ensure their optimal performance and to increase their useful life. Clogging by sediment has received the most attention. Mothersill et al. (2000) found that accumulated sediment decreased the performance of a small polishing biofilter located downstream of a pond in removing soluble nutrients, but the frequency of backwashing was not able to maintain optimal conditions. Brown and Hunt (2012) removed about 75 mm of the upper layer of the media in two bioretention systems to increase the storage volume and were able to improve their performance by decreasing the bypass volumes from about 35% to 11%. Sediment loading and clogging laboratory tests of biofilter media were also conducted by Ma et al. (2013), who concluded that the loading capacities of a tested media should result in a service life of 5 to 10 years, depending on site-specific conditions, maintenance, and biofilter sizing.

Performance checks using simulated stormwater at five streetside bioretention systems that had been in operation for 10 years were conducted by Lucke and Nichols (2015), who found that pollutant removal performance was highly variable, depending on the influent concentrations, media used, construction methods, and environmental factors. Thomas et al. (2016) conducted a literature review of maintenance activities of stormwater controls and found that current operation and maintenance practices of stormwater controls were generally poor, with expected reduced long-term performance. Blecken et al. (2017) reported that more than half of the 43 North Carolina bioretention systems they surveyed had maintenance deficiencies, with surface clogging due to internal erosion being common.

Investigations found that the most common failure mode of stormwater media treatment controls is clogging with sediment. Urbonas (1999) reported that the hydraulic capacity of treatment media was dependent on the total suspended solids load captured. As the media became clogged, the treatment flow rate decreased with increasing flows bypassing the treatment media with decreased overall system performance. Similar findings associated with clogging of media were reported by Clark and Pitt (1999), Clark (2000), and Li and Davis (2008).

The Institute for Sustainable Water Resources (and associated centers) at Monash University in Melbourne, Australia, has long conducted research on stormwater treatment, especially on media filtration operation and maintenance (Hatt et al. 2006, 2007; Le Coustumer et al. 2012; Harpreet et al. 2014; Kandra et al. 2014; McCarthy et al. 2015). The Monash researchers have prepared many design guidance documents for stormwater filters based on this extensive research.

Sileshi (2013) related treatment flow rate to sediment capture for different types of bioretention media and the associated longevity of the media mixture before a replacement was necessary due to clogging by different particle sizes. Sileshi et al. (2019) also found that compaction of the media had minor effects on the treatment flow rate if the organic matter content was low, but compaction had significant effects on the flow rates if the media contained large amounts of organic matter.

The International Best Management Practices (BMP) Database includes water quality performance data for over 700 studies (Clary et al. 2021). The most recent Summary Statistics report (Clary et al. 2016) described the evolution of this database over the last 20 years. Even with this large number of performance investigations, only 9 biofilters, bioretention, or rain garden sites have been monitored for at least 3 years (with a maximum of 6 years). Another large-scale review of multiple stormwater controls was conducted by Taylor et al. (2014) for the Transportation Research Board, mostly based on stormwater controls at highway sites. As part of this investigation, they reviewed long-term Department of Transportation performance studies at six vegetated sites having more than four years of data (one ecology embankment for four years in Washington, one swale for five years in Texas, and four grass strips for 5–7 years in California) to determine if the performance changed over time. Also examined were three sand filter installations in California (monitored for 4–6 years) and one permeable friction course overlay study in Texas (monitored for 5 years). They were not able to identify any changes in performance with time during these data reviews.

The purpose of this paper is to expand the available data set of long-term water quality performance of biofilters and media filter stormwater controls with monitoring data collected at several stormwater control installations at the SSFL in Southern California. The various maintenance activities that have been performed during the monitoring period have enabled consistent performance over the years of monitoring.

Background

This paper describes 10 stormwater controls located at the Santa Susana Field Laboratory (SSFL) in Ventura County, California, an industrial site being restored, which had historic rocket engine testing (until 2006) and nuclear energy research (until 1988) activities. Current activities on the site include demolition, remediation, and restoration. As part of these activities, stormwater is regulated by the Los Angeles Regional Water Quality Control Board through an individual industrial National Pollutant Discharge Elimination System (NPDES) permit that includes numeric effluent limits for many constituents, including metals, organic solvents, dioxins, and radionuclides, at multiple outfalls. The primary purpose of the stormwater controls is to reduce the occurrence of exceedances of NPDES permit limits at the regulated outfalls. In 2008, the Stormwater Expert Panel was formed to provide additional guidance, and their recommendations since 2009 have expanded stormwater control activities and other improvements, which have resulted in the general reduction of these exceedances. An associated paper (Pitt et al. 2021) described how laboratory tests were initially used to select and optimize a media mixture that has been used on this site and successfully compares the full-scale treatment observations with the early laboratory results.

As part of the stormwater control strategy, many locations within the site are sampled to identify appropriate locations for distributed stormwater controls. This process has been ongoing for almost 10 years, along with performance monitoring at influent and effluent locations at selected stormwater controls to verify their performance and identify maintenance issues. This paper describes the performance of 10 stormwater controls grouped by type (referred to as culvert modifications, which are media filters taking advantage of road crossings of drainages, detention bioswales, a large sedimentation/biofilter system, and a sedimentation/media filter treatment train). Data are available for about 6–9 years of monitoring at these internally distributed control locations.

Another paper (Pitt et al. 2021) described the SSFL site conditions and stormwater controls and reviewed the development of the treatment media based on earlier laboratory tests. Influent and effluent concentrations, reductions, and performance equations for the laboratory experiments were compared to field monitoring results for the different control categories. That paper showed that the SSFL stormwater concentrations are generally substantially lower than for typical industrial stormwater. The National Stormwater Quality Database (NSQD) light and medium industrial stormwater median concentrations are about 2 to 5 times greater than the SSFL influent concentrations for total suspended solids (TSS), total Cu, and total Pb, for example (Pitt and Maestre 2015). Because the influent concentrations were less for the SSFL locations, their corresponding effluent concentrations (and percent reductions) after treatment are also lower than those reported for similar stormwater controls at more intensive industrial locations.

This paper was prepared using data available prior to the Woolsey Fire, which began in November 2018 and which was widely reported in the national news media. A significant part of the site was burned during this fire. Based on previous fires at the site and surrounding areas, such as the 2005 Topanga Canyon fire, runoff events following fires were found to have often elevated levels of constituents, such as TSS, metals, and dioxins (a constituent of particular concern at this site), until the burned and exposed soil has been stabilized and/or revegetated. In light of these considerations, the authors emphasize that the water quality data and descriptions of facility maintenance in this paper do not represent recent postfire conditions but rather stabilized site conditions before the Woolsey Fire.

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Stormwater Control Descriptions

Outfall stormwater controls are not feasible at the SSFL Outfall 009 compliance monitoring location due to the large drainage area (220 ha) and severe site constraints (difficult access and steep slopes with minimal flat area at the outfall location). Therefore, a watershed-based, distributed stormwater control approach was implemented, with numerous applications of treatment trains incorporating pretreatment sedimentation and flow equalization followed by flow-through media filters (or *biofilters* when vegetated). 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.

As part of the initial stormwater control design activities, Boeing and Geosyntec Consultants partnered with the University of Alabama and Penn State Harrisburg to conduct laboratory performance studies to identify and evaluate stormwater treatment media filter mixtures (Pitt and Clark 2010). A companion paper (Pitt et al. 2021) summarized the bench-scale tests using stormwater that included clogging, breakthrough, and removal; contact time and media depth; media capacity and kinetics; and aerobic/anaerobic effects. Results indicated that of the 10 media mixes evaluated, a blended mixture of rhyolite sand (silica-rich sand of volcanic origin), surface modified zeolite (SMZ) (quaternary amine sorbed onto 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 a long service life before clogging or breakthrough. This media mixture was implemented at the stormwater control systems constructed at SSFL, which are discussed in this paper.

The site stormwater controls evaluated for performance trends in this paper were previously described by Pitt et al. (2021) and also in compliance reports submitted to the Los Angeles Regional Water Quality Control Board (LARWQCB) and are available on the Boeing SSFL surface water technical reports web page. Table 1 is a copy of a table summarizing the descriptions of the stormwater controls included in the paper by Pitt et al. (2021).

The site controls are all multistage treatment trains having sedimentation and flow-equalization followed by media treatment. The contact time of the stormwater is dependent on the surface infiltration rate of the stormwater entering the media (from 5 to about

Table 1. Characteristics of selected stormwater controls at SSFL examined in this paper

Stormwater control	Footprint of stormwater control	Drainage area (ha and 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 and %)
CM-1[a]	Media filter area: 3 m^2	17 to 21 ha (43 to 53 ac)	6.5 to 22	29	0.14 to 0.17 (0.001 to 0.002)
CM-8; background location (no known historical industrial activity)	Media filter area: 3 m^2	1 ha (2.6 ac)	36	n/a[b]	3 (0.03)
CM-9	Media filter area: 3 m^2	4.1 ha (10.2 ac)	48	33	0.73 (0.007)
CM-11; background location (no known historical industrial activity)	Media filter area: 3 m^2	2.3 ha (5.7 ac)	26	n/a	1.3 (0.013)
B-1 media filter	Biofilter area: 19 m^2	1.8 ha (4.4 ac) (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 to 6.2 ha (6.6 to 15.6 ac)	26 to 37	96	10.2 to 24.2 (0.1 to 0.2)
Northern detention bioswale	Top of ponding = ~330 m^2 and bottom of ponding = ~150 m^2	1.0 ha (2.6 ac)	50	91	150 (1.5)
Southern detention bioswale	Top of ponding = ~740 m^2 and bottom of ponding = ~450 m^2	5.7 ha (14.2 ac)	50	91	130 (1.3)
Lower lot biofilter	Sedimentation area: 300 m^2 biofilter area: 300 m^2	12 ha (29.9 ac)	53	79	50 (0.5)
Upper lot media filter	Media filter area: 35 m^2	2.0 ha (5.1 ac)	35	n/a	17.5 (0.18)

Source: Reprinted from Pitt et al. (2021), © ASCE.

[a]CM refers to culvert modifications that used sedimentation and media filters at road crossings.

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

20 m/day), the thickness of the media bed (about 0.5 m) and the porosity of the media (about 0.35 to 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 to 30 min (with no outlet controls). As described in the associated data appendices and the companion paper (Pitt et al. 2021), the effluent quality varied based on the designs of the stormwater controls and the areas and other characteristics of the drainage areas.

Flows treated by the stormwater controls were calculated using a calibrated stormwater management model (SWMM) for the site, based on the drainage area and rain characteristics, as described in the following subsection.

SWMM Calibration and Use

The SWMM was initially calibrated for the watershed draining to the NPDES regulated Outfall 009 in 2008 and then recalibrated in 2010, 2012, and 2015 as the site changed and new data became available. The model has been used for such tasks as sizing stormwater controls and storage facilities, for calculating peak flows for the design of channel stabilization practices, and for calculating the influent runoff volumes for each of the stormwater controls for each event, as used in the calculations for this paper. The 2015 calibration used flow data at the outfall from September 1, 2009, through October 6, 2015. Calibration was performed on the prestormwater control baseline model, and then adjusted parameters were applied to the model based on the stormwater controls as they were installed.

The final model utilizes hourly precipitation data from an onsite rain gage and incorporates 52 subcatchments. Subcatchments were delineated using a 2010 aerial survey and geographic information system (GIS tools) (with a 0.3-m topographic resolution), and the subcatchment imperviousness was determined from 2010 aerial photographs and field verifications. Infiltration was modeled using Green-Ampt soil parameters: suction head, saturated hydraulic conductivity, and initial soil moisture deficit. Monthly evapotranspiration (ET) rates were obtained from the California Irrigation Management Information System (CIMIS) website for the reference ET zone 9 (Pitt and Maestre 2015).

The parameters adjusted during the 2015 recalibration included soil hydraulic conductivity, subcatchment parameters (flow width, flow routing, and depression storage), Manning's n for overland flow, and evapotranspiration rates. Multiple measures of goodness-of-fit were used during the calibration process, including visual assessments of fit, mean absolute error, root mean square error, and Mann-Whitney comparisons of observed versus modeled values for total runoff volume and peak flow rates. Fig. 1 shows the runoff hydrograph comparison at Outfall 009 for the storm event with the highest observed peak flow rate on record for the September 2009 through October 2015 period (4.27 cm of rainfall with saturated soils, on January 20, 2010). The differences between the observed and modeled data over the periods of record were about 3% and 7% for total runoff volume and average flow rate, respectively.

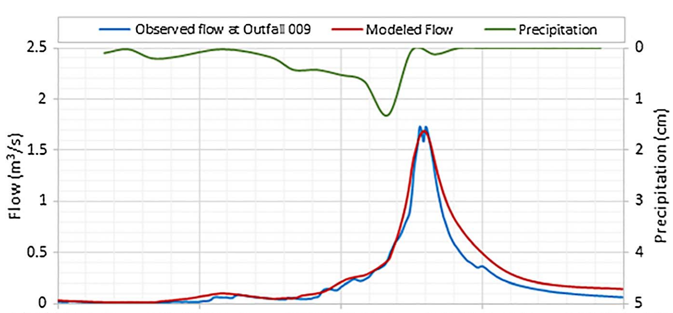

Fig. 1. Runoff hydrograph observed versus modeled comparison for Outfall 009 (largest peak flow on record).

Maintenance

Maintenance is necessary to ensure the continued satisfactory operation of stormwater controls. The many stormwater controls and ancillary activities on the SSFL site are routinely inspected and repaired as needed. Every year, the accumulated sediment amounts are calculated based on the monitored influent and effluent TSS concentrations and the SWMM calculated flows as part of the annual performance report. In addition, inspections are made about three days after each rain to note any extended ponding or evidence of overflows. The culvert modification CM-1 was rebuilt during the 2018 summer based on these observations and calculations. The other media filters are expected to have 2 to 20+ years of useful media life remaining. The end of the media life is therefore determined based on several indicators: (1) standing water more than several days after the end of the rain, indicating slow media treatment flow rates; (2) the accumulation of sediment on the media based on the measured retention of sediment and calculated flows; (3) breakthrough pollutant concentrations in the effluent, similar to influent concentrations; or (4) a distinct decrease in performance indicated by poorer quality effluent compared to previous events.

Routine maintenance needs are determined on inspections after each rain. Maintenance activities include erosion and sediment control in the watershed areas, along with drainage channel stabilization inspections and the removal of sediment and debris from outfalls following extreme storm events. Additional maintenance is conducted at the stormwater controls, including debris removal, the stabilization and repair of embankments, and the replacement of damaged vegetation in the biofilters. Improvements are also carried out at the stormwater controls, as described in the following examples:

- The B-1 media filter was modified with curb cut inlets along the adjacent road to allow additional runoff to be treated by the media filter. The modifications were made between the April 11–November 17, 2012, sampling dates.
- Excess water was seen to seep between the weir board slats after the first year or two of monitoring at the culvert modifications. Therefore, the weir boards were wrapped with filter fabric to reduce the seepage and capture larger particulates. These modifications were made between the December 12, 2011–January 23, 2012, sampling dates.
- Improvements at CM-9 were made between the March 15–October 5, 2011, sampling dates. These included diverting adjacent road runoff to flow as sheetflow over a wide vegetated area above the ponded area and enlarging the ponded area above the media filter.

Water quality data are available before and after these improvements at these three locations, and statistical analyses were therefore conducted to identify any changes in performance (results are presented subsequently in the analyses section of this paper).

Methodology and Monitoring Efforts

Stormwater samples were manually collected at influent and effluent locations of the distributed stormwater controls once per event after flows were well-established. The paired influent and effluent concentrations were then compared to evaluate concentration

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reductions. Annual performance reports are submitted to the California Regional Water Quality Board, Los Angeles region, which contain detailed descriptions of the site and stormwater control effectiveness. These reports are available online (Pitt 2018).

The following lists the laboratory methods used for the analyses evaluated in this paper (the same methods as used for the NPDES reporting at SSFL):

- 40CFR136A (EPA 2013)1613B dioxins and furans (HRGC/HRMS, or rather, high-resolution mass spectrometry with high-resolution gas chromatography), with separatory funnel and Soxhlet sample extraction and concentration for dioxin and furans,
- EPA 200.8 metals (ICP/MS, or rather, inductively coupled plasma/mass spectrophotometry), with total recoverable metals digestion,
- EPA 245.1 mercury (CVAA, or rather, cold vapor atomic absorption spectrophotometry), and
- Standard Methods (AWWA 2017) 2540D total suspended solids.

The number of samples per culvert modification (CM) ranged from 10 to 29 influent and effluent sample pairs for TSS and 0 to 29 pairs for dioxins, copper, and lead for 2011/2012 through 2017/2018 for each of the five CM sites (constructed in 2009) discussed in this paper. Influent grab samples were collected at these locations from the flowing surface water upstream of the maximum extent of ponding at each CM. All sampled CMs include a media filter and a slip-line high-density polyethylene (HDPE) lining through existing galvanized corrugated metal culvert pipes with the exception of B-1, which is a media bed with no slip-line element. Effluent grab samples at CM-1, CM-9, and B-1 were collected from the underdrain outlet (beginning in October 2011, rather than the culvert outlet), while other CM effluent grab samples were collected at the culvert outlets on the downstream side of the road, where the culvert pipes discharge to the Northern Drainage. Flows from the culvert outlets represent treated runoff (via sedimentation and media filtration), blended with partially treated runoff (flowing through or over the weir boards) during periods of high flows that exceeded the treatment flow rates of the media filters. However, only two effluent samples (at CM-1 and CM-9) were noted as occurring during overflowing conditions during the monitoring period.

Performance samples for the lower lot biofilter (construction completed in 2013) were collected in the cistern discharge pipeline, the midpoint samples were collected at the sediment basin outlet box, and effluent samples were collected from the discharge of the biofilter effluent pipe. There are 24 total sample pairs associated with the lower lot biofilter system.

The expendable launch vehicle (ELV) treatment train (located at a historical NASA launch vehicle research area), constructed during the 2013/2014 reporting year, included paired data from 10 events. The media bed for this system appears to have flushed fines during the first sampling event during the 2013/2014 sampling period. During this event, the ELV treatment train was also heavily loaded by sediments eroded from the denuded ELV channel prior to the implementation of subsequent erosion control improvements. Influent samples were collected from the influent pipe, midpoint samples were a composite of samples from the eastern and western sample ports between the settling tanks and media filter, and the effluent samples were collected from the effluent pipe from the middle tank, which contained the media filter.

The B1436 detention bioswales, which were constructed in December 2014, were sampled for the first time during the 2015/2016 reporting year. Influent samples for the southern detention bioswale were collected from both the east and west portions of the concrete swale diverting sheetflow into the rock crib, and effluent samples were collected from the underdrain. Influent samples for the northern detention bioswale were collected from the curb cut along the east side of the bioswale, and effluent samples were collected from the bioswale underdrain. Paired influent and effluent performance data were collected during 16 events at the southern detention bioswale. Samples were also collected at both the influent and effluent locations of the northern detention bioswale during eight events during the 2015/2016 and 2016/2017 reporting years.

The upper lot media filter was completed on May 16, 2017. Eight samples were collected during the 2016/2017 reporting year but only at the influent location. Paired samples were collected for the first time at the upper lot media filter during 2017/2018 (for two events).

During the December 2009 through March 2018 period covered by this paper, the site rainfall was highly variable (16 to 58 cm, or 6.1 to 23 in., and 4 to 14 rain events per year), with corresponding varying numbers of available samples (17 to 150 per year). The average annual rainfall during the years with samples was 33.3 cm (13.1 in.), compared to the long-term average rainfall of 42.7 cm (16.8 in.). Influent and effluent samples were collected during all events that had observed flows at influent and effluent locations, for a combined 225 total events for the 10 stormwater control locations.

The data analyses (mostly conducted using Microsoft Excel, SigmaPlot version 14, and Minitab version 18) described in this paper, and included in the supporting information, focus on evaluations of trends of effluent concentrations with time. Basic statistical summaries of influent and effluent concentrations, concentration reductions, filterable fractions of the metals, and particulate strengths of the metals and dioxin, by control measure category were initially conducted to describe the stormwater characteristics and performance of the stormwater controls, as these characteristics may affect effluent quality trends. Performance analyses included grouped log-normal probability plots of influent and effluent concentrations, using Anderson-Darling test statistics for normalcy, for grouped stormwater control types, and line plots illustrating concentration trends between unit processes in treatment systems. Comparisons of paired influent versus effluent concentrations using a nonparametric Wilcoxon Signed Rank test were also conducted to identify which constituents and control types resulted in significant differences between influent and effluent concentrations.

Comparisons of influent concentrations and statistical groupings between locations were tested using nonparametric Kruskal-Wallis one-way analysis of variance on ranks, all pairwise multiple comparison procedures using Dunn's method, and associated grouped box and whisker plots. Full factorial analyses (Box et al. 1978) of influent concentrations for selected control locations were conducted to identify significant factors and interactions of rain characteristics affecting pollutant concentrations and how they may change with time and use of the treatment systems. Paired influent and effluent concentrations were examined to identify significant regression coefficients and models (using ANOVA) to calculate effluent concentrations for given influent concentrations. Standard residual analyses (Draper and Smith 1981) of significant regression equations were then conducted to identify differences between stormwater controls within a grouped set and to identify residual trends with time.

Based on the preceding analyses, it was clear that the effluent concentrations were significantly related to the influent concentrations. Therefore, trend analyses focused on both influent and effluent concentration changes on the site with time. Particulate strengths of the influent and effluent particulates in the stormwater were also examined using regression analyses with ANOVA to identify significant trends with time.

Additional analyses to support the concentration trend analyses included calculations of accumulative sediment in the stormwater controls with time to identify maximum equilibrium loadings for comparison to the maximum loadings determined during the earlier laboratory tests (Pitt and Clark 2010; Pitt et al. 2021). Also, improvements were performed on some of the stormwater controls during the monitoring period. Therefore, comparisons of pre and postimprovement water quality were conducted using nonparametric Mann-Whitney tests, regression residual analyses, and probability plots to identify changes in water quality associated with the major maintenance operations and improvements.

Findings

The regulated NPDES outfalls on the SSFL site are monitored for many constituents for each flow-producing event, including solids and particle sizes, heavy metals, organic solvents, radionuclides, and many major ions and other organic compounds. In recent years, the outfall stormwater water quality has improved (based on decreasing violations in numeric effluent limits). However, periodic exceedances occur for dioxin (TCDD, TEQ no DNQ, Tetrachlorodibenzo-*p*-dioxin, toxicity equivalence, and detected not quantifiable excluded) and total lead. Infrequent benchmark exceedances of iron and pH have also occurred. The performance monitoring at the stormwater control locations focuses on a shorter list of constituents, including TSS, dioxin, total and filtered copper, total and filtered lead, total and filtered cadmium, total and filtered mercury, particle size distribution, conductivity, pH, temperature, and turbidity. These constituents are evaluated in this paper, especially examining any potential trends in effluent quality during the multiple years of operation of these stormwater controls.

Additional information with the appendices containing data and extended statistical analyses and plots are available on the SSFL surface water website found in the study by Pitt (2020). The appendices are as follows:

- 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 comparisons of laboratory column tests compared to full-scale field monitoring;
- Appendix E. Performance regression equations from laboratory column tests and full-scale stormwater treatment facilities;
- Appendix F. Influent and effluent concentration trends with time; and
- Appendix G. Particulate strength trends with time for Santa Susana Field Lab Stormwater Controls.

Appendices F and G are most relevant for this paper examining effluent concentration trends at the stormwater controls and are discussed in the following sections. Appendices A through E summarize the basic data and performance of the controls and are discussed in the associated paper that compares the initial laboratory measurements with the full-scale performance data (Pitt et al. 2021). SSFL stormwater control performance data are also included in various reports that are submitted annually to the Los Angeles Regional Water Quality Control Board and are also available on the Boeing SSFL web page noted previously.

Influent Concentration Differences by Location

Comparison analyses of SSFL influent stormwater concentrations for the different control locations in areas that had industrial activity or extensive buildings or roads were conducted to verify the logical groupings of the data for the performance calculations. In most cases, effluent quality is highly dependent on influent quality. Therefore, similar influent concentrations at all the control types would reduce the influent's effects on differences in the treatment performance. Fig. 2 shows box and whisker plots for influent TSS, TCDD TEQ no DNQ, Cu, and Pb for four groups of controls: (1) B-1, CM-1, CM-9, and upper lot media filter; (2) southern and northern detention bioswales; (3) lower lot biofilter and sedimentation treatment train; and (4) ELV treatment train. CM-8 and CM-11 were not included in these analyses as they are located at background locations not having prior industrial activities or development. Of the four main constituents shown in this study, copper indicated significant differences in influent quality ($P < 0.001$) based on the Kruskal-Wallis one-way analysis of variance on ranks test. This test indicated at least one control type having influent copper concentrations being significantly different from the others. The ELV treatment train influent copper concentrations appear to be relatively low, while the lower lot biofilter influent copper concentrations appear to be relatively high. The other constituent influent concentrations had more overlapping concentration ranges with higher Kruskal-Wallis p values indicating that the differences were not statistically significant based on the number of observations available ($P = 0.08$ and 0.13).

Concentration Changes Due to Maintenance

Statistical analyses were also conducted to compare the pre and postimprovement data to identify any changes in water quality associated with the major maintenance activities and improvements. Regression model residual plots versus time of sample collection were prepared when the regression equations were developed to relate the effluent concentrations to the influent concentrations. The regression equations are presented by Pitt et al. (2021) and are also shown in Appendices D and E from Pitt (2020). Residual plots did not indicate any discontinuity in the calculated relationships corresponding to when these maintenance and site improvement activities occurred. However, it is likely that any minor discontinuities would have been obscured by the variations in the residuals. Nonparametric Mann-Whitney tests were also used to compare the pre and postimprovement influent and effluent concentrations. These are summarized in Table 2 for the constituents having observed values during pre and postimprovement periods.

Effluent concentrations are generally dependent on influent concentrations. If the influent pre and postimprovements water quality concentrations are significantly different, any observed effluent concentration changes may be due to either the influent changes and/or the improved performance of the controls. If the differences in influent concentrations are not statistically significant, statistically different effluent concentrations are likely associated with the improvements in the control. Only B-1 TCDD changes are in this latter category. B-1 TSS, C-9 Pb, and C-9 conductivity had significant differences for both influent and effluent water quality, so the effluent differences cannot be unambiguously attributed to the improvements alone. The few statistically significant differences are likely due to only having a few precontrol improvement period samples available and typical high concentration variability.

If maintenance occurred after media failure, then improved effluent water quality would be expected. However, if maintenance occurred before failure (with predicted failure occurring soon), effluent water quality improvements may not be obvious or detected. The paucity of evidence indicating improvements in water quality due to the maintenance operations at these locations is likely due to the improving trends in water quality at the SSFL monitoring locations likely associated with improved stability of soils and

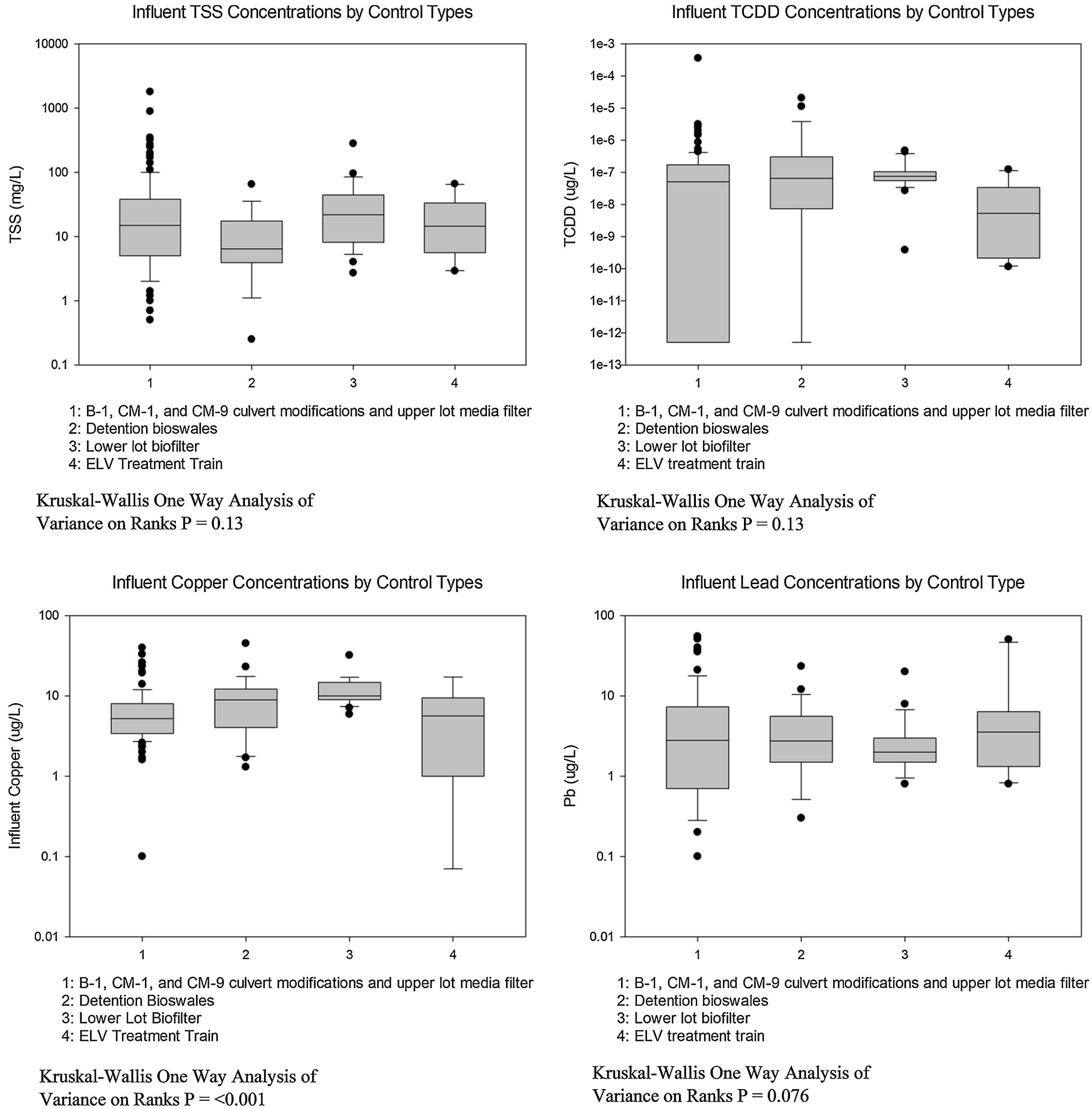

Fig. 2. Box and whisker plots of influent concentrations for different stormwater control types.

Table 2. Mann-Whitney *p* values comparing pre and postimprovement influent and effluent water quality

Constituent	B-1 influent (3 to 16 samples)	B-1 effluent (3 to 19 samples)	CM-1 influent (6 to 21 samples)	CM-1 effluent (0 to 21 samples)	CM-9 influent (13 to 25 samples)	CM-9 effluent (5 to 19 samples)
TSS	0.035[a]	0.026	0.025	0.32	0.010	0.85
TCDD	0.23	0.010	0.13	0.52	<0.001	0.098
Cu	0.39	0.47	0.039	n/a	<0.001	0.077
Pb	0.65	0.13	0.58	0.66	<0.001	0.041
Conductivity	0.91	0.44	0.002	<0.001	0.006	0.013
pH	0.11	0.60	0.015	0.18	0.018	0.44
Temperature	0.60	0.60	0.41	0.15	0.75	0.094
Turbidity	0.27	0.54	0.27	0.41	0.16	0.22

[a]*p* values <0.05 indicate statistically significant differences between pre and postimprovement water quality concentrations.

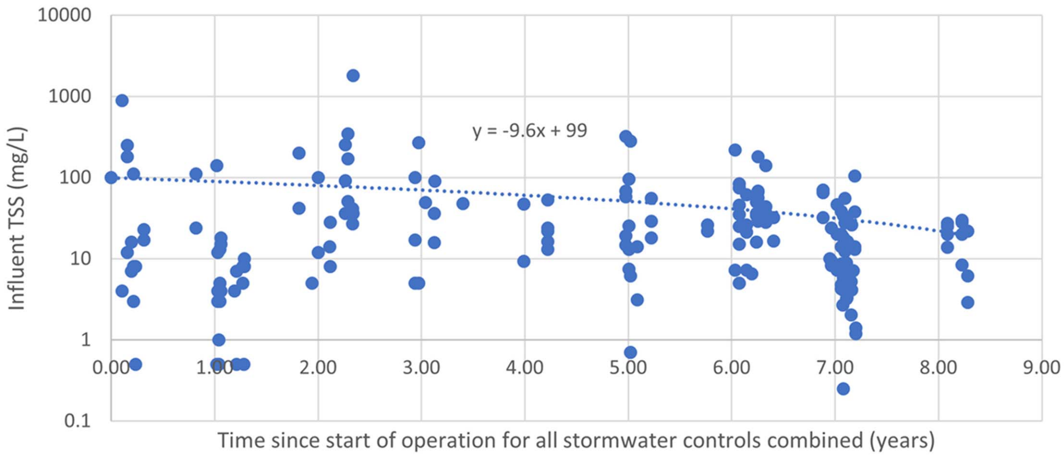

Fig. 3. Time series plot of all influent TSS data.

vegetation cover, removal of impervious areas and buildings, interim soil removal actions (ISRA) (mandated by the regional board) removal of contaminated soils, and other site restoration activities.

Influent and Effluent Concentration Trends with Time

As shown in the influent versus effluent concentration regression analyses (Pitt 2020, Appendix E), the effluent concentrations are dependent on influent concentrations for most cases. Therefore, identification of changes in effluent conditions with time due to the degradation of the stormwater controls cannot be directly detected without also considering possible changes in influent concentrations with time. For these analyses, all the influent data from locations having historical industrial activity (or significant pavement or buildings) were combined and plotted with time (CM-8 and CM-11 background data were not used). A regression analysis with ANOVA was conducted to see if the slopes of the trend lines with time were significant to identify possible changes of influent concentrations because the SSFL controls were established. Fig. 3 is the plot for influent TSS, while Appendix F [found in Pitt (2020)] contains plots and the regression statistics for the other constituents analyzed. The horizontal scale shows the years because the monitoring started at that location, while the vertical scales show the influent concentrations. Significant slope terms in the equations ($p < 0.05$) are noted on the figures and summarized in Table 3. As an example, the slope term is significant for influent TSS concentrations ($p = 0.033$), with an overall average decreasing concentration of 9.6 mg/year over the 9 years of monitoring. During this period, the influent TSS decreased by an overall average of about 85 mg/L due to changes in site conditions (i.e., interim removal of contaminated soils, erosion controls, and natural revegetation). Treatment by the stormwater controls further decreased the effluent concentrations. Other constituents with significant decreases in influent concentrations with time ($p < 0.05$) were the total Pb, conductivity, and pH, with the temperature and turbidity having marginally significant decreases ($0.05 \leq p \leq 0.10$).

Effluent concentration trends were examined for the four treatment groups separately for those constituents that did not have significant influent concentration trends. However, several of the constituents (filtered Pb, total Cd, and median particle size) had too few data observations for these analyses. Therefore, TCDD, along with total and filtered Cu, were the only constituents analyzed for effluent concentration trends for culvert modifications (having historical industrial activity), the detention bioswales, the lower lot biofilter, and the ELV treatment train. Fig. 4 is an example time series plot of the effluent concentrations of total copper for the lower lot biofilter, showing a significantly increasing concentration trend with time. Additional effluent concentration time series plots are also included in Appendix F, posted on the SSFL surface water website (Pitt 2020).

Table 4 summarizes the significant effluent concentration trends observed for these four control groups and the constituents that did

Table 3. Observed concentration trends in influent samples combined (except for background CMs)

Constituent	Significance of trend	Slope factor, if significant (all decreases)	Average overall concentration change over 9 years, if significant slope
TSS	**0.033**	9.6 mg/year	85 mg/L decrease
TCDD	0.93	—	—
Total Cu	0.78	—	—
Filtered Cu	0.35	—	—
Total Pb	**0.025**	0.72 μg/year	6.5 μg/L decrease
Filtered Pb	0.42	—	—
Total Cd	0.35	—	—
Conductivity	**<0.001**	0.025 mS/year	0.23 mS decrease
Median particle size	0.41	—	—
pH	**<0.001**	0.13 pH units/year	1.2 pH units decrease
Temperature	**0.054 (marginal)**	0.18°C/year	1.6°C decrease
Turbidity	**0.070 (marginal)**	5.9 NTU/year	53 NTU decrease

Note = Bold values signify statistically significant trends, ($p < 0.05$).

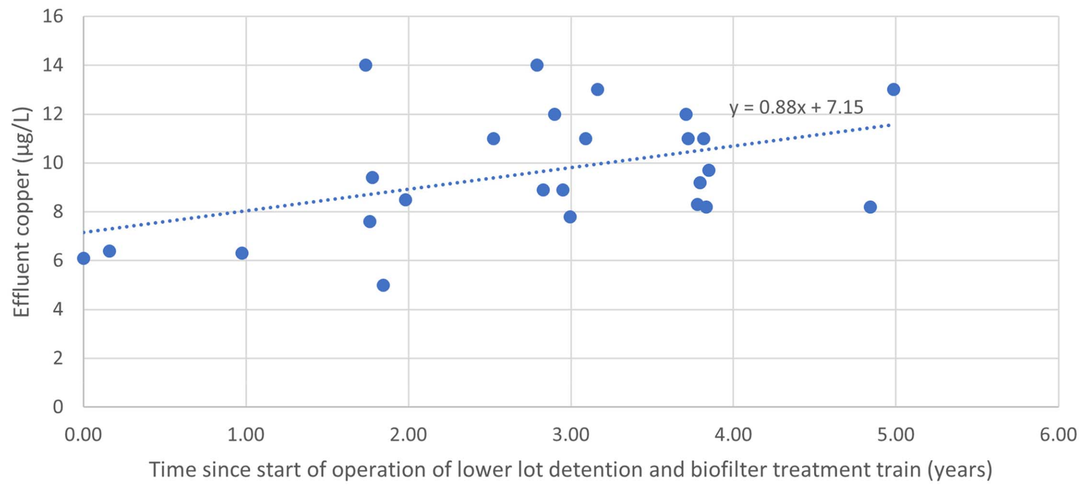

Fig. 4. Time series plot of lower lot biofilter effluent Cu concentrations.

not have any observed influent calculation trends. Although the filtered Pb, total Cd, and median particle size had too few effluent concentration observations for effluent trend analyses for each control type, they indicated no significant trends for influent concentrations when the data for all sites were combined. The culvert modifications and the detention bioswales had no observed significant effluent concentration trends. The lower lot biofilter system indicated statistically significant increasing total and filtered Cu effluent concentrations with time. The ELV treatment train indicated significant decreasing concentration trends for all three of these constituents with time.

It is not known with certainty why the lower lot biofilter indicated increasing trends in effluent copper concentrations with time (small increase totaling about 4 μg/L over 5 years), especially as the influent concentrations were not increasing. The detention bioswales had increased copper concentrations in their effluent compared to their influent (but no trends were observed). No other controls had increased copper trends in their effluent. However, both the lower lot biofilter system and the detention bioswales have a layer of topsoil as a growth media for the planted vegetation and have long media contact times. The detention bioswales also have large amounts of gravel compared to the other systems. It is possible that the copper is leached from this additional material. Similar copper increases in systems having substantial amounts of compost were previously noted at compost amended soil sites in Washington (Pitt et al. 1999) and at the Kansas City green infrastructure demonstration biofilter sites (Pitt et al. 2014). In all cases (at SSFL plus at the WA and MO locations), the copper influent stormwater concentrations were low (and below most regulatory thresholds), allowing these increases to be detected. The ELV treatment train did not have the growth media added to the media treatment mixture (no vegetation) and also had long contact times. No significant increases were noted in copper concentrations at the ELV treatment train, while significant decreases in copper concentrations were noted with time.

Therefore, it is not likely that chemical breakthrough occurred at any of the media treatment systems at SSFL during the period of monitoring; observed effluent trends were likely associated with influent trends due to changing site conditions and possibly with the leaching of copper from the topsoil growth media or underdrain material in the planted biofilters and swales having long contact times.

Table 4. Observed concentration trends in effluent samples that had no significant influent concentration trends

Constituent having no significant influent trends	Significance of trend	Slope factor, if significant	Average overall concentration change over data period
Media filters (B-1, C-1, C-9, ULMF): TCDD	0.70	—	—
Media filters (B-1, C-1, C-9, ULMF): total Cu	0.17	—	—
Media filters (B-1, C-1, C-9, ULMF): filtered Cu	0.94	—	—
Detention bioswales: TCDD	0.21	—	—
Detention bioswales: total Cu	0.72	—	—
Detention bioswales: filtered Cu	0.71	—	—
Lower lot biofilter: TCDD	0.41	—	—
Lower lot biofilter: total Cu	**0.024 (significant increasing trend)**	0.88 μg/year increase	4.4 μg/L increase over 5 years
Lower lot biofilter: filtered Cu	**<0.001 (significant increasing trend)**	1.7 μg/year increase	8.5 μg/L increase over 5 years
ELV treatment train: TCDD	**0.034 (significant decreasing trend)**	6.4×10^{-9} μg/year decrease	2.6×10^{-8} μg/L decrease after 4 years
ELV treatment train: total Cu	**0.020 (significant decreasing trend)**	1.0 μg/year decrease	4.0 μg/L decrease after 4 years
ELV treatment train: filtered Cu	**0.015 (significant decreasing trend)**	0.39 μg/year decrease	1.6 μg/L decrease after 4 years

Note = ULMF = upper lot media filter. Bold values signify statistically significant trends, ($p < 0.05$).

Particulate Strength Trends

Another indicator of treatment trends is a change in particulate strengths of stormwater particulates. Particulate strengths are the contaminant concentrations associated with the particulate matter in the stormwater. Constituents associated with large particulate sizes are more effectively retained by most stormwater controls, resulting in effluent particulate strengths being usually larger than the influent particulate strengths. This is due to the preferential removal of the larger particles generally having lower particulate strengths. The harder to control, smaller particle sizes usually have higher particulate strengths and are more abundant in the treated effluent. These values can also be compared to particulate strengths of potential source area particulates, such as eroding soil, atmospheric deposition, and pavement particulates (street dirt) to help identify the sources of the contaminants in the stormwater.

Particulate strengths are determined by calculating the pollutant concentrations only associated with the particulates (usually measured by TSS) in the stormwater. Particulate strength is calculated by Eq. (1)

$$particulate\ strength = \frac{(total\ conc. - filterable\ conc.)}{particulate\ solids\ conc.} \quad (1)$$

As an example, if the total copper concentration was 50 μg/L, the filtered copper concentration was 10 μg/L, and the TSS concentration was 150 mg/L, the particulate strength for this sample would be as shown in Eq. (2)

$$\frac{\left(50\frac{\mu gCu}{L} - 10\frac{\mu gCu}{L}\right)}{150\ mg/L} = 0.26\frac{\mu gCu}{mg\ solids} = 260\ \mu g\ Cu/g\ solids$$
$$= 260\ mg\ Cu/kg\ solids\ (also = 260\ ppm) \quad (2)$$

Table 5 shows the calculated particulate strengths for the influent and effluent stormwater at the SSFL stormwater controls. The TCDD TEQ no DNQ values were calculated assuming these compounds were all particulate bound, as they have very low filterable fractions. Few filtered concentrations were available for Hg and effluent Cd, as noted previously, so few particulate strength data are available for these constituents.

Trends of influent and effluent particulate strength with time since the start of monitoring at the SSFL stormwater control locations were examined and are shown in Appendix G from Pitt (2020) and summarized in this study. Any evidence for a breakthrough was specifically of interest. Breakthrough behavior would be indicated by abrupt changes in the effluent particulate strength values at some time in the time series, especially if the effluent values became similar to the influent values. Therefore, time series plots of particulate strengths were prepared and both visually examined and statistically evaluated for evidence of breakthrough of particulate bound pollutants. Plots were also prepared for the ratio of the effluent to influent particulate strengths with time since the beginning of the monitoring period. A breakthrough would be indicated as this ratio changed with time, especially if the ratio approaches 1.0.

Time series plots were prepared relating the concentrations of TSS and particulate strengths for dioxins (TCDD TEQ NoDNQ), copper, lead, cadmium, and mercury with time. These were plotted as a time series since the start of the monitoring period. Excel regression calculations were used to relate the particulate strengths versus time, with ANOVA to indicate if the trend equations and coefficients were statistically significant ($p \leq 0.05$).

Appendix G from Pitt (2020) contains summary tables, trend plots, and statistical analyses of these time series plots. If the ANOVA analyses of the regressions indicated significant regression equations and significant equation coefficients, those regression lines and resulting equations were plotted on the time series plots. In some cases, too few influent or effluent data were available to allow the statistical analyses. Table 5 includes the number of samples, along with the minimum, maximum, and median particulate strengths and the coefficients of variation (COV; the ratio of the standard deviation to the mean) of the particulate strengths. The tables in Appendix G [from Pitt (2020)] also include the significance of the regressions and the coefficients, along with comments.

In many cases, statistically significant particulate strength regression intercept values were observed, while the trends were not statistically significant. This would result in parallel lines representing constant (average) particulate strength values with time. No breakthrough would be evident under these conditions.

Figs. 5 and 6 are time series plots for copper for the B-1 media filter installation, and Table 6 is an excerpt of the summary table for copper at this location. This example shows that there was no significant trend in the copper particulate strengths with time in either the influent or effluent samples at the B-1 media filter. The summary table indicates overall regression and slope terms that are not significant, based on the number of samples available, while the full ANOVA did indicate significant intercept terms, represented in this study by the constant values. The time series plot shows the typical large variation in the particulate strengths with time, similar to the other examined particulate strength constituents and locations. The plot of the effluent/influent ratios of the particulate strengths with time on Fig. 6 indicates a constant but wide band with time.

No abrupt changes in the effluent particulate strengths were observed at any location for any constituent, although minor changes could be masked by data variations. In some cases, apparent parallel visual trends in the particulate strengths occurred for both the influent and effluent values (not for just the effluent values alone). These cases did not indicate breakthrough, especially as the regression and ANOVA evaluations resulted only in very small trends for both influent and effluent values.

Therefore, there was no visual or statistical evidence of breakthrough of particulate-bound pollutants at the SSFL stormwater control locations. As indicated in the laboratory studies (Pitt and Clark 2010), one of the features of the selected treatment media is that silt clogging (resulting in extended surface ponding) would occur before the pollutant treatment capacity would be exceeded or breakthrough would occur for most pollutants. This provides a factor of safety as any slit clogging of the controls would be directly indicated by extended ponding of water on the media several days after a rain before pollutant removal performance is jeopardized by media capacity failure.

Sediment Accumulation with Time

Time series plots of captured suspended solids in several of the stormwater controls were also prepared. The SWMM was calibrated using the Outfall 009 watershed data, which was then used to calculate the annual stormwater volume of each of these stormwater controls. SWMM was also used to calculate the portion of the stormwater volume that was treated by the controls and how much was bypassed during high flow periods. The suspended solids retention was calculated based on the differences between the influent and effluent TSS concentrations for each event (these were not blended samples and only included the effects of the treated flows, not the bypass partially treated flows). This TSS concentration retention was calculated for each event. These were then multiplied by the treated flow volume to obtain the mass TSS retained for each event. These were then used to calculate the cumulative suspended

Table 5. Particulate strengths for influent and effluent stormwater samples for SSFL stormwater controls

Influent location	Effluent location	TCDD inf part strgth mg/kg	TCDD efl part strgth mg/kg	Cu inf part strgth mg/kg	Cu efl part strgth mg/kg	Pb inf part strgth mg/kg	Pb efl part strgth mg/kg	Cd inf part strgth mg/kg	Cd efl part strgth mg/kg	Hg inf part strgth mg/kg	Hg efl part strgth mg/kg
CM-8 (background location)	Count	—	—	—	—	—	10	—	—	—	—
	Min	—	—	—	—	—	20.0	—	—	—	—
	Max	—	—	—	—	—	310	—	—	—	—
	Median	—	—	—	—	—	210	—	—	—	—
	COV	—	—	—	—	—	0.47	—	—	—	—
CM-11 (background location)	Count	12	12	—	—	—	—	—	—	—	—
	Min	5.26×10^{-11}	1.11×10^{-10}	—	—	—	—	—	—	—	—
	Max	1.95×10^{-08}	1.50×10^{-07}	—	—	—	—	—	—	—	—
	Median	4.17×10^{-10}	1.00×10^{-09}	—	—	—	—	—	—	—	—
	COV	1.70	2.84	—	—	—	—	—	—	—	—
B-1 media filter	Count	21	22	21	16	21	23	6	—	—	6
	Min	1.08×10^{-10}	1.85×10^{-10}	19.5	12.5	3.2	3.7	0.2	—	—	1.0
	Max	2.45×10^{-02}	1.08×10^{-05}	171	408	462	192	2.2	—	—	6.5
	Median	7.34×10^{-06}	2.25×10^{-06}	64.5	60.0	101	66.7	0.5	—	—	2.1
	COV	4.55	0.92	0.63	1.15	0.83	0.60	0.88	—	—	0.79
CM-1	Count	42	34	20	5	24	33	7	1	1	—
	Min	6.12×10^{-11}	5.71×10^{-12}	3.6	45.2	31.2	9.9	0.1	12.0	3.8	—
	Max	5.53×10^{-05}	2.46×10^{-04}	314	827	664	1,300	8.6	—	—	—
	Median	1.02×10^{-06}	2.28×10^{-07}	81.1	100	92.7	245	2.3	—	—	—
	COV	2.15	3.28	0.77	1.16	1.03	0.95	1.18	—	—	—
CM-9	Count	38	23	37	25	26	27	23	10	1	—
	Min	6.67×10^{-11}	1.00×10^{-10}	12.7	23.1	0.0	16.2	0.1	0.9	3.4	—
	Max	2.40×10^{-05}	7.13×10^{-06}	5,500	4,300	1,022	1,000	290	160	—	—
	Median	4.50×10^{-07}	1.06×10^{-08}	134	200	138	120	10.0	7.8	—	—
	COV	1.86	2.23	2.22	1.88	1.14	1.19	1.87	1.91	—	—
Upper lot media filter	Count	10	2	9	2	10	2	—	—	—	—
	Min	2.11×10^{-06}	3.21×10^{-08}	15.8	85.7	0.0	12.1	—	—	—	—
	Max	8.13×10^{-05}	1.32×10^{-05}	217	86.2	106	42.9	—	—	—	—
	Median	1.41×10^{-05}	6.61×10^{-06}	142	86.0	56.8	27.5	—	—	—	—
	COV	1.08	1.41	0.42	0.00	0.63	0.79	—	—	—	—
Southern detention bioswale	Count	17	18	16	15	16	16	16	—	—	—
	Min	4.88×10^{-07}	1.08×10^{-10}	18.2	55.6	32.7	0.0	2.4	—	—	—
	Max	9.45×10^{-04}	7.85×10^{-06}	168	1,200	245	259	16.8	—	—	—
	Median	3.71×10^{-06}	5.95×10^{-08}	110	200	108	83.9	10.1	—	—	—
	COV	3.01	2.05	0.45	1.11	0.48	0.82	0.40	—	—	—
Northern detention bioswale	Count	8	18	6	12	6	13	—	—	—	2
	Min	2.00×10^{-10}	3.70×10^{-11}	31.3	83.3	14.6	11.4	—	—	—	0.0
	Max	1.77×10^{-06}	1.12×10^{-06}	2,132	9,053	453	579	—	—	—	40.0
	Median	2.47×10^{-08}	2.82×10^{-10}	166	1,062	53.1	90.0	—	—	—	20.0
	COV	1.87	4.05	1.71	1.33	1.48	1.07	—	—	—	1.41
LLBF	Count	24	25	20	24	23	25	—	—	—	—
	Min	4.5×10^{-08}	9.1×10^{-12}	56.3	47.0	44.1	15.4	—	—	—	—
	Max	2.8×10^{-05}	6.6×10^{-06}	370.4	465.1	153.8	432.0	—	—	—	—
	Median	4.1×10^{-06}	1.3×10^{-08}	101.9	143.3	75.0	90.9	—	—	—	—
	COV	1.06	3.12	0.66	0.69	0.38	0.83	—	—	—	—
ELV	Count	10	13	6	7	9	13	—	—	—	—
	Min	2.0×10^{-08}	2.6×10^{-11}	21.1	4.0	60.5	16.7	—	—	—	—
	Max	5.6×10^{-06}	1.2×10^{-06}	253.1	48.8	287.6	133.2	—	—	—	—
	Median	2.8×10^{-07}	3.3×10^{-09}	113.2	21.4	168.1	47.2	—	—	—	—
	COV	1.58	3.38	0.69	0.69	0.34	0.55	—	—	—	—

solids load retained for each control device and plotted as time series, as shown in Figs. 7 and 8. These are conservative cumulative loading values as they do not include the accumulation of suspended solids from the partially treated bypass flows. It is expected that most of the larger particulates (probably > 50 μm based on the limited particle size data) would be captured during the ponding of the water before the excess would overflow the weir boards in the culvert modifications or overflows in the other control systems. Some of these plots show negative accumulations of solids indicating scour of previously captured material during some events (effluent TSS concentrations greater than influent TSS concentrations).

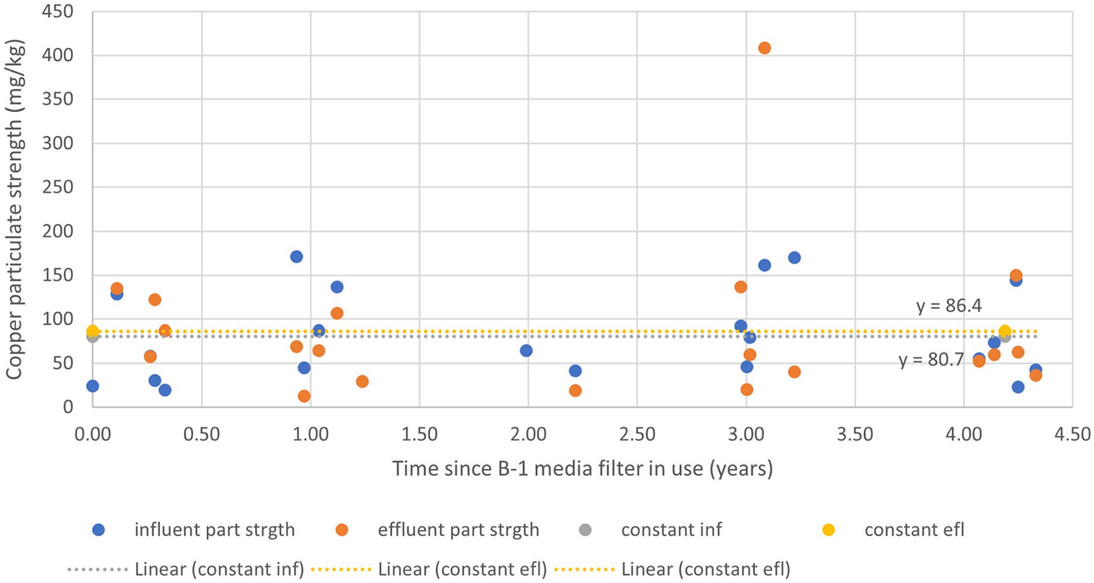

Fig. 5. Time series plot of influent and effluent copper particulate strengths for the B-1 media filter.

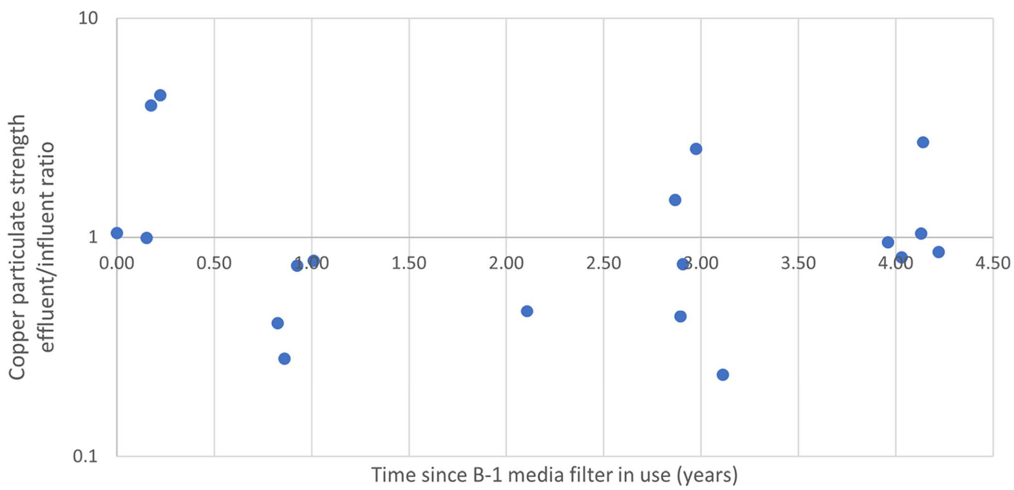

Fig. 6. Time series plot of the effluent/influent copper particulate strength ratios for the B-1 media filter.

The suspended solids accumulation for CM-1 shown in Fig. 7 indicates a large accumulation of suspended solids during the first year of operation. The accumulation then continued to increase, but at a lower rate, until about the fourth year of operation, in which it leveled off, with possible scour of material occurring during the 8th year. The apparent suspended solids accumulation capacity for this stormwater control appears to be about 20 kg/m^2 of media surface area, which was also in the range determined from the laboratory experiments for this media mixture, described by Pitt and Clark (2010) and Pitt et al. (2021). Again, this is a conservative estimate as the total loading is likely greater due to suspended solids captured during sedimentation processes with the overflowing larger flows. CM-1 was rebuilt during the summer of 2018 to remove the accumulated material and to replace the media. No data were available for the period since this rebuilding of the CM-1 when the analyses for this paper were conducted.

The sediment accumulations at the CM-9 and B-1 locations were also seen to have periodic short periods of large accumulations of suspended solids during their first and third years of operation. Both of these culvert modifications appear to be continuing to collect material after 8 years of operation, with total accumulation amounts of about 14 kg/m^2 at CM-9 and 3 kg/m^2 at B-1. With an assumed total capacity of 20 kg/m^2, CM-9 may have only a few more years of operation before needing media replacement, while B-1 may have another 20+ years of operation before media replacement. These time estimates would be affected by the highly variable rainfall occurring on the site, including several recent years of drought conditions.

The suspended solids accumulation time series for the lower lot biofilter system and at the ELV treatment train are shown in Fig. 8. These plots show accumulations for the sediment and the biofilter/filter sections of the treatment systems separately, as these controls also included a sampling port between the two-unit processes. In both cases, the total sediment accumulations in the sediment pond/tank sections were only about 1 or 2 kg/m^2 during the four years of operation. The lower lot biofilter showed only small net

Table 6. Summary table excerpt for copper particulate strength time-series trends for B-1 media filter

Control practice	B-1 media filter
Start of monitoring period	12/12/2011
End of monitoring period	2/18/2016
Monitoring duration (years)	4.2
Influent sample count	21
Effluent sample count	20
Influent median (mg/kg)	65
Effluent median (mg/kg)	61
Influent COV	0.63
Effluent COV	1
Influent regression F	0.67
Effluent regression F	0.85
Influent adjusted R^2	n/a
Effluent adjusted R^2	n/a
Influent slope P	0.67
Effluent slope P	0.85
Influent slope coefficient	n/s
Effluent slope coefficient	n/s
Comments	No obvious breakthrough, no significant slopes, no significant intercept, and no significant trend lines

accumulation changes with time in the biofilter, while the ELV showed losses of sediment material from the filter, likely due to the washout of fines from the media mixture. The washout assumption is further supported by the low contaminant-related particulate strengths of the effluent sediment, indicating media material instead of stormwater fines, which have higher particulate strengths. Recent reviews of this stormwater control indicated an inadequate separation layer between the media and the drainage layers. This is currently being corrected during the 2021 summer months.

Generally, the best performance and longest life are expected for relatively large stormwater controls compared to the drainage areas. Depending on the influent TSS concentration, large ratios of the media surface area to the drainage area results in a lower unit area sediment deposition on the media, prolonging their useful life before clogging. The contact time of the stormwater with the treatment media is dependent on the rate of the stormwater passing through 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 to 0.5 for the selected media). This results in media contact times of about 10 to 30 min, in the absence of additional outlet controls. If the media bed is larger and the effluent flow rate is restricted with outflow controls, the contact time can be increased while still treating the same volume of stormwater in the same time period (but requiring a larger footprint for the control). The large lower lot sediment pond and biofilter treatment train have an approximate media contact time of about 2 h; the large detention bioswales 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 within the coarse gravel layer; and the culvert modifications have media contact times of about 10 to 30 min. These different contact times generally result in different levels of performance of the stormwater controls, especially for fine particles and filtered pollutants. Pitt et al. (2021) showed that media footprints of about 0.1% of the drainage area resulted in about half of the annual flows being fully treated, while about 0.4% was needed to provide full treatment of about 75% of the annual flows, and >1% was necessary to fully treat about 90% of the annual flows for the SSFL site and rain conditions. CM-1, the first media treatment system rebuilt due to clogging, has a media treatment area to drainage area ratio of only 0.001% to 0.002%, the smallest of the site controls. CM-9, the control with only a short useful life remaining, has a media treatment area to drainage area ratio of only 0.007%, the second smallest treatment area to drainage area ratio for the controls. The culvert modifications were installed early in the process in 2009 and 2010 before data were collected and analyzed, as these could be installed quickly and at relatively low cost. They were sized based on the available area at the culvert road crossings, with the understanding that they were treating larger drainage areas than desired for optimal performance. CM-9 has undergone several phases of enhancements, and CM-1 was recently rebuilt. These data show that small stormwater treatment facilities compared to their drainage areas require increased maintenance and more frequent repairs and media replacements. As noted previously, the analyses of the constituent time series equations did not indicate any breakthrough of constituents during the monitoring period. One of the features of the media testing and selection was that the sediment accumulation would cause clogging well before the breakthrough of the constituents of concern, making needed media replacement obvious.

Summary of Statistical Analyses

A series of different data analyses, as described previously, comprise the weight of evidence pertaining to trends with time in the performance of the stormwater media treatment controls at SSFL. The following is a summary of the findings from the statistical analyses:

- TSS, dioxin, Cu, and Pb influent concentrations were compared for the different stormwater controls. These analyses indicated that at least one control type had influent copper concentrations significantly different from the others. The ELV treatment train influent copper concentrations appeared to be relatively low, while the lower lot biofilter influent copper concentrations appeared to be relatively high. The other constituent influent concentrations had more overlapping concentration ranges, and the statistical tests indicated that the differences were not statistically significant for the different controls for the amount of data available. Therefore, any effluent differences were not likely to be associated with differences in influent quality, although extra caution is needed when interpreting copper results.
- Statistical analyses were also conducted to compare pre and postmaintenance and improvement data to identify any changes in water quality. There was a lack of evidence indicating changes in effluent water quality due to the maintenance operations. This was likely due to maintenance being conducted before failure that would have resulted in degraded effluent conditions.
- The constituents with significant decreases ($p \leq 0.05$) in influent concentrations with time were TSS, total Pb, conductivity, and pH, with temperature and turbidity having marginally significant ($0.05 < p \leq 0.1$) decreases. No increasing trends in effluent quality with time were identified at any of the locations or constituents, except for total and filtered copper at the lower lot biofilter system. It was not likely that chemical breakthrough occurred at any of the media treatment systems at SSFL during the period of monitoring; observed effluent trends were likely associated with influent trends due to changing site conditions (contaminated soil removal, removal of impervious areas, and erosion control, for example) and possibly with the leaching of copper from the topsoil growth media or underdrain material in the planted biofilters and swales having long contact times.
- Another indicator of treatment trends is a change in particulate strengths of stormwater particulates with time. There was no

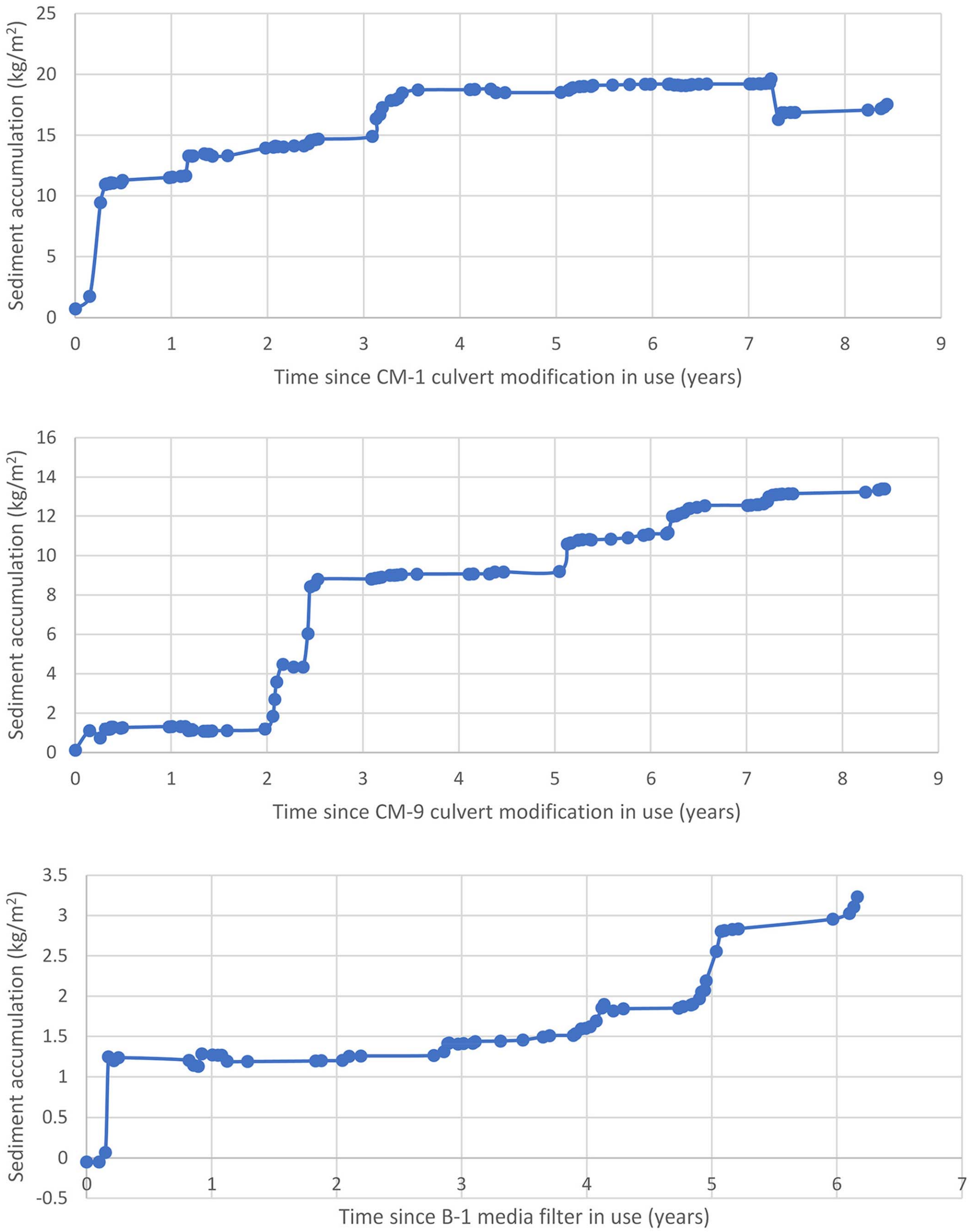

Fig. 7. Time series of sediment retention in SSFL culvert modification stormwater controls.

visual or statistical evidence of breakthrough of particulate-bound pollutants at the SSFL stormwater control locations when examining particulate strength behavior.

- Time series plots of captured suspended solids in several of the stormwater controls were also examined to detect loads associated with media clogging. Depending on the influent TSS concentration, large ratios of the media surface area to the drainage area result in a lower unit area sediment deposition on the media, prolonging their useful life before clogging. The apparent suspended solids accumulation capacity for the stormwater controls appeared to be about 20 kg retained TSS/m^2 of the media surface area, which was in the range determined from the laboratory experiments for this media mixture. These data show that small stormwater treatment facilities compared to their drainage areas require increased maintenance and more frequent repairs and media replacements.

Practical Applications

The data from the long-term monitoring of the stormwater controls at SSFL supplements the data from the few other long-term stormwater control monitoring efforts available in the literature. The objective of this paper was to examine the performance of the SSFL stormwater controls over several years to identify changes in their performance and to identify indicators of failures and needed maintenance. The following lists some of the practical applications of the findings from these analyses:

- Prolonged life of media filters is possible with suitable designs. At SSFL, media filter areas of about 0.5% of the drainage area were shown to have several decades of useful life before clogging, while very small media filters ($\ll 0.1\%$) were found to clog after only several years of use, especially in the absence of effective pretreatment. Media footprints 0.1% of the drainage

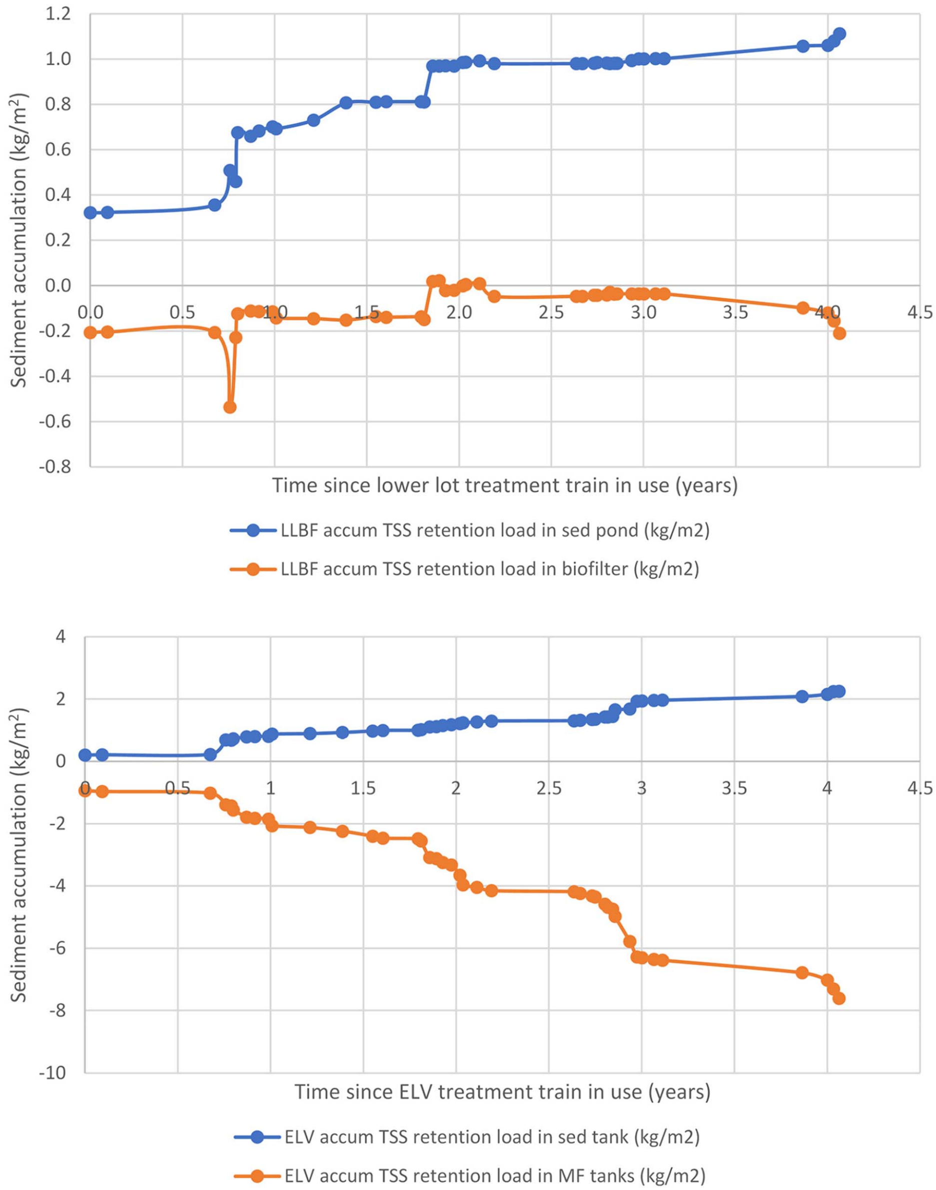

Fig. 8. Time series of sediment retention in SSFL lower lot biofilter system and ELV treatment train stormwater controls.

area resulted in a full treatment of about half of the annual flows; media footprints of about 0.4% of the drainage area resulted in a full treatment of about 75% of the annual flows; and footprints >1% resulted in a full treatment of about 90% of the annual flows. Obviously, the findings for these media to drainage area ratios are highly dependent on the site and rain characteristics. The impervious covers (pavement, roofs, and massive rock outcrops) of the drainage areas for the SSFL controls ranged from about 22% to 53%. The average annual rainfall during the monitoring period was highly variable, ranging from 16 to 58 cm (6.1 to 23 in.), and averaged 33.3 cm (13.1 in.), with 4 to 14 rain events per year.

- The life of the stormwater controls was enhanced with efforts to reduce the amount of sediment to the media filters. All the SSFL distributed stormwater controls included treatment trains incorporating pretreatment by sedimentation before the treatment media. Watershed surveys are also periodically conducted to identify and repair areas of erosion to minimize the delivery of sediment to the controls.
- The initial laboratory tests used to test and select the media for use at SSFL found that siltation and clogging of the media occurred before chemical breakthrough for most of the pollutants of concern. This may vary for other media mixtures. Failure indicators can therefore be used to identify when the media needs replacement. Standing water on the media for extended periods after the end of the rain was the most obvious indicator of clogging. The accumulative loading of sediment on the media can be calculated by using influent and effluent particulate monitoring data in conjunction with treatment flow values. Tracking these loading values with time was found to be useful to predict the remaining useful life of the media before clogging.

Conclusions

Stormwater biofilters and bioretention controls have been extensively studied and are commonly encouraged as effective stormwater controls. However, there is remaining uncertainty concerning their long-term performance and required maintenance needs. Although they have been extensively studied, most monitoring efforts have been of short duration, with only a few in the International Stormwater BMP Database having monitoring periods longer than four years, with maximum study durations of about seven years, for example. The literature includes many laboratory studies that have investigated the failure mechanisms of media-based stormwater controls. In all cases, clogging by accumulated sediment was found to be critical. However, few studies have been of sufficient duration to quantify this clogging at field installations. The information in this paper illustrates how other locations can be evaluated to better estimate useful life before required maintenance to make decisions on the sizing of biofilters and bioretention control practices and to design pretreatment to extend maintenance intervals.

Many statistical analyses were conducted to identify and quantify changes in the performance of these stormwater controls with time, stressing effluent quality for the critical constituents of concern. Some effluent concentration trends were observed for some of the controls that did not have any influent concentration trends. These included the lower lot sedimentation/biofilter system that had statistically significant and consistent increases in effluent total and filtered Cu concentrations with time. These Cu increases may be due to the leaching of topsoil growth media used to support the vegetation due to the long contact times of stormwater, as observed during prior monitoring. However, the resulting effluent Cu concentrations were low, and the increases would not likely be observed at sites having typically higher influent Cu concentrations. The ELV sedimentation/media filter treatment train had significant decreases in total and filtered effluent concentrations for many constituents compared to influent concentrations, indicating improving performance with time; although, increased TSS was observed in the effluent, likely due to a washout of fines from the treatment media. The ELV treatment train also had significantly decreasing effluent concentrations with time for TCDD and total and filtered Cu, in the absence of significant influent concentration trends for these constituents. Therefore, it is not likely that chemical breakthrough occurred at any of the media treatment systems at SSFL; effluent trends were likely associated with influent trends due to changing site conditions. Particulate strength trends of influent and effluent samples also did not indicate any significant changes with time, supporting the lack of breakthrough of fine particulates during the monitoring period.

The accumulative suspended solids loading in several of the controls was calculated based on calibrated SWMM runoff volume calculations and the measured TSS concentration changes with treatment. The ELV and lower lot sediment pond/biofilter treatment trains have intermediate sampling locations that enabled accumulative suspended solids calculations in the media treatment sections alone. The accumulative solids calculations for the other controls do not separate the sedimentation removals from the media removals. The CM-1 culvert modification was observed to have ponded water after rains longer than desired and to bypass flows more frequently than others. This location had a total sediment accumulation of about 20 kg/m^2 of media area, reached after about 3 1/2 years of operation, and held steady for about the following 5 years. Based on visual observations of ponded water after events and accumulation calculations, this stormwater control was rebuilt during the 2018 summer with new media. This control was the first installation on the site, and filter fabric was used as a silt barrier above the media. However, it was soon realized that the fabric was silting and not allowing the stormwater to pass through the media. This was then corrected soon after construction, and the newer installations do not use filter fabric barriers. The other controls are likely to have from 2 to 20+ more years before they reach this sediment accumulation level based on the average annual sediment loading rates at the site. Continued monitoring and observations at the individual controls will be used to track future maintenance needs.

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 performance data and associated appendices for this paper are available online: http://www.boeing.com/assets/pdf/aboutus/environment/santa_susana/water_quality/tech_reports/Supporting_Information_Pitt_2020.pdf.

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