

# Assessing the performance of sand filter basins in treating urban stormwater runoff

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**Abstract** This study has assessed the efficiency of sand filter basins in treating urban stormwater runoff by analyzing available data in the literature, the International Stormwater BMP Database, and data collected in a sand filter basin located in the main campus of the University of Texas at San Antonio (UTSA). Ten storm events were monitored starting in March 2016 until February 2017. Total suspended solids, volatile suspended solids, nitrate, ortho-phosphate, copper, zinc, lead, pH, and conductivity were measured in the inlet and the outlet of the basin.

Statistical analysis, including linear regression modeling, scatter plotting, and non-parametric testing, using data from the literature and the International Stormwater BMP Database was performed. The sand filter basin removed, on average, 94% and 86% of TSS and VSS, respectively. Such high removal rates were not observed for other constituents, with exception of lead (79%) that already showed a low mean concentration in the inlet of the basin ( $41.47 \pm 27.41 \mu\text{g/L}$ ). Nitrate and ortho-phosphate mean concentrations were not significantly different in the outlet than inlet. The basin effluent concentration of zinc was higher than acceptable stormwater benchmarks defined by EPA. The results indicated that the monitored sand filter basin met its primarily design criteria, which is TSS removal by at least 80% of mass. Better stormwater treatment practices, however, are needed to remove other pollutants more efficiently, in particular, because this area is located on top of the recharge zone of the Edwards Aquifer, a major source of water supply for the region.

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## Introduction

Urban development has had adverse impacts on both surface and groundwater quality and quantity (Hammer 1972; Hollis 1975; McCuen 1979). The change of natural land cover to impervious surfaces such as roads, parking lots, rooftops, and sidewalks, typical in urban areas, decreases water quality by concentrating

pollutants, such as sediments, nutrients (Kayhanian et al. 2012), bacteria, heavy metals (US EPA 1993), and increasing temperature (Jones and Hunt 2009; Wardynski et al. 2014). Urbanization also increases the volume of surface runoff and decreases infiltration rates during storm events, reducing the recharge of groundwater aquifers (Hejazi and Markus 2009). Moreover, urban drainage infrastructure is designed to remove excess runoff from the surface, which concentrates flows and alters the timing characteristics of the flow regime while reducing important base flow in streams. The effects include higher runoff volumes and faster and higher peak flows, which can cause downstream flooding, and loss of property and life (Fang et al. 2014; Sharif et al. 2014), erosion (Booth 1990), and habitat degradation (Booth and Jackson 1997) especially in intermittent or ephemeral streams (Levick et al. 2008). The adverse impacts of urbanization are especially dangerous in areas located on top of recharge zones of karst aquifers. Approximately 15% of the contiguous USA has limestone or other carbonate rock formations (Peck et al. 1988) and, therefore, are vulnerable to contamination from urban stormwater.

The mitigation of the some of the negative impacts of urbanization is the goal of stormwater Best Management Practices (BMPs). One of the most commonly adopted BMPs in the USA, especially in arid and semi-arid regions, are sand filter basins, which are stormwater controls that collect and filter runoff through a bed of sand (TCEQ 2005). Pollutants in runoff are treated through the processes of settling, filtration, and adsorption. The typical design criteria of sand filter basin is to remove a certain percentage of total suspended solids (80% of TSS for instance). The removal efficiency for other pollutants, such as metals and nutrients, can be moderate and often low. Sand filter basins can also provide peak flow attenuation of small-to-medium storm events. Some of the advantages of sand filter basins with respect to other BMPs are (1) it requires less land; (2) it is applicable in arid climates; (3) it provides high TSS mass removal; and (4) it is easy to inspect. Some of the limitations of sand filter basins include (1) poor water quality treatment for dissolved pollutants; (2) it can require more maintenance than other controls; (3) high solids loads can cause clogging; and (4) poor esthetic and safety performance (Dorman et al. 2013).

Several studies have evaluated the treatment performance of sand filter basins (Barrett 2010, 2003, 2005;

Birch et al. 2005; Kandasamy et al. 2008), most of them performing assessments of individual BMPs operating under limited number of rain events. For instance, Barrett (2003) investigated the performance, cost, and maintenance requirements of five Austin-style sand filters built in Los Angeles and San Diego that treat stormwater generated over maintenance yards and park-and-ride facilities. In a follow-up study, Barrett (2005) proposes a methodology using linear regression to calculate a BMP's pollutant removal ability. This method is proposed because the reduction in pollutant concentration is highly affected by the influent concentration, and misrepresented reductions can be generated when influent concentration are low. Birch et al. (2005) monitored seven rain events over one infiltration sand filter basin located in a suburban area in eastern Sydney (Australia) to assess treatment efficiencies in removing total suspended solids (TSS), nutrients, trace metals, organochlorine, and fecal coliforms. Kandasamy et al. (2008) performed similar assessment to test the removal efficiency of a double-cell sand filter (one cell with fine sand and another cell with coarse sand) during an 18-month monitoring campaign. Seven events were sampled, and influent and effluent concentrations were analyzed and compared to data found in the literature. In a more comprehensive study, water quality data collected in five sand filter basins located in the City of Austin between 1985 and 1997 were analyzed (Barrett 2010). The water quality parameters total suspended solids (TSS), volatile suspended solids (VSS), total phosphorus, dissolved phosphorus, total Kjeldahl nitrogen, nitrate plus nitrite, fecal coliform, fecal streptococcus, biological oxygen demand (BOD), chemical oxygen demand (COD), zinc, copper, and lead were analyzed. The analysis included determining the distribution of the data, plotting influent and effluent EMCs, calculating the removal reduction, displaying how concentrations fluctuate during storm events, and relating discharge inflows with influent concentrations and residence time.

Another large body of water quality data of sand filter basins and other stormwater BMPs can be found in the International Stormwater BMP Database ([www.bmpdatabase.org](http://www.bmpdatabase.org)), which is an online database containing performance analysis results obtained for over 500 BMP studies around the world (Clary et al. 2011). The purpose of this database is to provide scientifically sound information to improve the selection, design, and overall performance of stormwater BMPs.

The International BMP Database includes data of biofilters, bioretentions, detention basins, green roofs, infiltration basins, media filters, percolation trenches, porous pavement, retention ponds, wetland basins, and channels. The database contains influent and effluent concentrations of several sand filter basins operating under a range of pollutant loads and climate conditions (Barrett 2008).

The main goal of the present article was to assess the performance of sand filter basins in treating stormwater runoff generated over a large parking lot. To achieve this goal, two main steps were performed. First, the treatment performance of a sand filter basin located in the main campus of the University of Texas at San Antonio (UTSA) was evaluated. The selected sand filter basin-treated storm water runoff generated primarily over a parking lot built in the early 1970s. Ten storm events were monitored from March 2016 to February 2017. Rainfall, inflows, and outflows were measured, and water samples were collected for laboratory analysis of the following water quality parameters: TSS, VSS, nitrate, ortho-phosphate, copper, zinc, lead, pH, and conductivity. Second, data from 30 sand filter basins available in the literature and in the International Stormwater BMP Database were analyzed to provide an overview and comparison of the treatment performance of this type of BMP.

## Methods and data

### Site description

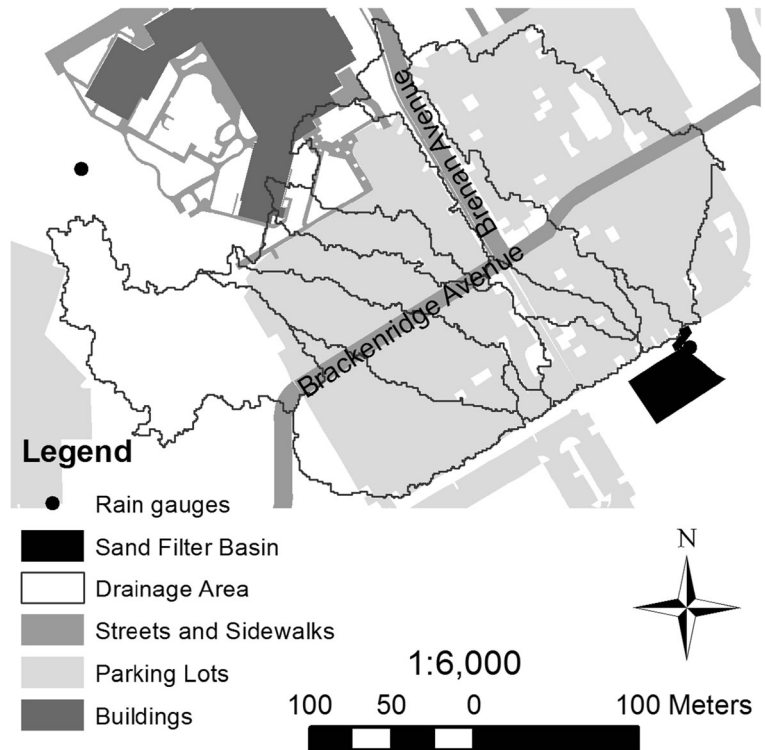
The main campus of UTSA is located north west of the City of San Antonio and lies on top of the recharge zone of the Edwards Aquifer. The Edwards Aquifer is a karst formation, which extends over 180 miles along the southern and eastern edges of the Edwards Plateau (Roos and Peace 2015) and supplies fresh water for more than two million people in South-Central Texas. The Edwards Aquifer is a very prolific source of water and, due to its geological formation, is very vulnerable to reduced recharge and contamination from stormwater runoff, wastewater, industrial leaks and spills, and non-point sources such as agriculture fertilizers and pesticides. The southern portion of the Edwards Aquifer is also the main source for three major springs: Barton, San Marcos, and Comal springs. San Marcos and Comal

springs supply water to the Guadalupe River and provide a habitat for several animal and plant species, many of them listed as endangered species according to the US Endangered Species Act (United States Congress. Senate. Committee on Commerce 1973). Due to increasing water demands in the region of South-Central Texas and the prolonged periods of droughts registered in the last years, the Edwards Aquifer is under extreme pressure.

The UTSA main campus currently operates seven sand filter basins. In this project, the sand filter basin no. 3 (latitude 29° 34' 46.7", longitude -98° 37' 12.7") was selected for monitoring (Fig. 1). The volume of the basin is approximately 1953 m<sup>3</sup> (69,000 ft<sup>3</sup>), and it receives stormwater generated during storm events from a drainage area of approximately 6.5 ha (16 acres) which includes Brackenridge parking lot, Brackenridge and Brenan Avenues, and a natural area. During 5 months, the sand filter basin received substantial amounts of sediment produced in a construction site located behind the UTSA Recreational Center, where a swimming pool was being built. A site survey conducted in July 2016 observed a layer of fine sediments and soils deposited on the top of the sand layer, which increased the system's residence time. After July 2016, some of the thin sediment layer was scraped and the residence time of the sand filter was decreased. Moreover, Brenan Avenue was rebuilt and the Brackenridge parking lot was seal-coated between the months of May and June 2016.

Stormwater enters this basin through a 4.57-m (15 ft)-wide inlet concrete channel that discharges into a pre-treatment chamber (area, 70 m<sup>2</sup> (753 ft<sup>2</sup>) and volume, 116.9 m<sup>3</sup> (4128 ft<sup>3</sup>)) that retains coarse sediments and debris. Water runs through a gabion basket screen into the main chamber that contains a 0.4-m (1.3 ft) layer of typical silica-based sand (area, 795 m<sup>2</sup> (8557 ft<sup>2</sup>) and volume, 127.2 m<sup>3</sup> (4492 ft<sup>3</sup>)). On top of the sand, there is a pond storage volume of 1709 m<sup>3</sup> (60,353 ft<sup>3</sup>). After water is filtered through the sand layer, it enters into a perforated pipe collection network which releases the treated effluent downstream. The effluent enters a vegetated swale and reaches creeks that feed into the Leon Creek. Once the sand filter basin is full, the excess inflows are diverted through a 7.62-m (25 ft) bypass weir located at the right of the system. Figure 2 shows the sand filter basin's main components and schematics.

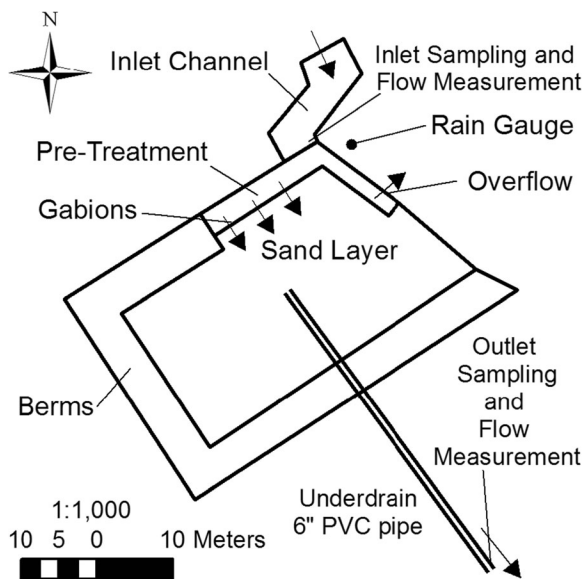
**Fig. 1** Location of sand filter basin no. 3, drainage area, and impervious cover



Data collection

Rainfall, temperature, flow discharge, storage depth, and water samples were collected from March 2016 to February 2017. Two ISCO Signature flow meters

with ISCO 3700 auto-samplers and solar panels were installed in the inlet and outlet of the basin. The inflow discharge rate was estimated using depth of flow measured inside the inlet channel by a tube attached to a side wall. A modified Manning’s equation was initially used to calculate flow discharge. The inflow data was further validated and corrected based on total volumes (the total inlet volume is approximately equal to total outlet volume because the sand filter basin has an impermeable liner (no infiltration) and the evaporation volume is relatively small in comparison to the inflow volumes). This correction was necessary because the inflow channel is not straight and is short and relatively wide (bottom width is 4.57 m (15 ft)). These characteristics are likely to invalidate the assumption that normal depth develops inside the inlet channel, and the use of Manning’s equation results in inaccurate flow rates. The inflow hydrographs for all storms were therefore adjusted to reflect volume equal to the outflow of the basin for the storms that did not overflow through the bypass. Then, a rating curve was created. The outflow discharge rate was measured using a weir insert placed inside the 154.4-mm (6 in) outfall pipe. Two tipping-bucket rain gauges (TE525-WS) were



**Fig. 2** Sand filter basin no. 3 schematics

installed near the inlet channel and across the drainage area, to obtain a better spatial representation of the rainfall events (see Fig. 1). One pressure transducer was installed inside the pre-treatment chamber of the basin to measure storage depth. The transducer was placed inside of a 50.8 mm (2 in)  $\times$  1.68 m (5.5 ft) PVC pipe and positioned 61 mm (0.2 ft) above the bottom of the pre-treatment chamber floor.

The time-weighted sampling method was selected, as an alternative to flow-weighted composites, which is the method most commonly used in stormwater monitoring studies, because the flow measurements in the inlet were based on the depth of water in left side wall of a very wide rectangular channel (15 ft). The flow measurements are not very accurate because normal depth is not ensured and required volume adjustments after the storm occurred. The inlet flow meter was configured to start the sampling once the depth of flow inside the inlet channel reaches 24.4 mm (0.08 ft). This minimum depth allowed the intake tube to lay completely submerged during a storm event. The auto-sampler was configured to sample two sampling groups. The first sampling group consisted of the first four bottles. Each bottle collected 200 mL of runoff at 5-min intervals for a total of 15 min each, providing a 15-min composite samples during the first 1 h of the storm event. The second group continued the collection process by sampling 600 mL of runoff at 30-min intervals starting after the first hour and continued until all 24 bottles had received samples or the inlet flow depth dropped below the minimum requirement of 24.4 mm (0.08 ft).

The outflow samples were collected through a tube inserted into a cleanout box connected to the 152.4-mm (6 in) outfall PVC pipe. The cleanout was located approximately 7.62 m (25 ft) upstream from the outlet and provides a means of positioning the sampling tube down in the stream flow about 1.52 m (5 ft) in front of (upstream) the orifice weir insert. The automatic sampling started once the stream flow reached a depth of 76.2 mm (0.25 ft). This depth is the minimum requirement allowed for the intake tube to be completely submerged in the runoff stream. The auto-sampler was configured to run in “time interval” mode which involved programming the control system to schedule one sampling group. The configuration was set to collect 600 mL of runoff at 30-min intervals and continue until all 24 bottles had received samples or the flow depth dropped below the minimum limit of 76.2 mm (0.25 ft). This sampling interval allowed for

approximately 75 to 90% of the storm event to drain from the basin within a 12-h period. After the storm events, all the samples were transported to the laboratory and stored in the refrigerator at 4 °C.

### Water quality experiments

All the water quality testing was performed at the UTSA Environmental Engineering Laboratory. All samples were characterized based on typical testing parameters in accordance with the United States Environmental Protection Agency approved HACH methods displayed in Table 1. This table shows the water quality parameters, instrument methods, and detection limits. The methods used for the testing parameters are in accordance with the standard methods (AWWA 1998).

### Data analysis

Data analysis was performed in a two-step process. First, the event-mean concentration (EMC) for each storm event was calculated for each pollutant listed in Table 1 for the inlet and outlet of the sand filter basin. The EMC is a statistical metric that represents the flow proportional average concentration of a given parameter for a particular rain event, and is calculated by the following equation:

$$EMC = \frac{\sum_{i=1}^n V_i C_i}{\sum_{i=1}^n V_i}$$

where  $V_i$  is the volume of flow during period  $i$ ;  $C_i$  is the concentration associated with period  $i$ ; and  $n$  is the total number of measurements taken during an event. Concentration values were identified as outliers if they fall outside of 1.5 times the interquartile range and were excluded from the EMC calculation. The average EMC for each parameter was calculated, and box plots showing the median (central line), first and third quartile (box), mean (cross sign), and the minimum and maximum values (whiskers) were created. For each parameter, the non-parametric Wilcoxon test (Helsel and Hirsch 2002; Wilcoxon 1945) and the paired  $t$  test were performed to verify whether the influent and effluent EMCs are statistically different at a 95% confidence level ( $p < 0.05$ ), therefore attesting the ability of sand filter basins in reducing stormwater pollution. The non-parametric Wilcoxon test was included in the methodology because it was not clear whether the inlet

**Table 1** Water quality parameters, units, methods, instruments, and detection limits

| Parameter                               | Units                              | Method                                                                                       | Instrument                          | Detection limits |
|-----------------------------------------|------------------------------------|----------------------------------------------------------------------------------------------|-------------------------------------|------------------|
| pH                                      | –                                  | Standard method 4500-H+B                                                                     | HACH® sensION156                    | 2 to 14          |
| Conductivity                            | µS/cm                              | Standard method 2510 B                                                                       | HACH® sensION156                    | 0.01 to 200      |
| Total suspended solids (TSS)            | mg/L                               | USEPA gravimetric method for water and wastewater of solids, non-filterable suspended solids | Desiccator, furnace                 | NA               |
| Volatile suspended solids (VSS)         | mg/L                               | USEPA gravimetric method for water and wastewater of solids, non-filterable suspended solids | Desiccator, furnace                 | NA               |
| Phosphorous, reactive (ortho-phosphate) | mg/L PO <sub>4</sub> <sup>3-</sup> | USEPA PhosVer 3® (ascorbic acid) method for water, wastewater, and seawater                  | HACH® DR 2800                       | 0.02 to 2.50     |
| Nitrate                                 | mg/L NO <sub>3</sub> <sup>-</sup>  | Cadmium reduction method for water, wastewater, and seawater                                 | HACH® DR 2800                       | 0.3 to 30.0      |
| Zinc                                    | µg/L                               | Acid digestion preparation with ICP mass spectrometry                                        | PerkinElmer ELAN DRC-e spectrometer | 0.045            |
| Lead                                    | µg/L                               |                                                                                              |                                     | 0.007            |
| Copper                                  | µg/L                               |                                                                                              |                                     | 0.005            |

and outlet EMCs met the assumption of following the normal distribution. For the parameters where the influent and effluent average EMCs are statistically different, the percent removal was calculated. The effluent average EMCs for all the storms were aggregated and compared to the acceptable range defined by EPA for stormwater runoff (US EPA 1999). These benchmarks are the pollutant concentrations above which they represent a level of concern that could potentially impair, or contribute to impairing, water quality or affect human or ecosystem health.

In the second step, a regression analysis is performed. The data collected in the sand filter basin no. 3 was compared with water quality data of sand filter basins compiled from the literature and from the International Stormwater BMP Database. The database contains data from a total of 41 media filters, of which 28 are sand filters. The influent and effluent median EMC for each of the sand filter basins was obtained and graphed in a scatter plot. The non-parametric Wilcoxon test was performed to verify whether the influent and effluent EMCs are statistically different at a 95% confidence level, and linear regression models with confidence interval were built. The linear regression model estimates the effluent EMC concentration ( $EMC_{eff}$ ) using the following equation:

$$EMC_{eff} = m \times EMC_{inf} + b \quad (1)$$

where  $m$  is the slope of the regression line,  $EMC_{inf}$  is the influent event-mean concentration (mg/L or µg/L); and

$b$  is the intercept. According to this linear model, when the influent concentration is near zero ( $EMC_{inf} \rightarrow 0$ ), the effluent concentration is equal to the intercept ( $EMC_{eff} \rightarrow b$ ), which can represent an irreducible minimum effluent concentration, often observed during low influent concentrations in other BMP monitoring investigations (Barrett (2003)). However, this physical interpretation fails when the intercept  $b$  is negative. For large influent EMC, the slope of the regression line ( $m$ ) can be used to represent the removal efficiency or percent reduction of a pollutant ( $1 - m$ ). For instance, if  $m < 1$ , the effluent concentration is lower than the influent concentration and the BMP is treating the stormwater; if  $m > 1$ , the BMP is acting as an emitter of a particular pollutant. The confidence and prediction intervals of effluent EMC at a level of 95% was estimated according to Navidi (2006):

$$s_y = s \sqrt{\frac{1}{n} + \frac{(x - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}} \quad (2)$$

$$s_{pred} = s \sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}} \quad (3)$$

where  $s_y$  is standard deviation of the measured EMC;  $s_{pred}$  is standard deviation of the predicted error;  $s$  is the standard error;  $n$  is number of paired data points;  $x$  is influent EMC of interest;  $\bar{x}$  is the average measured inflow EMC;  $x_i$  is measured influent EMC at time  $i$ .

The upper and lower confidence ( $EMC_{\text{eff}}^{\text{conf}}$ ) and predicted ( $EMC_{\text{eff}}^{\text{pred}}$ ) lines are drawn based on the standard deviations and the  $t$  value for the particular probability (95%) and degrees of freedom ( $n - 2$ ):

$$EMC_{\text{eff}}^{\text{conf}} = EMC_{\text{eff}} \pm t_{0.05} S_j \tag{4}$$

$$EMC_{\text{eff}}^{\text{pred}} = EMC_{\text{eff}} \pm t_{0.05} S_{\text{pred}} \tag{5}$$

## Results

### Storm events

In total, ten storm events were monitored. Table 2 shows for each storm event the beginning and ending date and time, rainfall depth, duration, maximum intensity, number of antecedent dry days, and inlet and outlet peak flows.

The number of samples and average concentration in the inlet and outlet for all tested water quality parameters for each of the ten storm events are shown in Table 3. The average and standard deviation of the inflows and outflows, percentage removal, and the corresponding EPA acceptable range are listed in Table 4. The EPA acceptable ranges indicate the limits of which a stormwater discharge with higher concentrations could

potentially impair, or contribute to impairing, the water quality of the receiving water body or affect human health from ingestion of water or fish (EPA 1999). The analysis of the results follows below.

### pH and conductivity

The results indicated that the sand filter basin did not alter significantly the pH of the stormwater ( $p > 0.05$  in both tests). Figure 3 shows the box plot of the inflow (left) and outlet (right) average concentrations of pH and conductivity. All box plots in this article show the median (central line), first and third quartile (box), mean (cross sign), and the minimum and maximum values (whiskers). The average inflow and outflow pH is  $7.49 \pm 0.93$  and  $7.42 \pm 0.75$ , respectively. This range is consistent with typical pH values of urban stormwater runoff found in other studies (Baralkiewicz et al. 2014). The electric conductivity has increased as stormwater passed through the sand filter basin, increasing, in average, from  $71.37 \pm 23.79$  in the inlet to  $137.45 \pm 49.96$   $\mu\text{S}/\text{cm}$  in the outlet, and is significantly different with a confidence interval of 95% ( $p < 0.05$ ). Since electric conductivity is an indicator of dissolved inorganic materials such as nitrogen and phosphorous, potential causes for this increase include nitrate and phosphate leaching to the outlet during some storm events.

**Table 2** Storm events selected for modeling and water quality experiments

| Storm no. | Date/time              |                        | Rainfall   |                  |                          |                               | Peak flow (l/s) |        |
|-----------|------------------------|------------------------|------------|------------------|--------------------------|-------------------------------|-----------------|--------|
|           | Beginning              | End                    | Depth (mm) | Duration (hours) | Maximum intensity (mm/h) | Number of antecedent dry days | Inlet           | Outlet |
| 1         | April 21, 2016 8:05    | April 21, 2016 12:55   | 12.95      | 1 h 55 min       | 33.53                    | 1 day 23 h                    | 285.2           | 2.1    |
| 2         | May 14, 2016 13:00     | May 14, 2016 17:20     | 6.86       | 2 h 05 min       | 9.14                     | 3 days 7 h                    | 84.7            | 0.6    |
| 3         | May 31, 2016 14:20     | May 31, 2016 18:00     | 14.22      | 1 h 10 min       | 67.06                    | 1 day 5 h                     | 643.9           | 11.9   |
| 4         | June 28, 2016 17:00    | June 28, 2016 22:45    | 25.65      | 3 h 35 min       | 128.02                   | 2 days 2 h                    | 983.4           | 16.4   |
| 5         | July 27, 2016 14:15    | July 27, 2016 19:05    | 34.80      | 2 h 30 min       | 106.68                   | 1 day 15 h                    | 852.3           | 14.7   |
| 6         | August 16, 2016 14:20  | August 16, 2016 22:20  | 21.84      | 5 h 35 min       | 27.43                    | 19 h                          | 84.1            | 17.6   |
| 7         | November 8, 2016 2:30  | November 8, 2016 8:40  | 22.86      | 2 h 55 min       | 57.91                    | 16 h                          | 743.9           | 15.0   |
| 8         | December 2, 2016 10:50 | December 2, 2016 20:35 | 5.08       | 7 h 15 min       | 9.14                     | 23 days                       | 59.2            | 9.1    |
| 9         | January 15, 2017 21:30 | January 16, 2017 5:00  | 37.85      | 3 h 30 min       | 137.16                   | 1 day 10 h                    | 1097.0          | 16.4   |
| 10        | February 14, 2017 2:15 | February 14, 2017 9:55 | 39.62      | 5 h 5 m          | 54.86                    | 10 days                       | 980.0           | 18.7   |

**Table 3** Summary results of water quality parameters for ten storm events

| Storm event | No. of samples | pH | Conductivity ( $\mu\text{S}/\text{cm}$ ) | Total suspended solids (TSS) (mg/L) | Volatile suspended solids (VSS) (mg/L) | Ortho-phosphate (mg/L) | Nitrate (mg/L) | Copper ( $\mu\text{g}/\text{L}$ ) | Zinc ( $\mu\text{g}/\text{L}$ ) | Lead ( $\mu\text{g}/\text{L}$ ) |      |
|-------------|----------------|----|------------------------------------------|-------------------------------------|----------------------------------------|------------------------|----------------|-----------------------------------|---------------------------------|---------------------------------|------|
| 1           | Inlet          | 7  | 7.96                                     | 98.2                                | N/A                                    | N/A                    | 0.20           | 1.56                              | 8.9                             | 30.2                            | 1.0  |
|             | Outlet         | 16 | 8.00                                     | 226.7                               | N/A                                    | N/A                    | 0.13           | 0.81                              | 42.2                            | 168.3                           | 4.6  |
| 2           | Inlet          | 5  | 6.55                                     | 78.6                                | 18.6                                   | 8.8                    | 0.17           | 2.65                              | 36.2                            | 290.9                           | 25.5 |
|             | Outlet         | 12 | 7.40                                     | 179.7                               | 10.9                                   | 6.7                    | 0.18           | 1.2                               | 33.2                            | 192.9                           | 4.7  |
| 3           | Inlet          | 5  | 7.94                                     | 68.4                                | 68.3                                   | 12.0                   | 0.23           | <0.3                              | 42.6                            | 224.8                           | 74.7 |
|             | Outlet         | 12 | 7.63                                     | 133.9                               | 14.3                                   | 8.4                    | 0.15           | <0.3                              | 43.1                            | 159.3                           | 11.1 |
| 4           | Inlet          | 4  | 7.87                                     | 71.0                                | 524.2                                  | 135.1                  | 0.07           | 1.24                              | 110.7                           | 403.9                           | 64.7 |
|             | Outlet         | 12 | 7.95                                     | 148.7                               | 18.3                                   | 10.0                   | 0.27           | <0.3                              | 68.9                            | 142.3                           | 15.4 |
| 5           | Inlet          | 5  | 9.03                                     | 69.6                                | 519.5                                  | 148.6                  | <0.02          | <0.3                              | 135                             | 334                             | 31.6 |
|             | Outlet         | 12 | 7.63                                     | 121.4                               | 5.2                                    | 2.6                    | 0.35           | <0.3                              | 40.9                            | 181                             | 4.8  |
| 6           | Inlet          | 7  | 5.58                                     | 59.3                                | 11.5                                   | 6.2                    | 0.28           | 0.35                              | 58.2                            | 289.1                           | 17.0 |
|             | Outlet         | 12 | 5.46                                     | 93.5                                | 7.4                                    | 4.8                    | 0.17           | 0.34                              | 74.9                            | 170.1                           | 4.7  |
| 7           | Inlet          | 9  | 7.53                                     | 47.0                                | 48.0                                   | 15.1                   | 0.47           | <0.3                              | 71.1                            | 375.2                           | 73.5 |
|             | Outlet         | 12 | 7.96                                     | 93.2                                | 7.5                                    | 6.0                    | 0.60           | <0.3                              | 26.6                            | 144.4                           | 14.8 |
| 8           | Inlet          | 4  | 7.82                                     | 122.6                               | 67.4                                   | 21.4                   | 0.39           | 0.85                              | 114.9                           | 253.1                           | 43.9 |
|             | Outlet         | 9  | 7.70                                     | 198.9                               | 13.8                                   | 10.6                   | 0.56           | <0.3                              | 32.1                            | 102.7                           | 8.3  |
| 9           | Inlet          | 7  | 6.97                                     | 48.6                                | 29.9                                   | 8.9                    | 0.70           | <0.3                              | N/A                             | N/A                             | N/A  |
|             | Outlet         | 6  | 7.15                                     | 89.6                                | 3.8                                    | 0.8                    | 0.75           | <0.3                              | N/A                             | N/A                             | N/A  |
| 10          | Inlet          | 7  | 7.65                                     | 50.9                                | 57.5                                   | 8.5                    | 1.07           | <0.3                              | N/A                             | N/A                             | N/A  |
|             | Outlet         | 8  | 7.34                                     | 88.9                                | 6.5                                    | 2.8                    | 0.79           | <0.3                              | N/A                             | N/A                             | N/A  |

### Total suspended and volatile solids

The results indicated that the sand filter basin no. 3 removed on average 93.5% of TSS, which is a higher removal rate than the design criteria (80% removal of TSS according to the TCEQ (2005)). Figure 4 shows the

box plots that represent the distribution of TSS and VSS concentrations in the inlet and outlet of the basin. As it can be seen, the concentrations in the outflow are substantially reduced, from  $149.43 \pm 212.10$  to  $9.75 \pm 4.86$  mg/L ( $p < 0.05$ ). A few observations with very high TSS concentrations were registered as a result of the

**Table 4** Average EMC of water quality parameters in the inlet and outlet, % removal, and EPA acceptable ranges

| Parameters                               | Inlet (average $\pm$ standard deviation) | Outlet (average $\pm$ standard deviation) | Wilcoxon test $p$ value | Paired $t$ test $p$ value | % removal | EPA acceptable range |
|------------------------------------------|------------------------------------------|-------------------------------------------|-------------------------|---------------------------|-----------|----------------------|
| pH                                       | $7.49 \pm 0.93$                          | $7.42 \pm 0.75$                           | 0.44                    | 0.36                      | NA        | 6 to 9               |
| Conductivity ( $\mu\text{S}/\text{cm}$ ) | $71.37 \pm 23.79$                        | $137.45 \pm 49.96$                        | 0.002                   | 0.00004                   | -92.6     | <200                 |
| Total suspended solids (TSS) (mg/L)      | $149.43 \pm 212.10$                      | $9.75 \pm 4.86$                           | 0.002                   | 0.041                     | 93.5      | <100                 |
| Volatile suspended solids (VSS) (mg/L)   | $40.5 \pm 57.72$                         | $5.85 \pm 3.42$                           | 0.01                    | 0.05                      | 85.5      | <100                 |
| Ortho-phosphate (mg/L)                   | $0.40 \pm 0.31$                          | $0.40 \pm 0.26$                           | 0.45                    | 0.48                      | NA        | NA                   |
| Nitrate (mg/L)                           | $1.33 \pm 0.87$                          | $0.78 \pm 0.35$                           | 0.29                    | 0.11                      | NA        | <0.68                |
| Copper ( $\mu\text{g}/\text{L}$ )        | $72.2 \pm 44.11$                         | $45.23 \pm 17.47$                         | 0.13                    | 0.07                      | NA        | <63.6                |
| Zinc ( $\mu\text{g}/\text{L}$ )          | $275.17 \pm 115.59$                      | $157.63 \pm 27.99$                        | 0.02                    | 0.015                     | 42.7      | <117.0               |
| Lead ( $\mu\text{g}/\text{L}$ )          | $41.47 \pm 27.41$                        | $8.55 \pm 4.66$                           | 0.02                    | 0.003                     | 79.4      | <81.6                |



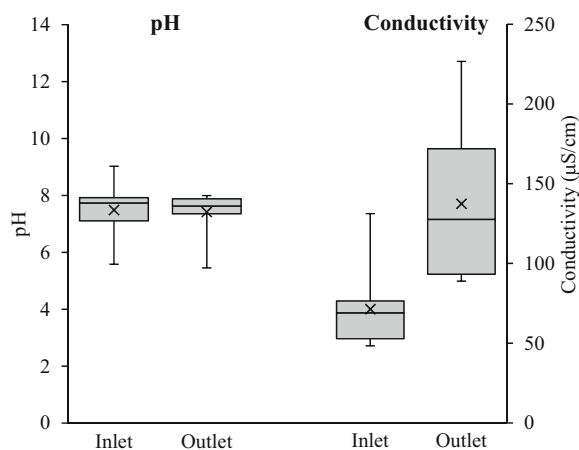
high sediment loads coming from construction sites during storm events 4 and 5. These same storm events produced very high rainfall intensities as shown in Table 2. The removal rate of VSS was approximately 85.5% ( $p = 0.01$  and  $p = 0.05$ , according to the Wilcoxon and  $t$  tests, respectively).

### Nitrate and phosphate

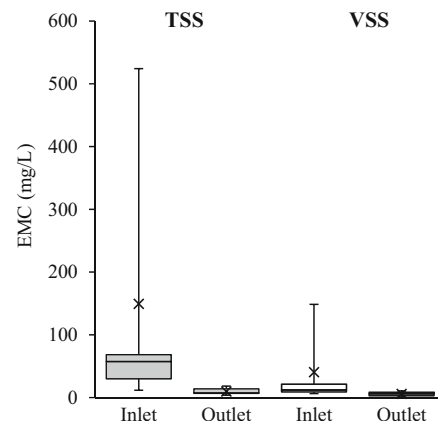
The nutrients ortho-phosphate and nitrate concentrations were analyzed. This study found that over the ten storm events, ortho-phosphate mean concentrations were equal. The mean outflow and inflow concentrations are  $0.40 \pm 0.31$  and  $0.40 \pm 0.26$  mg/L, respectively. However, the inflow and outflow EMCs were not statistically different with a 95% confidence ( $p = 0.45$  and  $0.48$ ). These values are significantly higher than averages recorded by other sand filter basins with data available in the International BMP Database (Clary et al. 2017), which show inflow and outflow concentrations averaging 0.07 and 0.05 mg/L, respectively. In the BMP database, leaching of ortho-phosphate has been observed in only one BMP. Barret (2003) also observed a very low ortho-phosphate reduction in five Austin-Style sand filters. Particularly to the sand filter basins no. 3, a potential source of ortho-phosphate in the effluent might be the presence of grass on the inside berms of the basins. The berms are maintained by UTSA Facilities Department, which regularly mows the grass and does not remove the cut grass from inside the BMP. Specific sources of nutrients in the catchment, including nitrogen, were not identified in conversations with

UTSA Facilities, which states that fertilizers are rarely used on campus.

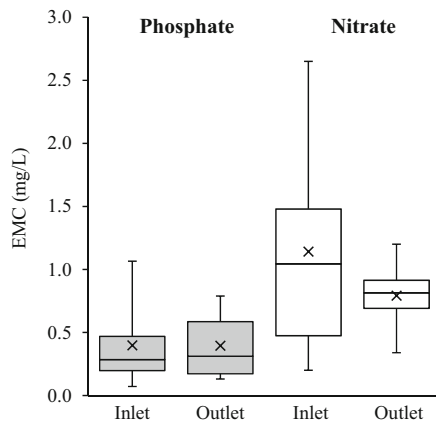
A large majority of samples collected in this study presented nitrate concentrations below the detection limit of the testing method ( $< 0.3$  mg/L); therefore, this article does not draw any definitive conclusions about this pollutant. Out of the ten storm events that generated 20 EMCs, only nine resulted measurable concentrations. For these events, incoming nitrate concentrations were in average three times as high as ortho-phosphates ( $1.33 \pm 0.87$  mg/L). Although average effluent concentrations were lower ( $0.78 \pm 0.35$  mg/L), there were no statistically significant difference between the influent and effluent ( $p = 0.29$  and  $p = 0.11$ , according to the Wilcoxon and  $t$  tests). Over the ten storm events, very high variability of concentrations of nitrates were observed, with higher values noted in the first storms events (events 1, 2, and 4), which were measured between April 21 and June 28, 2016. During the first two events, significant amounts of rainfall occurred in San Antonio, accounting for approximately 35% (390 mm in April and May 2016) of the entire rainfall amounts recorded during the monitoring campaign (1112 mm were recorded from April 2016 to June 2017). This period also coincides with construction occurring at the watershed, which produced significant loads into the basin. Data in International BMP Database shows that media filter basins consistently increases effluent nitrate concentrations (influent and effluent median values of 0.32 and 0.56 mg/L, respectively), most probably due to oxidation of TKN (Clary et al. 2017). Barrett (2003) shows similar behavior too (Fig. 5).



**Fig. 3** Inlet and outlet pH and conductivity



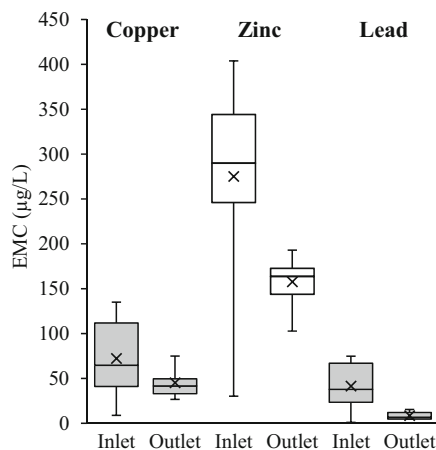
**Fig. 4** Event mean concentration of total suspended solids and volatile suspended solids



**Fig. 5** Inlet and outlet event mean concentration of orthophosphate and nitrate

## Metals

The EMC for metals found in this study are higher than typical urban watersheds, as represented by the data of the International BMP Database. Figure 6 shows the influent and effluent box plot of EMCs for copper, zinc, and lead. Data from approximately 24 sand filters shows average influent concentrations of  $16.6 \pm 18.1$ ,  $91.19 \pm 99.4$ , and  $14.4 \pm 11.8$   $\mu\text{g/L}$  for copper, zinc, and lead, while the study recorded influent averages of  $72.2 \pm 44.11$ ,  $275.17 \pm 115.59$ , and  $41.47 \pm 27.41$   $\mu\text{g/L}$ , respectively. A potential source of such high concentrations is the high volume of cars that drive either for parking or through the Brackenridge and Brenan Avenues (see Fig. 1), although some literature shows lower EMCs on highways. These two streets are major artery roads that



**Fig. 6** Inlet and outlet event mean concentration of copper, zinc, and lead

connect the south and eastern parts of the campus with the west and north facilities. The Brackenridge parking lot, which was built in the early 1970s, is one of the largest on UTSA campus, holding 1346 parking spaces for cars and 39 spaces for UTSA shuttles. Another potential source of metals is from metal gutter and downspouts of the REC center. UTSA campus Services seal-coats the parking lots every 2 years, having had done that in May and June of 2016.

All the effluent EMCs were lower than influents, which indicates the sand filter basin is able to reduce discharge of metals downstream. Although the average removal rate of copper is approximately 37.3%, no statistically significant difference between the inlet and outlet EMCs was observed ( $p=0.13$  and  $p=0.07$  for both tests). Average effluent concentration of copper ( $45.23 \pm 17.47$ ) was below the EPA acceptable range for stormwater of 63  $\mu\text{g/L}$ . Zinc is the metal with higher concentrations, with EMCs ranging in average from  $275.17 \pm 115.59$   $\mu\text{g/L}$  in the inlet and  $157.63 \pm 27.99$   $\mu\text{g/L}$  in the outlet, indicating a removal efficiency of approximately 42% ( $p < 0.02$ ). Contributions of zinc are a major concern because effluent EMC are systematically higher than the acceptable range defined by EPA ( $< 117$   $\mu\text{g/L}$ ). Influent EMCs of lead ( $41.47 \pm 27.41$   $\mu\text{g/L}$ ) are substantially lower than zinc but lead was removed at a higher rate of approximately 79.4% ( $p = 0.02$  and  $p = 0.003$ ). Recent research by Brown et al. (2013) also showed lower removal rates of copper and zinc. Brown's study in the Ballona Creek Watershed in the Los Angeles area found that approximately 50% of copper, zinc, and nickel loads were associated with particles smaller than 6  $\mu\text{m}$ . Also, Taylor and Barrett (2004) found that sand filters did not remove the smallest fraction of TSS which can be attributed to metal particles inside the stormwater (Tables 5 and 6).

## Linear models of EMC

The median influent and effluent event mean concentration (EMC) of TSS, VSS, Cu, Zn, and Pb and correspondent removal efficiencies measured in 31 sand filter basins were compiled from the International Stormwater BMP Database. The compiled results indicate that sand filter basins' median TSS removal efficiency is 82% ( $p < 0.0000$ , range 95 to  $-40\%$ ). The influent and effluent EMC of metals are statistically different at a 95% confidence interval ( $p < 0.0000$ ) and the median

**Table 5** Removal efficiencies (R), inlet (I), and outlet (O) event median concentrations of TSS, VSS, Cu, Pb, and Zn

| BMP name/site                                                               | Drainage area (ha) | TSS (mg/L)                                       |       |       | VSS (mg/L) |      |       | Cu (µg/L) |       |       | Pb (µg/L) |      |       | Zn (µg/L) |       |       |
|-----------------------------------------------------------------------------|--------------------|--------------------------------------------------|-------|-------|------------|------|-------|-----------|-------|-------|-----------|------|-------|-----------|-------|-------|
|                                                                             |                    | I                                                | O     | R (%) | I          | O    | R (%) | I         | O     | R (%) | I         | O    | R (%) | I         | O     | R (%) |
|                                                                             |                    | Amandale/Sydney (Birch et al. 2005) <sup>a</sup> | 2.67  | 42    | 21         | 50   | -     | -         | -     | 22    | 7         | 68   | 41    | 3         | 93    | 285   |
| Fine sand filter/Drummoine Pk, Sydney (Kandasamy et al. 2008) <sup>b</sup>  | 6.0                | 14.4                                             | 9.8   | 32    | -          | -    | -     | -         | -     | -     | -         | -    | -     | 0.28      | 0.06  | 79    |
| Corse sand filter/Drummoine Pk, Sydney (Kandasamy et al. 2008) <sup>b</sup> | 6.0                | 14.4                                             | 3.4   | 76    | -          | -    | -     | -         | -     | -     | -         | -    | -     | 0.28      | 0.05  | 83    |
| Vertical filter no. 6/Austin, TX                                            | 1.87               | 62.77                                            | 46    | 27    | 12.76      | 7    | 45    | 6.05      | 1     | 83    | 10.96     | 5.99 | 45    | 60        | 40    | 33    |
| Jollyville sand filter/Austin, TX                                           | 2.84               | 187.8                                            | 10.46 | 94    | 26.45      | 1    | 96    | 13.1      | 4.39  | 66    | 32.9      | 4.33 | 87    | 110.1     | 19.1  | 83    |
| Appleyard Drive/Tallahassee, FL                                             | 0.32               | 182.6                                            | 50    | 73    | -          | -    | -     | 94.23     | 44.89 | 52    | 38.82     | 7.89 | 80    | 1.41      | 0.75  | 47    |
| Willow Oaks sand 1/North Potomac, MD                                        | 3.24               | 14                                               | 5     | 64    | -          | -    | -     | 8         | 9.2   | -15   | 2         | 1    | 50    | 36        | 21    | 42    |
| University New Hampshire/Durham, NH                                         | 0.4                | 45.26                                            | 19.2  | 58    | -          | -    | -     | -         | -     | -     | -         | -    | -     | 56        | 11.21 | 80    |
| Meggins Ck. /Tallahassee, FL                                                | 1105               | 105.2                                            | 4.87  | 95    | 28.53      | 1.78 | 94%   | -         | -     | -     | -         | -    | -     | -         | -     | -     |
| Parkrose SF/Portland, OR                                                    | 0.33               | 58.4                                             | 6.6   | 89    | -          | -    | -     | 15.65     | 5.28  | 66    | 13.95     | 1.13 | 92    | 108       | 13.65 | 87    |
| Bodie Oaks/Austin, TX                                                       | 12.5               | 49.07                                            | 12    | 76    | -          | -    | -     | 10        | 10    | 0     | 9.66      | 2    | 79    | 25.28     | 14.1  | 44    |
| SE landfill/Birmingham, AL                                                  | 41.3               | 12                                               | 1.5   | 88    | -          | -    | -     | -         | -     | -     | -         | -    | -     | -         | -     | -     |
| La Costa PR/Carlsbad, CA                                                    | 1.13               | 70                                               | 6     | 91    | -          | -    | -     | 14        | 6.7   | 52    | 22        | 1.2  | 95    | 170       | 9.7   | 94    |
| Lakewood/Downey, CA                                                         | 0.77               | 26.5                                             | 8     | 70    | -          | -    | -     | 9.71      | 7.2   | 26    | 3.55      | 1    | 72    | 95.1      | 34    | 64    |
| Eastern SF/Whittier, CA                                                     | 0.61               | 44                                               | 11    | 75    | -          | -    | -     | 13        | 7.5   | 42    | 24        | 4.36 | 82    | 86        | 28.05 | 67    |
| Mountain Gate sand filter/Redding, CA                                       | 1.04               | 32.95                                            | 4.65  | 86    | -          | -    | -     | 9.99      | 2.7   | 73    | 2.7       | 0.5  | 81    | 55.58     | 4.5   | 92    |
| Mt. Shasta maintenance stat./Shasta, CA                                     | 1.06               | 18                                               | 1     | 94    | -          | -    | -     | 4         | 1.4   | 65    | 0.86      | 0.36 | 58    | 33.1      | 3.2   | 90    |
| Barton Ridge sand filter/Austin, TX                                         | 1.23               | 59.22                                            | 8.46  | 86    | 10.62      | 2.47 | 77    | 5.76      | 2.49  | 57    | 6.03      | 1.88 | 69    | 31.34     | 29.25 | 7     |
| Termination/Norwalk, CA                                                     | 1.13               | 28                                               | 4     | 86    | -          | -    | -     | 16        | 9.5   | 41    | 5.25      | 1    | 81    | 88        | 55    | 38    |
| Delaware sand filter/Newark, DE                                             | 0.26               | 32                                               | 6.5   | 80    | -          | -    | -     | 14        | 11.5  | 18    | 12        | 5    | 58    | 50        | 23.5  | 53    |
| Vertical filter no. 6/Austin, TX                                            | 2                  | 339.5                                            | 96.08 | 72    | -          | -    | -     | -         | -     | -     | 12.4      | 5.88 | 53    | 40        | 20    | 50    |
| Lakewood sand filter (95)/Lakewood, CO                                      | 0.66               | 157                                              | 24    | 85    | -          | -    | -     | 27        | 11.5  | 57    | -         | -    | -     | 155       | 30    | 81    |
| Seton pond filtration Fac. (2)/Austin, TX                                   | 33.6               | 21                                               | 1.7   | 92    | -          | -    | -     | -         | -     | -     | -         | -    | -     | 3         | 35    | -1067 |
| 78/I-5/Vista, CA                                                            | 0.32               | 125                                              | 9     | 93    | -          | -    | -     | 28.5      | 11.5  | 60    | 14        | 1.15 | 92    | 355       | 52.5  | 85    |
| Upper sand filter/Sammamish, WA                                             | 7.49               | 3.57                                             | 0.5   | 86    | -          | -    | -     | -         | -     | -     | -         | -    | -     | 0.01      | 0     | 100   |
| Willow Oaks/North Potomac, MD                                               | 3.24               | 5                                                | 7     | -40   | -          | -    | -     | 9.2       | 9     | 2     | 1         | 1    | 0     | 21        | 26    | -24   |
| Airpark sand filter/Alexandria, VA                                          | 0.28               | 47                                               | 14    | 70    | -          | -    | -     | 7.5       | 7.5   | 0     | -         | -    | -     | 82        | 2     | 98    |
| Barton Creek Square Mall/Austin, TX                                         | 32.17              | 40.19                                            | 15.72 | 61    | -          | -    | -     | 7.46      | 4.86  | 35    | 20.26     | 3.77 | 81    | 95.62     | 16.47 | 83    |
| Highwood Apt. filtration/Austin, TX                                         | 1.21               | 71.16                                            | 9.83  | 86    | -          | -    | -     | 10        | 7.06  | 29    | 7.61      | 2.35 | 69    | 22.24     | 15.41 | 31    |
| Escondido/Escondido, CA                                                     | 0.32               | 94                                               | 17    | 82    | -          | -    | -     | 16.5      | 7.3   | 56    | 13        | 2.7  | 79    | 350       | 36    | 90    |
| Foothill SF/Monrovia, CA                                                    | 0.73               | 75                                               | 10    | 87    | -          | -    | -     | 19.6      | 9.65  | 51    | 22        | 3.71 | 83    | 229       | 57.5  | 75    |

<sup>a</sup> (Birch et al. 2005)

<sup>b</sup> (Kandasamy et al. 2008)

**Table 6** Removal efficiencies (R), inlet (I), and outlet (O) event mean concentrations of nutrients (N and P)

| BMP name/site                                                    | Nitrate (mg/L) |      |        | TKN (mg/L) |      |       | Total N (mg/L) |      |       | NOx (mg/L) |      |        | Ortho-phosphate (mg/L) |      |       | Total P (mg/L) |      |       |
|------------------------------------------------------------------|----------------|------|--------|------------|------|-------|----------------|------|-------|------------|------|--------|------------------------|------|-------|----------------|------|-------|
|                                                                  | I              | O    | R (%)  | I          | O    | R (%) | I              | O    | R (%) | I          | O    | R (%)  | I                      | O    | R (%) | I              | O    | R (%) |
| Annandale/Sydney (Birch et al. 2005)                             | -              | -    | -      | 1.52       | 0.47 | 69.1  | 2.14           | 1.81 | 15.4  | 0.62       | 1.34 | -116.1 | -                      | -    | -     | 0.25           | 0.12 | 52.0  |
| Fine sand filter/Drummoynne Pk, Sydney (Kandasamy et al. 2008)   | -              | -    | -      | 1.1        | 0.33 | 70.0  | 2.2            | 0.85 | 61.4  | 1.1        | 0.52 | 52.7   | -                      | -    | -     | 0.21           | 0.12 | 42.9  |
| Course sand filter/Drummoynne Pk, Sydney (Kandasamy et al. 2008) | -              | -    | -      | 1.1        | 0.33 | 70.0  | 2.2            | 0.86 | 60.9  | 1.1        | 0.52 | 52.7   | -                      | -    | -     | 0.21           | 0.13 | 38.1  |
| Vertical filter no. 6/Austin, TX                                 | -              | -    | -      | 0.62       | 0.57 | 8.1   | 0.96           | 0.78 | 18.8  | 0.27       | 0.21 | 22.2   | -                      | -    | -     | 0.13           | 0.10 | 23.1  |
| Jollyville sand filter/Austin, TX                                | -              | -    | -      | 0.99       | 0.37 | 62.6  | 1.33           | 1.03 | 22.6  | 0.38       | 0.67 | -76.3  | 0.09                   | 0.06 | 33.3  | 0.23           | 0.08 | 65.2  |
| Appleyard Drive/Tallahassee, FL                                  | 0.06           | 0.03 | 50.0   | 0.89       | 0.37 | 58.4  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.44  | 0.19           | 56.8 |       |
| Willow Oaks sand 1/North Potomac, MD                             | 0.35           | 0.4  | -14.3  | 0.9        | 0.45 | 50.0  | 1.1            | 1    | 9.1   | -          | -    | -      | 0.09                   | 0.06 | 33.3  | 0.15           | 0.11 | 26.7  |
| University New Hampshire/Durham, NH                              | -              | -    | -      | -          | -    | -     | -              | -    | -     | 0.34       | 0.43 | -26.5  | -                      | -    | -     | 0.12           | 0.06 | 50.0  |
| Meggins Ck. /Tallahassee, FL                                     | 0.14           | 0.19 | -35.7  | -          | -    | -     | 0.61           | 0.16 | 73.8  | -          | -    | -      | -                      | -    | 0.33  | 0.15           | 54.5 |       |
| Parkrose SF/Portland, OR                                         | 0.26           | 0.59 | -126.9 | 2.02       | 0.63 | 68.8  | -              | -    | -     | -          | -    | -      | 0.01                   | 0.07 | -600  | 0.19           | 0.11 | 42.1  |
| Bodie Oaks/Austin, TX                                            | -              | -    | -      | 0.57       | 0.28 | 50.9  | -              | -    | -     | 0.26       | 0.43 | -65.4  | -                      | -    | -     | 0.16           | 0.07 | 56.3  |
| SE landfill/Birmingham, AL                                       | -              | -    | -      | -          | -    | -     | -              | -    | -     | -          | -    | -      | -                      | -    | -     | -              | -    | -     |
| La Costa PR/Carlsbad, CA                                         | 0.64           | 0.69 | -7.8   | 2.8        | 1.5  | 46.4  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.37  | 0.19           | 48.6 |       |
| Lakewood/Downey, CA                                              | 0.39           | 0.68 | -74.4  | 1.53       | 1.22 | 20.3  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.16  | 0.12           | 25.0 |       |
| Eastern SF/Whittier, CA                                          | 0.41           | 0.66 | -61.0  | 0.87       | 0.57 | 34.5  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.13  | 0.09           | 30.8 |       |
| Mountain Gate sand filter/Redding, CA                            | 0.37           | 0.82 | -121.6 | 0.8        | 0.3  | 62.5  | -              | -    | -     | -          | -    | -      | 0.02                   | 0.02 | 0.0   | 0.09           | 0.05 | 44.4  |
| Mt. Shasta maintenance Stat./Shasta, CA                          | 0.11           | 0.2  | -81.8  | 0.3        | 0.16 | 46.7  | -              | -    | -     | -          | -    | -      | 0.02                   | 0.01 | 50    | 0.05           | 0.01 | 80.0  |
| Barton Ridge sand filter/Austin, TX                              | -              | -    | -      | 1.05       | 0.59 | 43.8  | 1.63           | 1.2  | 26.4  | 0.4        | 0.54 | -35.0  | -                      | -    | -     | 0.15           | 0.09 | 40.0  |
| Termination/Norwalk, CA                                          | 0.58           | 0.9  | -55.2  | 1.76       | 0.5  | 71.6  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.15  | 0.09           | 40.0 |       |
| Delaware sand filter/Newark, DE                                  | -              | -    | -      | 0.65       | 0.87 | -33.8 | -              | -    | -     | 0.54       | 1    | -85.2  | 0.05                   | 0.05 | 0.0   | 0.06           | 0.05 | 16.7  |
| Vertical filter no. 6/Austin, TX                                 | -              | -    | -      | 0.91       | 0.55 | 39.6  | -              | -    | -     | 0.35       | 0.52 | -48.6  | -                      | -    | -     | 0.28           | 0.14 | 50.0  |
| Lakewood sand filter (95)/Lakewood, CO                           | -              | -    | -      | 2.9        | 1.4  | 51.7  | -              | -    | -     | 0.32       | 0.61 | -90.6  | 0.06                   | 0.02 | 66.7  | 0.46           | 0.17 | 63.0  |
| Seton pond filtration fac. (2)/Austin, TX                        | 1.01           | 0.29 | 71.3   | 1.07       | 0.56 | 47.7  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.19  | 0.13           | 31.6 |       |
| 78/I-5/Vista, CA                                                 | 0.46           | 0.94 | -104.3 | 2.65       | 1.7  | 35.8  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.71  | 0.33           | 53.5 |       |
| Upper sand filter/Sammamish, WA                                  | -              | -    | -      | -          | -    | -     | -              | -    | -     | -          | -    | -      | -                      | -    | 0.03  | 0.02           | 33.3 |       |
| Willow Oaks/North Potomac, MD                                    | 0.4            | 0.34 | 15.0   | 0.45       | 0.6  | -33.3 | 1              | 0.93 | 7.0   | -          | -    | -      | 0.06                   | 0.03 | 50.0  | 0.11           | 0.10 | 9.1   |
| Airpark sand filter/Alexandria, VA                               | -              | -    | -      | 4.8        | 1.75 | 63.5  | 6.35           | 3.42 | 46.1  | 1.2        | 1.6  | -33.3  | 0.24                   | 0.09 | 62.5  | 0.46           | 0.15 | 67.4  |
| Barton Creek Square Mall/Austin, TX                              | -              | -    | -      | 0.6        | 0.31 | 48.3  | 0.92           | 0.89 | 3.3   | 0.32       | 0.43 | -34.4  | -                      | -    | -     | 0.11           | 0.07 | 36.4  |
| Highwood Apt. filtration/Austin, TX                              | -              | -    | -      | 0.39       | 0.35 | 10.3  | 0.67           | 0.66 | 1.5   | 0.22       | 0.35 | -59.1  | -                      | -    | -     | 0.16           | 0.17 | -6.3  |
| Escondido/Escondido, CA                                          | 0.33           | 0.53 | -60.6  | 2          | 1.05 | 47.5  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.31  | 0.06           | 80.6 |       |
| Foothill SF/Monrovia, CA                                         | 0.37           | 0.66 | -78.4  | 1.4        | 0.8  | 42.9  | -              | -    | -     | -          | -    | -      | -                      | -    | 0.21  | 0.13           | 38.1 |       |

removal efficiencies for copper, lead, and zinc are 52.1, 79.5, and 74.9%, with ranges between  $-15$  and  $83.5\%$ ,  $0$  and  $94.5\%$ , and  $-1066$  to  $100\%$ , respectively. The compiled data shows that sand filter basins effectively remove constituents that are attached to particulate matter but underperforms when the pollutant of concern is dissolved. The inlet and outlet EMCs and removal efficiencies for several forms of nitrogen (nitrate, TKN, total N, and NO<sub>x</sub>) and phosphorus (ortho-phosphate and total P) were analyzed, demonstrating that these basins can serve as net negative sources. The influent and effluent EMCs of nitrate, total N, NO<sub>x</sub>, and ortho-phosphate are not statistically different in a 95% confidence interval, according to the Wilcoxon test. The median removal efficiency of nitrate and NO<sub>x</sub> are negative (approximately  $-61$  and  $-42\%$ ), ranging from  $-127$  to  $71\%$  and  $-116$  to  $53\%$ , respectively. The constituents TKN and total P median removal rates are approximately 48 and 42%, with ranges of  $-34$  to  $72\%$  and  $-6.3$  to  $81\%$ , and influent and effluent EMCs are statistically different ( $p < 0.0000$ ).

A regression analysis of the EMCs obtained in the International BMP Database was performed. The measured influent and effluent EMCs, linear regression lines, equations, coefficients of determination ( $R^2$ ), and associated 95% confidence and predicted intervals are shown in the scatter plots (Fig. 7). The coefficients of determination ranged from 0.13 (nitrate) to 0.9 (copper), indicating that some models presented high performance and others the goodness-of-fit is poor. The intercepts values ( $b$  in Eq. (2)) are relatively close to zero, with exception of nitrate and zinc, indicating that the sand filter basins only emit detectable pollutant concentrations for high influent concentrations. The slopes of the regression lines ( $m$  in Eq. (2)), indicating the removal efficiency or percent reduction of a pollutant, are all less than one, suggesting that collectively, most of the cataloged BMPs reduce pollution under a variety of environmental conditions and design configurations. According to this regression analysis, the removal efficiency of lead and TSS are 90% and 79%, respectively, which are in similar order to the removal efficiencies obtained by the sand filter basins no. 3 (Table 4).

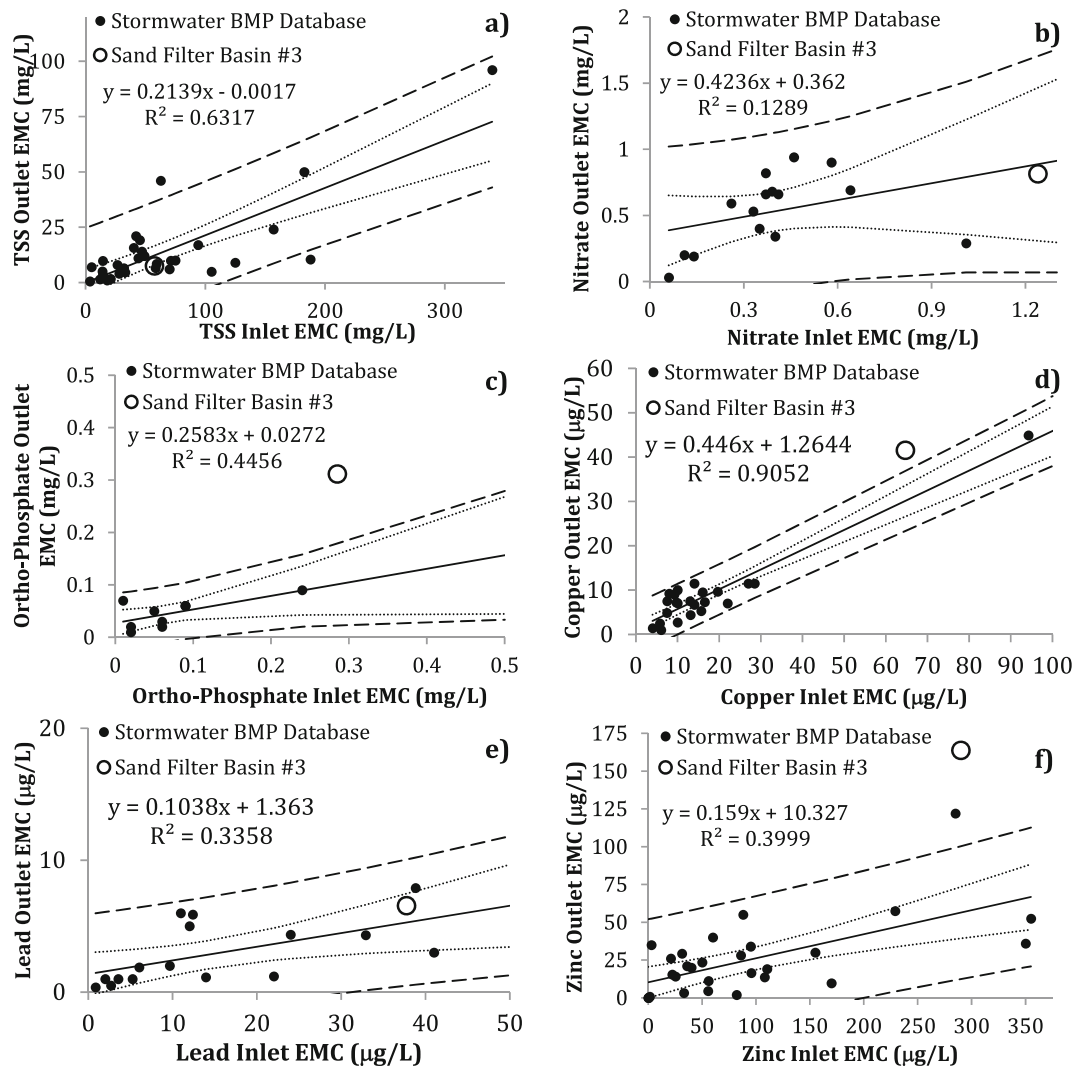
The regression analysis was used in this study to assess whether linear models are able to accurately predict effluent EMCs. The median influent and effluent EMCs measured for the sand filter basin no. 3 was plotted in the scatter plots of Fig. 7. As observed, the EMCs of nitrate and lead fall within the 95% confidence

interval of the data, and the EMC of TSS fall within the 95% predicted interval. The EMC data points for ortho-phosphate, copper, and zinc are outside the confidence and predicted intervals. It shows that the collected data are outside of EMCs values found in typical urban watersheds and suggests that linear models are not effective methods to predict effluent concentrations and removal efficiencies of sand filter basins, particularly for the dissolved phase of pollutants in locations of high influent concentrations. Potential sources of loads leading to high concentrations were discussed in previous sections. The main pollution source identified are vehicles (both regular cars and shuttles) that circulate in high volumes throughout the year.

### Summary and conclusion

The present study investigated the water quality and determined the effectiveness of sand filter basins, based on data available in the literature, the International Stormwater BMP Database, and samples collected in a sand filter basin located at the UTSA main campus. Ten storm events were monitored starting in March 2016 until February 2017. The following water quality parameters were measured in the inlet and the outlet of the basin: pH, conductivity, nitrate, ortho-phosphate, TSS, VSS, copper, zinc, and lead. Based on the expected removal rates found in the literature and efficiency criteria defined for the sand filter basin design, it was observed that the sand filter basin no. 3 removed TSS as expected for the basin design. Moreover, lead removal was above 80%, while other constituents presented low and variable removal rates. The results indicate EMCs for nutrients and metals at this particular parking lot of the UTSA main campus are typically higher than what other studies found of typical urban watersheds.

The results indicated that the sand filter basin meets design standards when it comes to TSS. Some of the results obtained here, however, show that some dissolved pollutants are not being properly retained in sand filter basins, which is a concern in sensitive areas such as the recharge zone of the Edwards Aquifer. The literature suggests that LID stormwater controls can potentially outperform sand filter basins because of the bioaccumulation and biotransformation processes, longer residence times, and lower loading rates. Future studies should focus on the



**Fig. 7** Inlet and outlet EMC scatter plots, regression lines, 95% confidence (dotted line) and prediction (dash line) intervals for **a** TSS, **b** nitrate, **c** ortho-phosphate, **d** copper, **e** lead, and **f** zinc

implementation and testing of other best management practices in order to compare removal efficiency and hydrologic performance with traditional sand filter basins. Given zinc and copper loadings from vehicle tires and brake pads, it is important to understand the size distribution of TSS that is associated with pollutants of concern. Additional particle size distribution analysis on the influent and samples collected from this study would help guide selection of BMPs to maximize removal of metals and bacteria that typically fall in the sub 6- $\mu\text{m}$  particle range. Based on the modest metal removal rates found in this study, it would be expected a higher than normal proportion of metal constituents in the dissolved

form, potentially leaching from the seal coat. The authors recommend, consequently, future work to analyze the total and dissolved metal concentrations to better understand the performance of sand filter basins.

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