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Small-Scale Pilot Testing of Stormwater Treatment Systems to Meet Numerical Effluent Limits in the Lake Tahoe Basin

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SMALL-SCALE PILOT TESTING OF STORMWATER TREATMENT SYSTEMS TO MEET NUMERICAL EFFLUENT LIMITS IN THE LAKE TAHOE BASIN

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ABSTRACT:

To stem the continuing loss of clarity in Lake Tahoe, stringent numerical discharge requirements for storm water discharges in the Tahoe basin have been promulgated. In 2008, discharges to surface water must meet limits for turbidity (20 NTU), total phosphorus (0.1 mg/L), total nitrogen (0.5 mg/L), total iron (0.5 mg/L), and oil and grease (2 mg/L). The California Department of Transportation (Caltrans) has undertaken a multi-year small-scale storm water treatment pilot project to identify, test, and evaluate potential treatment technologies to meet the effluent limits. Treatment technologies investigated include simple "non-mechanized" sedimentation and granular media filtration systems (with and without chemicals), plus more complex "mechanized" systems involving combinations of coagulation, flocculation, sedimentation, filtration, and ion exchange. During the first two years of operation covered in this paper, thirty different non-mechanized systems and eight mechanized systems were tested. In terms of turbidity and phosphorus removals, conventional storm water treatment systems (detention and filtration without chemicals) were consistently unable to meet the discharge limits, whereas similar non-mechanized systems preceded by chemical coagulation performed much better, frequently meeting the limits. Sedimentation without chemicals followed by filtration through activated alumina or expanded shale adsorptive media also performed well in removing turbidity and phosphorus, but resulted in elevated pH and dissolved aluminum concentrations. Most of the mechanized systems were successful in meeting the turbidity and phosphorus limits, though these systems are not well suited to the roadside environment. The nitrogen limit was not consistently met by any of the systems tested.

Keywords: stormwater treatment, Lake Tahoe, turbidity, phosphorus, stormwater BMP, chemical treatment, coagulation, filtration, sedimentation

INTRODUCTION

Lake Tahoe is known worldwide for its stunning clarity and deep blue water. Over the past four decades, though, the clarity of the lake has declined, partially due to algae growth, and partially due to small particles being washed into the lake. In response, the Lahontan Regional Water Quality Control Board has prescribed stringent effluent limits for all storm water discharges (Table 1), which are scheduled to take effect in 2008. These limits pose a significant challenge to agencies such as the California Department of Transportation (Caltrans), which owns and maintains over 68 miles of roadway in the basin. As seen in Table 1, constituent concentrations in highway runoff exceed, sometimes greatly, the legal effluent limits.

In 2001, Caltrans initiated a multi-year small-scale pilot testing program at the lake. The objective of this program is to identify, test, and evaluate potential treatment methods for highway storm water runoff to meet the effluent limits for surface water discharge. Surface water effluent limits are the primary target because Caltrans has limited access to land for storm water infiltration. In this paper, an overview of program activities and results during the 2001-02 and 2002-03 wet seasons is presented. These are referred to as "Year 1" and "Year 2" respectively in this paper. Details can be found in reports available from Caltrans (Caltrans 2003b, 2003c).

Table 1 - Highway Runoff Characteristics and Legal Effluent Limits in the Tahoe Basin

Parameter	Tahoe Basin Highway Runoff (Mean Values)[a]	Effluent Limits for Storm Water[b] Discharge to Surface Water	Effluent Limits for Storm Water[b] Discharge to Land (Infiltration)
Turbidity (NTU)	477	20	200
Total Phosphorus (mg/L as P)	2.1	0.1	1
Total Nitrogen (mg/L as N)	2.7	0.5	5
Total Iron (mg/L as Fe)	17.7	0.5	4
Oil and Grease (mg/L)	18	2	40

(a) Caltrans, 2003a
(b) LRWCB, 1994

PILOT TREATMENT FACILITIES OVERVIEW

In the Fall of 2001, Caltrans constructed a 2400-ft2 small-scale pilot storm water treatment facility at the South Lake Tahoe Maintenance Station (Figure 1). This facility houses two categories of treatment systems: 1) "non-mechanized" systems requiring little or no power or operator attention that could be deployed in a roadside setting, and 2) "mechanized" systems utilizing powered mechanical equipment requiring operator attention and probably a building enclosure. In general, the non-mechanized systems involve relatively slow-rate treatment methods that require a large footprint area per unit of flow to be treated and would be mostly applicable to rural settings where land is readily available. Mechanized systems, in contrast, provide relatively high-rate treatment and would be more appropriate for urban settings where large volumes of flow must be treated in a small area.

All of the non-mechanized experimental treatment systems were based on sedimentation and/or granular media filtration with and without chemical addition. A total of 30 different treatment systems were tested, as listed in Table 2. Sedimentation tanks were operated in batch mode for convenience. Filters were operated as slow rate systems without backwash, as they would be in a roadside installation. Key data for the various media are shown in Table 3. The different sandbased media were expected to provide treatment by mostly physical means (straining, impaction, etc.), whereas the remaining media were expected to adsorb ammonia nitrogen or phosphorus.

All of the mechanized treatment systems included one of two configurations of chemical coagulation, flocculation, and sedimentation as the first or only treatment step: 1) a batch version of an Actiflo® (Kruger, Inc., Cary, NC) process including the use of ballast sand, and 2) conventional operation without ballast sand. Subsequent treatment was investigated in a stepwise manner, with the second step involving either a pressure sand filter or a proprietary high-rate synthetic media filter (Fuzzy Filter®, Schreiber Wastewater Treatment Technologies, Trussville, Al). The third treatment step was ion exchange using separate cation and anion resin beds. In total, eight treatment systems were investigated as delineated in Table 4.

Figure 1 – Small-Scale Pilot Treatment Facility Showing Exterior with Storm Water Storage Tanks (Left) and Interior with Non-Mechanized Treatment Units (Right)

The chemicals used in the various treatment systems and the doses and methods of application are discussed in following sections.

The pilot facilities were operated in response to runoff events (rainfall or snowmelt). When runoff occurred, a water truck was dispatched to collect storm water from one or more catchment basins in the Lake Tahoe area. The collected storm water was trucked to the pilot treatment facility and stored in a 25,000 L (6,500 gal) polyethylene storage tank until processed through the treatment units. While in storage, the storm water was continuously mixed with a submersible mixer.

NON-MECHANIZED TREATMENT SYSTEMS CONFIGURATION AND OPERATION

The sedimentation units and gravity filters were constructed from 2.1-m (7-ft) tall, 0.76-m (30-inch) diameter polyethylene tanks on steel stands (Figure 2). These were followed by 1.1-m (3.5-ft) tall, 0.76-m (30-inch) diameter polyethylene effluent collection tanks at floor level.

For each batch run, the sedimentation tanks were filled to a depth of 1.8 m (6 ft) and then allowed to settle for either 2 or 24 hours (Table 2). The sedimentation tank effluent sampling port and outlet were located 0.9 m (3 ft) above the tank bottom. For those treatment systems including filtration, only the upper 0.9 m (3 ft) of settled storm water in the settling tank was transferred to the filter.

Table 2 – Non-Mechanized Treatment Systems

No.	Chemical	Sed.Time, Hrs	Filter Medium	Filter Loading Rate	Filter Hydraulic Condition	Year 1 (01-02)	Year 2 (02-03)
Sedimentation							
1	—	2	—	—	—	◆	◆
2	—	24	—	—	—		◆
Sedimentation with Chemicals							
3	Chitosan	24	—	—	—		◆
4	PAC	2	—	—	—	◆	◆
Filtration							
5	—	—	Fine Sand	Fast	Free-Drain	◆	
6	—	—	Coarse Sand	Fast	Free-Drain	◆	
7	—	—	Zeolite	Fast	Free-Drain	◆	
8	—	—	Activated Alumina	Fast	Free-Drain	◆	
9	—	—	Aluminum Oxide	Fast	Free-Drain	◆	
Filtration with Chemicals							
10		—	Fine Sand	Fast	Free-Drain	◆	
11		—	Coarse Sand	Fast	Free-Drain	◆	
12		—	Fine Sand	Fast	Free-Drain	◆	
13		—	Coarse Sand	Fast	Free-Drain	◆	
Sedimentation and Filtration							
14	—	2	Conc. Sand	Fast	Free-Drain	◆	
15	—	2	Fine Sand	Fast	Free-Drain		◆
16	—	2	Fine Sand	Slow	Free-Drain		◆
17	—	2	Fine Sand	Slow	Submerged		◆
18	—	2	Fine Sand	Fast	Submerged		◆
19	—	24	Fine Sand	Slow	Free-Drain		◆
20	—	24	Fine Sand	Slow	Submerged		◆
21	—	24	Expanded Shale	Slow	Submerged		◆
22	—	24	Limestone	Slow	Submerged		◆
23	—	24	Wollastonite	Slow	Submerged		◆
24	—	24	Activated Alumina	Slow	Submerged		◆
Sedimentation and Filtration with Chemicals							
25	PAC	2	Fine Sand	Fast	Free-Drain	◆	
26	PAC	2	Fine Sand	Slow	Free-Drain		◆
27	PAC	2	Coarse Sand	Fast	Free-Drain	◆	
28	PAC	2	Zeolite	Fast	Free-Drain	◆	
29	PAC	2	Activated Alumina	Fast	Free-Drain	◆	
30	PAC	2	Aluminum Oxide	Fast	Free-Drain	◆	

Table 3 - Filter Media Tested

Filter Media	Characteristics / Description	Effective Size(a) (D_{10}, mm)	Uniformity Coefficient(a) (D_{60}/D_{10})
Fine Sand	0.45-0.55 mm	0.47	1.5
Coarse Sand	0.8-1.2 mm	0.7	1.9
Concrete Sand	ASTM C-33	0.13	8.7
Activated Alumina	Alcoa DD-2 28 x 48	0.30	1.6
Aluminum Oxide	White Aluminum Oxide, 30 Grit	0.45	1.4
Zeolite	Clinoptilolite	0.45	1.4
Limestone	Limestone #4 Sand	0.15	8.2
Expanded Shale	Utelite Fines	0.61	2.5
Wollastonite	Wollastonite Tailings (media passing #50 sieve removed)	0.38	2.6

(a) Before conditioning

Table 4 - Mechanized Treatment Systems

No.	Configuration	Year 1	Year 2
1	Actiflo®	♦	♦
2	Actiflo® + Fuzzy Filter®	♦	♦
3	Actiflo® + Pressure Sand Filter	♦	
4	Actiflo® + Fuzzy Filter® + Ion Exchange	♦	♦
5	Actiflo® + Pressure Sand Filter + Ion Exchange	♦	
6	Conventional Coagulation, Flocculation and Sedimentation		♦
7	Conventional Coag/Floc/Sed + Pressure Sand Filter		♦
8	Conventional Coag/Floc/Sed + Press. Sand Filter + Ion Exch.		♦

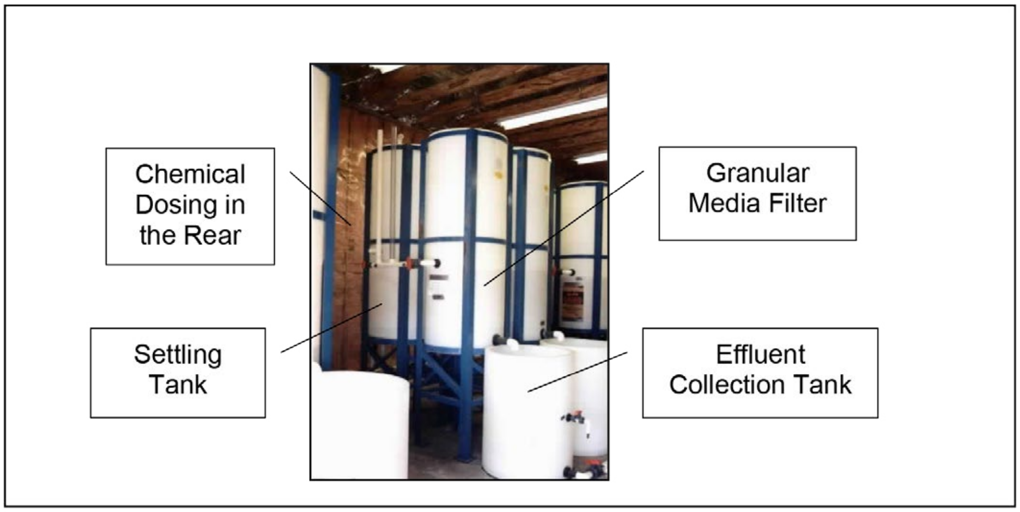


Figure 2 – Typical Non-Mechanized Treatment System

In Year 1, each experimental run included two 416 L (110 gal) batches. After the first batch was settled, the settling tanks were drained down to the 0.9 m (3 ft) depth by discharging to the filters (for those systems including filtration). The tanks were then refilled to the 1.8 m (6 ft) depth with fresh storm water, allowed to settle, and discharged again. For systems without filters, the sedimentation tanks were operated in the same manner, but discharged to drain. In Year 2, the sedimentation tanks were filled and discharged only once per run, meaning that each run consisted of only one 416 L (110 gal) batch.

The filtration units contained 610 mm (24 inches) of filter media above 203 mm (8 inches) of pea gravel, separated by a layer of geotextile fabric. A perforated pipe extending across the unit within the pea gravel was used to collect and discharge filter effluent. After placement in the filters, the media were rinsed to remove fines by thoroughly flushing with tap water using a section of 19-mm (¾-in) PVC pipe connected to a hose. The rinsing pipe was moved up and down through the media bed at various locations, dislodging media fines and dirt particles. Rinsing was continued until the turbidity of water draining through the media was 2 NTU or less.

During the first year of operations, the transfer of water from the settling tank to the filters was accomplished by opening a 38-mm (1.5-inch) sedimentation outlet valve and allowing the water to drain down through the filter as fast as allowed by filter permeability. Filters not preceded by settling were loaded by pumping storm water directly to the filters at a rate of 91 L/min (24 gpm), which resulted in a filter surface loading rate of 200 L/min·m2 (4.9 gpm/ft2). Both cases are designated as “fast” loading in Table 2. Also in Year 1, all of the filter effluents were discharged freely to the atmosphere from the underdrain outlet pipe at the underdrain elevation, resulting in a “free-draining” filter hydraulic condition (Table 2).

In the second year, all of the filters followed sedimentation and most were loaded at a “slow” rate by using a peristaltic pump to transfer the 416 L (110 gal) batch feed volume from the settling tank over a period of six hours at a rate of 1.16 L/min (0.306 gpm), resulting in a surface loading rate of 2.5 L/min·m2 (0.062 gpm/ft2). Some of the filters were operated in the free- draining hydraulic condition, while others were operated in a “submerged” condition (Table 2), meaning that the filter effluent pipe was extended upward to a level just above (10 mm +/-) the filter media surface before discharge to atmosphere. This assured that the media bed was always saturated, which was intended to cause the influent to be distributed uniformly over the entire filter area.

As indicated in Table 2, three different chemicals were used in various non-mechanized treatment systems, including a polyaluminum chloride (PAC), a polyacrylamide (PAM), and chitosan.

The PAC product used was PASS-C® (Eaglebrook Inc., Matteson, IL), which was chosen based on preliminary jar testing with various storm water samples prior to the first pilot run. Several other PAC products are also known to provide effective storm water treatment. PAC was applied by using a peristaltic pump to meter the chemical into an in-line static mixer in the treatment unit influent piping. This provided uniform dosing at the desired rate. During Year 1, PAC was applied at a constant dose of 100 mg/L (as liquid product), based on the results of preproject jar testing. In Year 2, the PAC dose was based on jar testing conducted for each run (i.e., optimized for that particular storm water) and ranged from 75 to 200 mg/L.

A granular anionic PAM, Superfloc® A-836 (Cytec Chemical, West Paterson, NJ), was used in two of the non-mechanized treatment systems during Year 1. A passive “tea bag” dosing system was employed. This involved suspending a small (40 mm x 50 mm) geotextile fabric bag containing the chemical in the influent flow stream.

Chitosan, which was used in one non-mechanized system during Year 2, is a refined natural polymer extracted from chitin, a substance found in the shells of crustaceans such as crabs, shrimp, and lobsters. The chitosan used was obtained from Natural Site Solutions, Redmond, WA. Both solid (Gel-Floc™) and liquid (Liqui-Floc™) products were used as discussed later in this paper. The solid form was used in the first two runs and was applied using the same tea bag approach as used for PAM. For the subsequent four runs, the liquid product was used at a constant dose rate of 0.5 or 1.0 mg/L (dry basis) using a metering pump and static mixer.

MECHANIZED TREATMENT SYSTEMS CONFIGURATION AND OPERATION

The equipment used in the mechanized treatment systems is illustrated in Figure 3. Coagulation, flocculation, and sedimentation (Actiflo® and conventional) for the mechanized treatment systems were accomplished in a 915-mm (36-inch) square, 1370-mm (54-inch) tall fabricated stainless steel tank. The tank was fitted with a vertical-shaft mixer that was controlled to attain the desired speed and mixing intensities using a variable frequency drive. For each run, the tank was filled with 984 L (260 gal) of storm water and then operated through a timed sequence of micro-sand (Actiflo® only) and chemical additions, rapid and slow mixing, and then settling as indicated in Table 5.

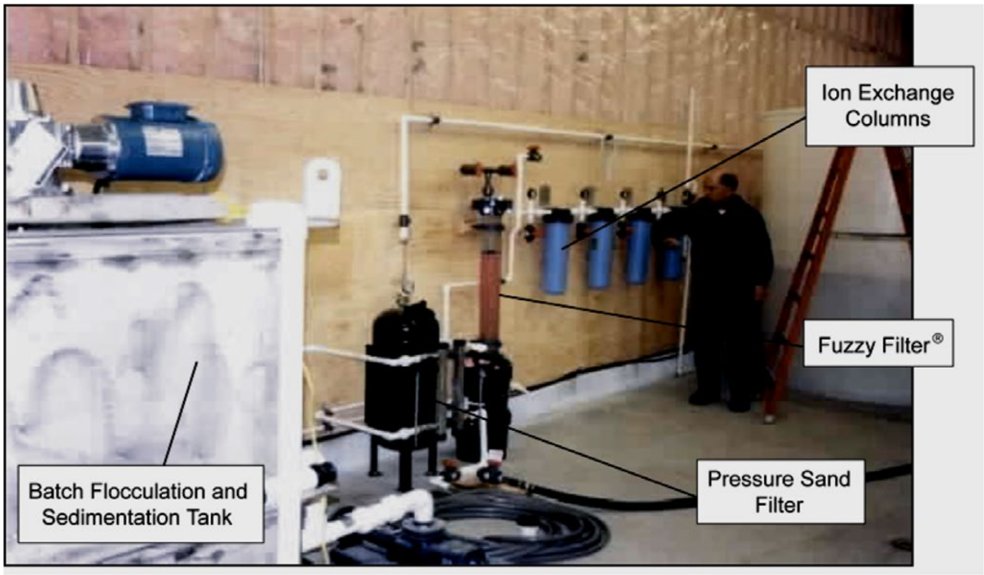


Figure 3 – Mechanized Treatment Systems

Table 5 - Operational Steps for Mechanized Treatment Coagulation, Flocculation, and Sedimentation

Step	Activity	Actiflo®		Conventional	
		Mixer Speed, rpm	Duration, Min	Mixer Speed, Rpm	Duration, min
1	Add Ballast Sand [(a)]	175	—	—	—
2	Add PAC	175	—	175	—
3	Rapid Mix	175	3.0	175	2.0
4	Add Polymer Solution	175	—	175	—
5	Rapid Mix	175	0.5	175	0.5
6	Slow Mix	117	1.5	18	15
7	Settle	0	3 to 10	0	30

(a) Actiflo® only; 5.0 L of sand were added in each run.

Two chemicals were used to aid coagulation and flocculation. Coagulation was accomplished using the same PAC as previously described. The PAC dose during Year 1 was 100 mg/L (as liquid product) in the first three runs and 125 mg/L in the next three runs. Flocculation was promoted by the use of an anionic polymer, Magnafloc® LT25 (Ciba Chemicals, Suffolk, VA). The polymer dose during Year 1 was 0.8 mg/L (dry weight basis) in the first three runs and 1.0 mg/L in the next three runs. In Year 2, appropriate dose rates for both the PAC and the polymer were determined by jar testing for each run. Doses ranged from 75 to 200 mg/L for the PAC and 0.5 to 1.5 for the polymer.

After settling, the upper portion of the settling tank was pumped at a constant flow rate of 9.8 L/min (2.6 gpm) through either the Fuzzy Filter® or the pressure sand filter, and then through the ion exchange columns. In Year 1, the Actiflo® process was used with both the Fuzzy Filter® and the pressure sand filter. In Year 2, the Actiflo® process was used only with the Fuzzy Filter® and the conventional coagulation, flocculation, and sedimentation process was used only with the pressure sand filter. In all cases, a total of 380 L (100 gal) of settled storm water was pumped through each filter for each run.

The Fuzzy Filter® unit was constructed of 102-mm (4-inch) diameter clear PVC pipe, approximately 914 mm (36 in) long with capped (blind flange) ends. Inside that vessel, the filter bed was comprised of a 762 mm (30 in) depth of wet (water saturated) fiber spheres compacted to 533 mm (21 in) using perforated plastic compression plates. Influent piping was connected to the bottom of the unit and effluent piping to the top to provide an upflow configuration. The surface loading rate for this unit was 1200 $L/min \cdot m^2$ (30 gpm/ft^2).

The pressure sand filter was a prefabricated steel unit manufactured by Process Efficiency Products, Mooresville, NC (Model CL-12). The filter contained a filter sand (0.55 mm effective size) bed with a surface area of 0.093 m^2 (1.0 ft^2) and a depth of 305 mm (12 in). The surface loading rate for this filter was 105 $L/min \cdot m^2$ (2.6 gpm/ft^2).

The cation and anion exchange columns and housings were obtained from American Filter Works, Los Angeles, CA. The volume of ion exchange resin in each column was 1,900 cm^3 (114 in^3). The influent flow rate of 9.8 L/min (2.6 gpm) represented a volumetric loading rate equal to 5.2 bed volumes per minute.

SAMPLING AND LABORATORY ANALYSIS

Physical and chemical data were collected during each experimental run to assess treatment efficiencies. The water quality parameters monitored during Year 2 are shown in Table 6. In Year 1, additional parameters, including minerals (calcium, potassium, sulfate, chloride, magnesium, sodium, boron, and silica) and metals (total and dissolved cadmium, chromium, copper, lead, nickel, and zinc) were monitored.

Table 6 – Water Quality Parameters Monitored in Year 2

Field-Measured Parameters	Laboratory-Measured Parameters	
Specific Conductance	Alkalinity – Total	Total Phosphorus (Filtered)
pH	Total Dissolved Solids	Total Phosphorus (Un-Filtered)
Turbidity	Total Suspended Solids	Ortho-Phosphate (Filtered)
Temperature	Nitrate Nitrogen	Ortho-Phosphate (Un-Filtered)
	Nitrite Nitrogen	Total Aluminum (Unfiltered)
	Ammonia Nitrogen	Total Aluminum (Filtered)
	Total Kjeldahl Nitrogen (Filtered)	Acid Soluble Aluminum
	Total Kjeldahl Nitrogen (Un-Filtered)	Total Iron (Unfiltered)
	Total Organic Carbon	Total Iron (Filtered)
	Oil and Grease	

In general, samples of the influent and the effluents of the various treatment units were composites formed from multiple grab samples collected manually over the course of an experimental run. For the final step of the non-mechanized treatment systems (the filter effluent for the systems with sedimentation and filtration), the entire effluent volume for each half-run in Year 1 and for each run in Year 2 was collected in a sample collection tank as previously described. A grab sample was then taken from the filled tank (while being stirred) at the completion of the half run or run. In Year 1, the grab samples from each half run were composited to characterize the effluent for the entire run. Complete descriptions of the sampling procedures followed during Year 1 and Year 2 can be found in the respective Monitoring and Operations Plans (Caltrans, 2002 and 2003d).

Field sample processing activities included splitting the sample into multiple sample containers for various contaminant analyses and filtering various samples for dissolved analyses. All sampling and laboratory analyses were in accordance with the sampling and analytical requirements established by Caltrans for the monitoring of storm water (Caltrans, 2000). Environmental contamination of the samples during processing was minimized by making use of "clean sampling techniques" (Caltrans, 2000).

RESULTS OVERVIEW

The small-scale pilot treatment project discussed in this paper included assessments of the hydraulic characteristics and pollutant removal performances of the various treatment systems. All systems were analyzed with regard to all of the parameters listed in Table 6 for Year 2 and the additional parameters previously discussed for Year 1. In the space available here, it is impossible to discuss all of the results. Therefore, the focus of this paper is on turbidity and total phosphorus because these are the most important constituents for Lake Tahoe clarity. Algae and small particles washed into the lake are thought to contribute directly to loss of clarity, and Lake Tahoe is considered to be phosphorus-limited with regard to algae growth.

In the sections that follow, the hydraulic performances of the various filter systems are discussed, turbidity and phosphorus results for all of the treatment systems are presented and discussed in detail, followed by consideration of other constituents. Complete information on parameters monitored but not considered in detail here can be found in Caltrans 2003b and 2003c.

Six experimental runs were completed in each of the first two years of pilot operations. For various reasons, however, some of the treatment units were not operated in some of the runs. Therefore, the graphs in which treatment results are shown in the following sections have different numbers of data points for the various treatment units.

HYDRAULIC PERFORMANCE OF FILTER SYSTEMS

As previously noted, in Year 1, a total of 1.8 m (6 ft) of storm water was applied during each run to each of the non-mechanized filters. In Year 2, only 0.9 m (3 ft) was applied during each run. While the filters were in operation, filter head loss and/or drain-down times were observed and recorded. In Year 1, all of the filters were operated in the fast-load, free-drain configuration and many were not preceded by sedimentation basins. In Year 2, different loading rates and hydraulic conditions were tested, but all of the filters were preceded by sedimentation basins.

None of the non-mechanized filters following sedimentation failed hydraulically. Many of the filters not preceded by sedimentation, however, failed because of media blinding or clogging. Failure was judged to occur when the applied water remained on top of the media several hours after application. Except as otherwise noted later in this paper, after a filter failed, it was not used in subsequent runs. The filters that failed are listed in Table 7, together with the time of failure (Run Number, Fill Number) and the depth of storm water and solids load that had been applied from the beginning of the study to the point of failure.

The non-mechanized filters that were tested without chemical addition failed after 6.4 to 8.2 m (21 to 27 ft) of water and 2.0 to 2.3 kg/m2 (0.41 to 0.47 lb/ft2) were applied. This is of concern since it is anticipated that the average annual hydraulic loading for filters in the Lake Tahoe area will be in the range of 27 to 91 m (90 to 300 ft), depending on the specific configuration used. It is desirable that non-mechanized filters be able to operate for at least one full year without maintenance. As shown in Table 7, the filters that received chemicals failed even faster, most likely due to flocs accumulating on the filter surface. The only filters not preceded by sedimentation that did not fail were those using coarse sand as a filter media.

Table 7– Non-Mechanized Filter (Without Sedimentation) Hydraulic Failures (Year 1)

Filter Medium	Chemical	FailureRun,Fill	Applied Water, m (ft)	Applied TSS(a), kg/m2 (lb/ft2)
Fine Sand	None	5, 1	7.3 (24)	2.2 (0.44)
Zeolite None	None	5, 2	8.2 (27)	2.3 (0.47)
Activated Alumina	None	4, 2	6.4 (21)	2.0 (0.41)
Aluminum Oxide	None	5, 2	8.2 (27)	2.3 (0.47)
Fine Sand	PAM	1, 1	0.9 (3)	0.34 (0.07)
Coarse Sand	PAM	2, 1	2.7 (9)	0.72 (0.15)
Fine Sand	PAC	4, 2	6.4 (21)	2.0 (0.41)

(a) TSS = total suspended solids, expressed as mass per unit of filter surface area.

Since the storm water influent to the mechanized filters was always pre-treated by coagulation, flocculation, and sedimentation and had low turbidity, no significant head loss buildup was noted in either the Fuzzy Filter® or the pressure sand filter. Therefore, the pressure sand filter was not backwashed in Year 1 or in Year 2. The Fuzzy Filter® media, which were visible through the clear PVC vessel wall, became discolored (gray/brown) and were replaced with new media before Run 4 of Year 1. As a subsequent standard procedure, the Fuzzy Filter® media were replaced with cleaned or new media before Run 6 of Year 1 and before all runs in Year 2.

TURBIDITY REMOVAL

As noted in Table 1, the average turbidity of Tahoe area highway runoff is about 500 NTU, while the effluent limit for discharge to surface waters is 20 NTU. In the paragraphs that follow, the turbidity removal results for the various treatment systems are presented. Throughout the presentation, the performance of each treatment unit is illustrated in graphical form, with the influent concentration plotted on the horizontal axis and the effluent concentration plotted on the vertical axis (see Figure 4). A diagonal line indicates equal influent and effluent values. Data points falling below the diagonal line indicate that constituent removal (i.e., treatment) occurred. Also on each graph is a dashed horizontal line that indicates the regulatory requirement for discharge to surface waters (20 NTU).

Non-Mechanized Sedimentation With and Without Chemical Assistance

Turbidity removal performances of the non-mechanized sedimentation systems tested in Year 2 are shown in Figure 4. The systems represented by Figures 4a and 4e were tested in Year 1 also, giving similar results to those shown.

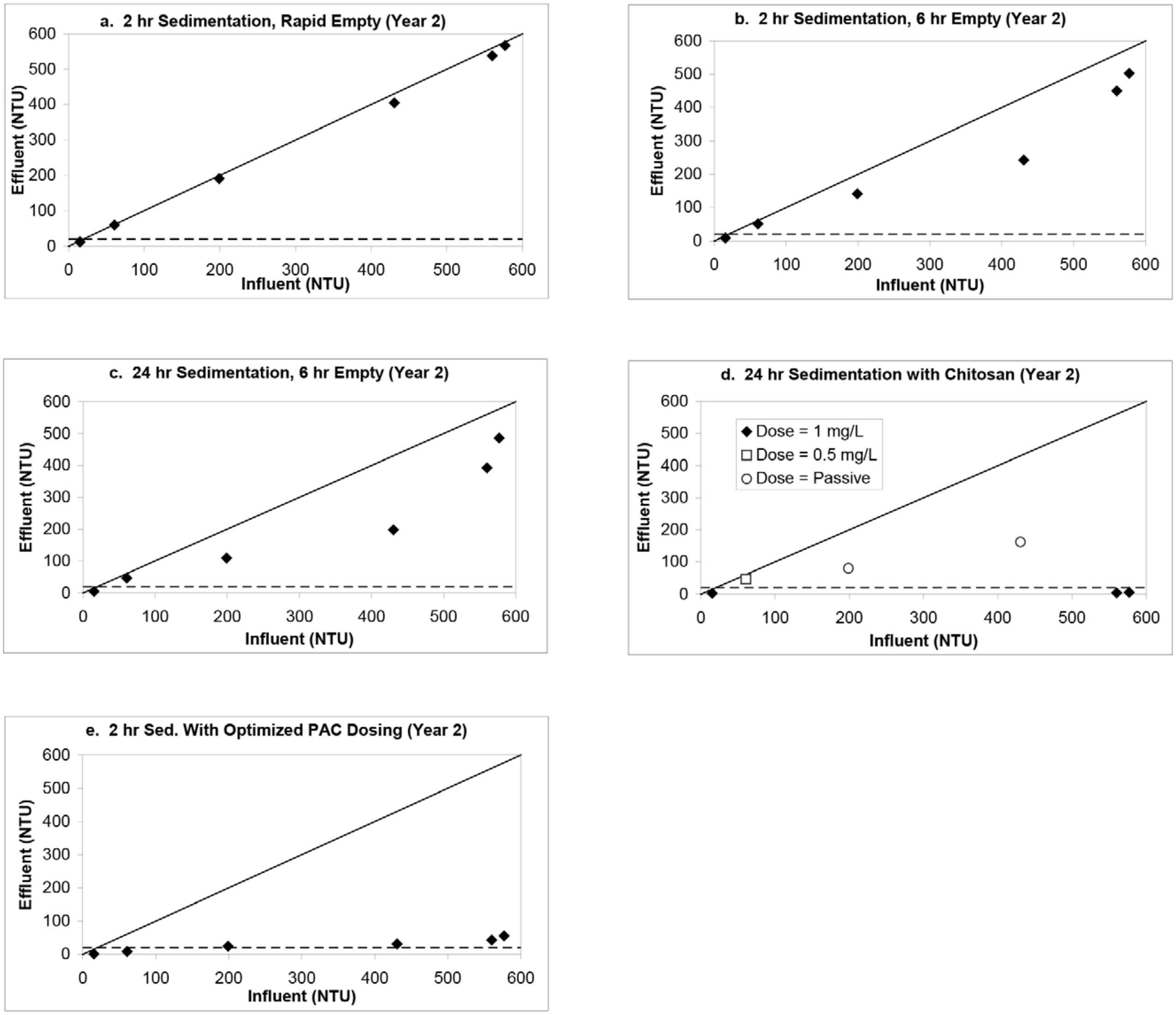


Figure 4 – Turbidity Results for Non-Mechanized Sedimentation Systems

As can be seen in Figures 4a, 4b, and 4c, sedimentation without chemicals was generally ineffective. Lengthening the detention time improved turbidity removals only minimally (compare Figure 4c to 4b). Comparing Figures 4b and 4c, it appears that most sedimentation occurs within a relatively few hours and that long holding times (i.e., 24 hours) provide little extra benefit.

Providing chemical coagulation in front of sedimentation greatly increased turbidity removals as seen in Figures 4d and 4e. When the dose was controlled, as it was with PAC and the liquid chitosan (the 0.5 and 1 mg/L doses in Figure 4d), the legal limit was achieved or almost achieved with sedimentation alone. The passive (tea bag) dosing method used in this study did not allow adequate dose control and this resulted in less efficient turbidity removals. It would appear that the passive dosing system tried here did not deliver a sufficient quantity of chitosan.

It’s important to note that in these experimental runs, the slow-mixing step commonly used in drinking water treatment plants was omitted. As previously described, the coagulant was injected, mixed in-line, and delivered directly to the sedimentation facility.

Non-Mechanized Filtration Without Sedimentation

As previously noted, all of these filters, except those containing coarse sand, failed hydraulically before completing even five runs in Year 1. From a practical point of view, then, this is not a viable approach. Nevertheless, examination of the water quality results gives some useful insights. Turbidity results for the runs that were completed or partially completed are shown in Figure 5. The coarse sand filter without chemical addition (Figure 5b) didn’t clog, but neither did it provide much treatment. Even with PAC, coarse sand was only moderately effective (Figure 5g). In contrast, the fine sand filter with chemical addition (Figure 5f) was very effective. Of the other filters not using chemicals (Figures 5a, 5c, 5d, and 5e), the activated alumina media (Figure 5d) showed the greatest promise.

Non-Mechanized Filtration Following Sedimentation Without Chemicals

Turbidity results for these systems are shown in Figure 6. All of the data are from Year 2, except for the concrete sand filter (Figure 6a), which was tested in Year 1. As noted earlier, none of these systems clogged during the study, suggesting that pre-filtration sedimentation is an essential component to successful operation, even when chemicals are not used.

The systems represented in Figure 6 incorporate a number of different sedimentation and filtration conditions. Comparing turbidity results can give insight into how to optimize design and operations of these kinds of systems. Although a little difficult to see from Figures 6a and 6b, the concrete sand and fine sand filters performed about the same in the fast load, free drain mode with 2 hours of sedimentation. Performance improved when the filter loading was slowed and controlled (Figure 6c). Arranging the outlet to submerge the media bed (Figure 6d) further improved performance, though not by a large amount. The effects of increasing the sedimentation time from 2 to 24 hours can be seen by comparing Figures 6c and 6e, and Figures 6d and 6f. Increasing detention time had little or no effect, an observation consistent with what was seen in the sedimentation-only systems (Figures 4b and 4c).

The results from the non-sand filters, expanded shale, limestone, Wollastonite, and activated alumina, are shown in Figures 6g through 6j. These were all slow-load, submerged filters following 24 hours of sedimentation. The equivalent sand filter is represented in Figure 6f. Under these conditions, the expanded shale (Figure 6g) and activated alumina (Figure 6j) media were more effective than sand and were the only media that consistently met or nearly met the 20 NTU regulatory limit, even without chemical addition. Limestone (Figure 6h) also performed better than sand, though not as well as expanded shale and activated alumina. Because of difficulties in obtaining the Wollastonite media, it was available for only two runs (Figure 6i), and its performance was similar to that of fine sand (Figure 6f).

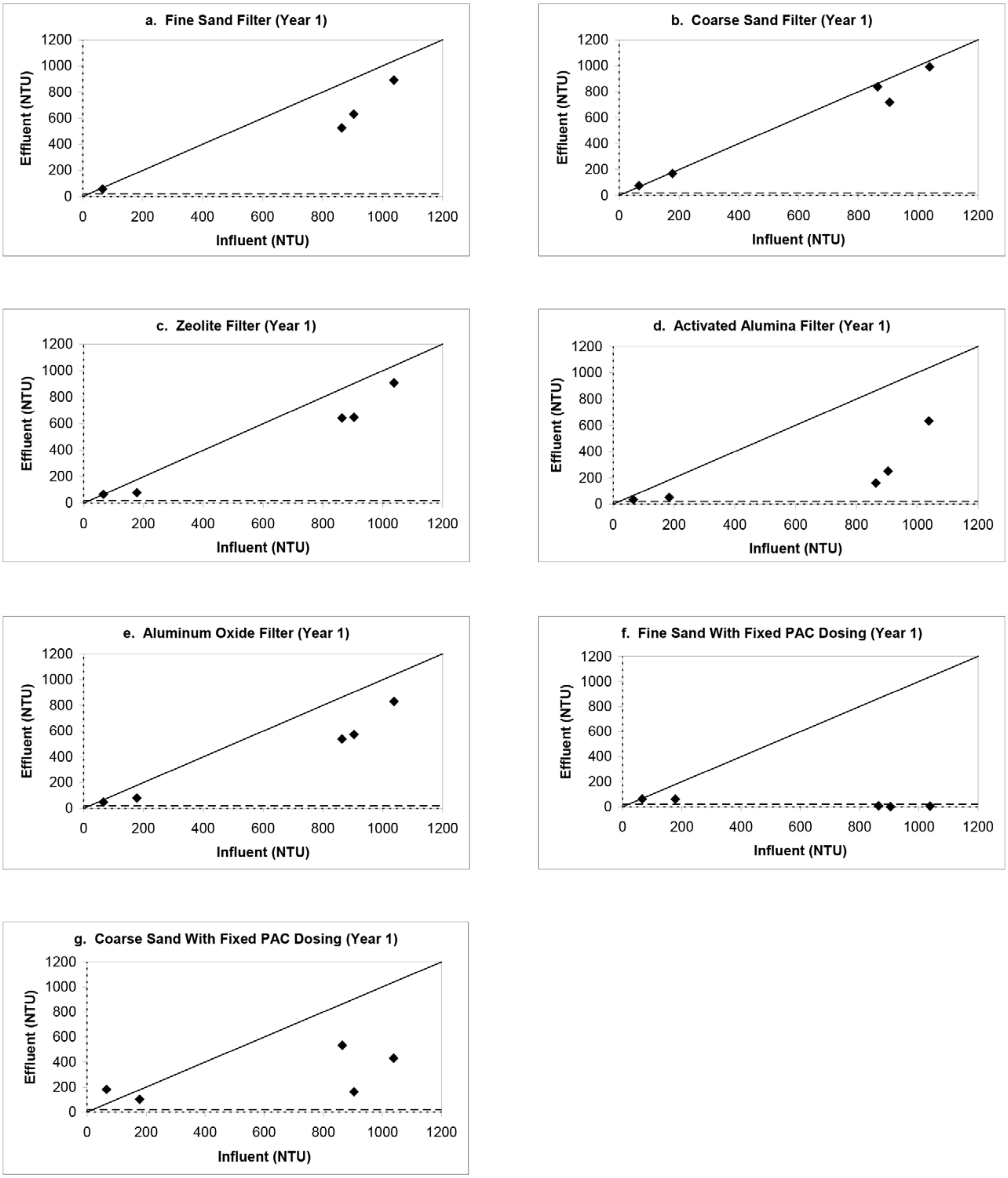


Figure 5 – Turbidity Results for Non-Mechanized Filtration Systems Without Sedimentation

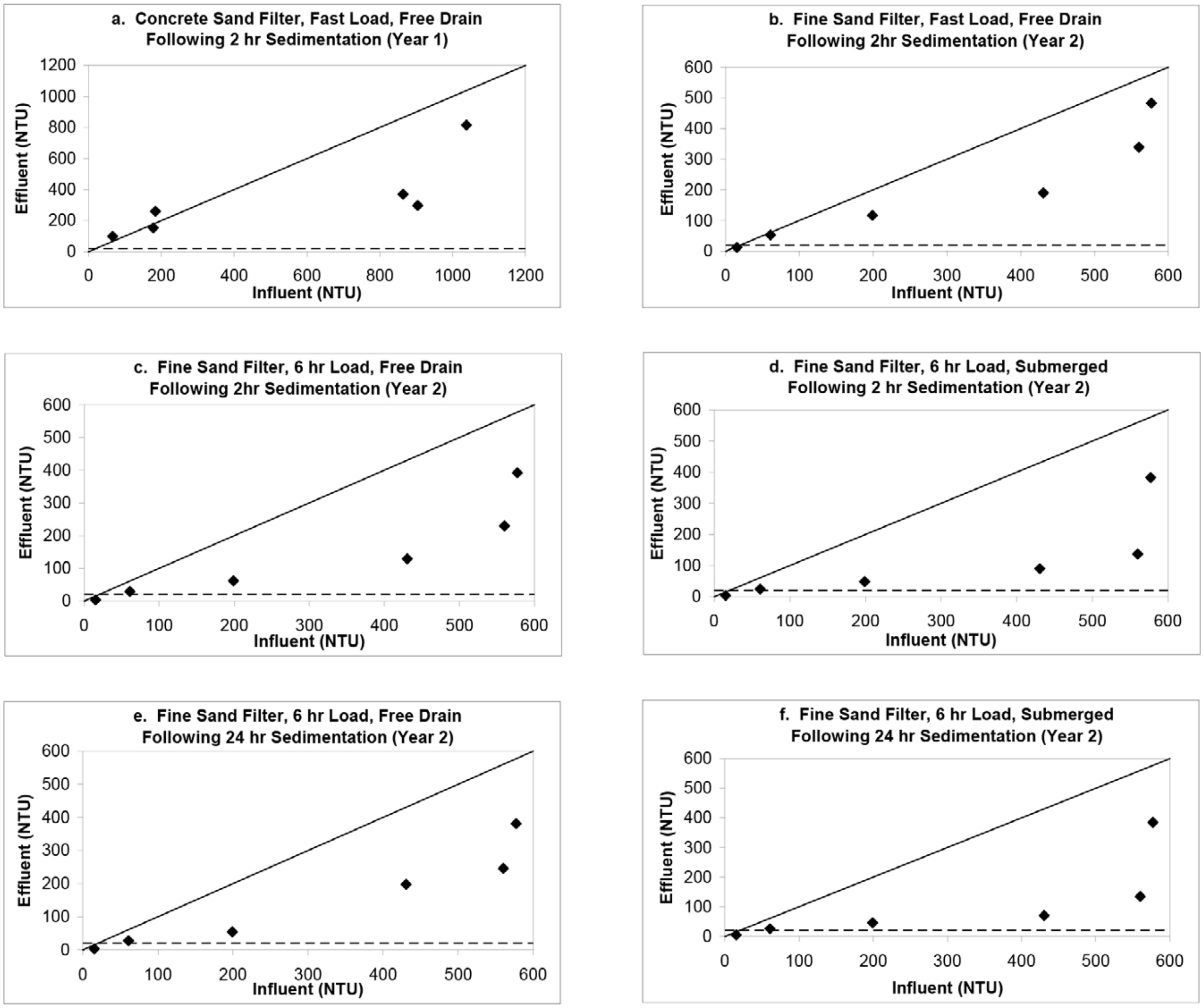


Figure 6 (Part 1) – Turbidity Results for Non-Mechanized Filtration Following Sedimentation Without Chemicals

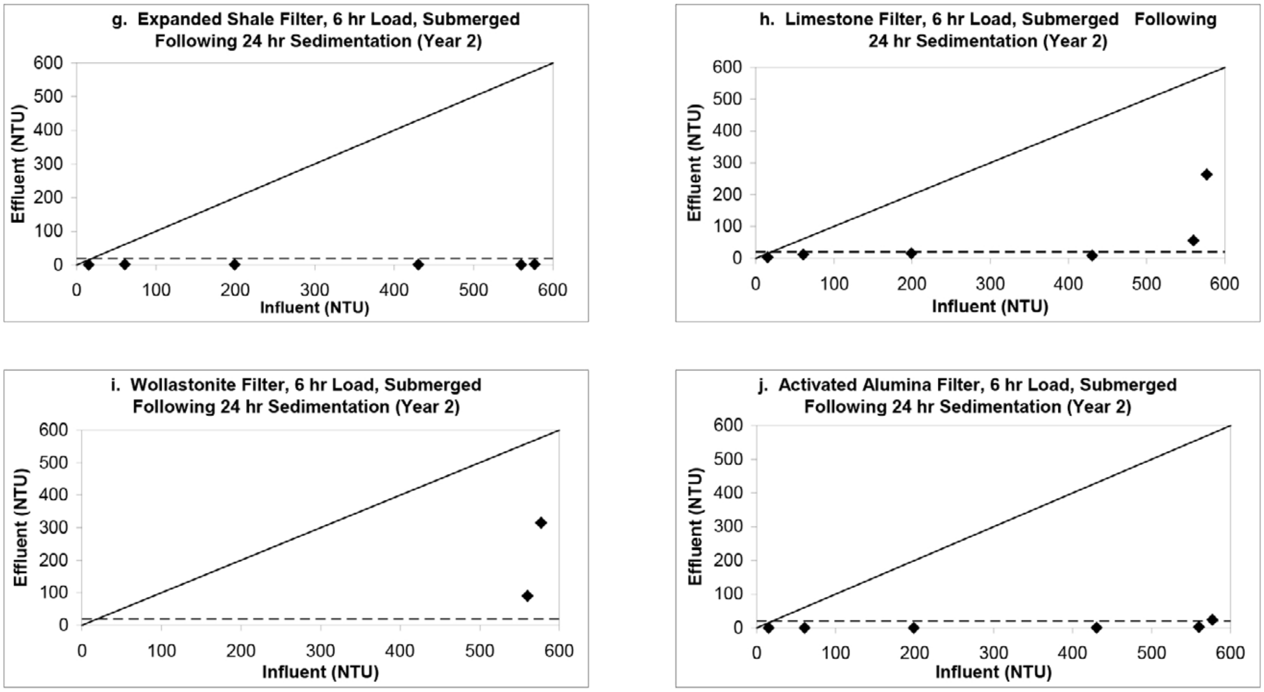


Figure 6 (Part 2) – Turbidity Results for Non-Mechanized Filtration Following Sedimentation Without Chemicals

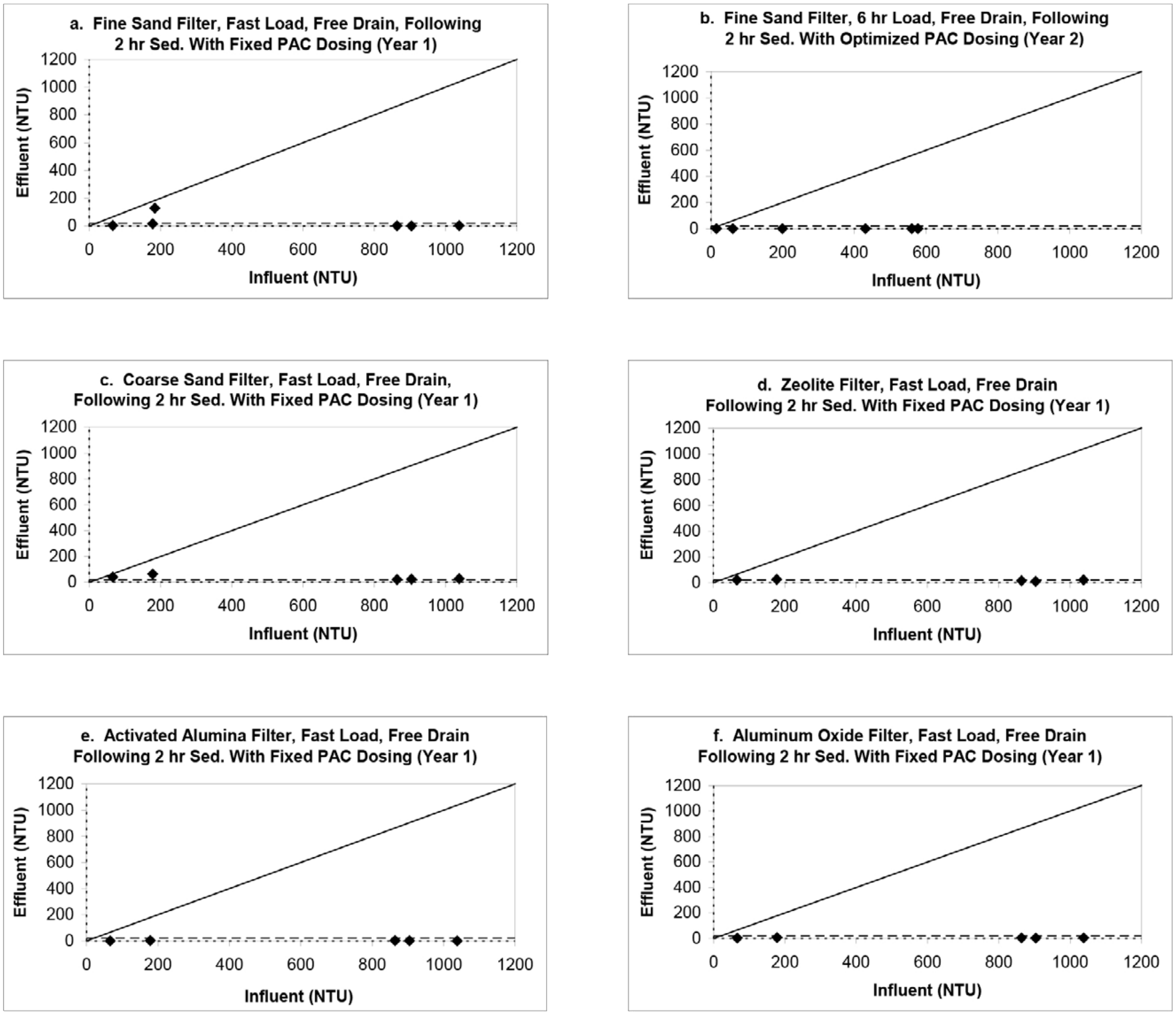
Non-Mechanized Filtration Following Sedimentation With Chemicals

In Year 1, five different filter media following 2-hour sedimentation and coagulation using PAC were tested. All of the filters were fast-load, free-drain units which, as described above, was the least effective operational mode when chemical addition was not used. Despite this, all five systems consistently met or nearly met the 20 NTU turbidity limit (see Figures 7a, and 7c through 7f). In Year 2, the fine sand filter following 2-hour sedimentation and coagulation with PAC. was tested again. In this case, however, the free-drain filter was loaded over six hours and the PAC dose was optimized by running jar tests on each influent sample. As shown in Figure 7b, this system consistently met the 20 NTU turbidity limit. Although it is likely that the slow loading and optimized chemical dosing used in Year-2 enhanced the performance of the system represented in Figure 7b as compared to the system represented in Figure 7a, that conclusion can not be firmly made because different storm waters were tested (Year 1 versus Year 2).

Mechanized Treatment Systems

Turbidity results for the mechanized coagulation, flocculation, and sedimentation processes tested in Years 1 and 2 are shown in Figure 8. Recall that the mechanized systems incorporated both fast and slow mixing and use of both coagulant and flocculant chemicals. As can be seen in Figure 8, both the Actiflo® and the conventional coagulation, flocculation, and sedimentation systems consistently met the 20 NTU turbidity limit, with the exception of one run in Year 1. Because downstream treatment processes added no meaningful improvement in water quality except for the one run in Year 1, the results from these systems (listed as systems 2, 3, 4, 5, 7 and 8 in Table 4) are not shown here. In the one run in Year 1 that the 20-NTU limit wasn't met after sedimentation, the influent turbidity of 184

NTU was reduced to 30 NTU in the Actiflo® unit, and was further reduced to 25 and then 19 NTU in the subsequent Fuzzy Filter® and ion exchange systems, respectively.


a. Fine Sand Filter, Fast Load, Free Drain, Following 2 hr Sed. With Fixed PAC Dosing (Year 1)

b. Fine Sand Filter, 6 hr Load, Free Drain, Following 2 hr Sed. With Optimized PAC Dosing (Year 2)

c. Coarse Sand Filter, Fast Load, Free Drain, Following 2 hr Sed. With Fixed PAC Dosing (Year 1)

d. Zeolite Filter, Fast Load, Free Drain Following 2 hr Sed. With Fixed PAC Dosing (Year 1)

e. Activated Alumina Filter, Fast Load, Free Drain Following 2 hr Sed. With Fixed PAC Dosing (Year 1)

f. Aluminum Oxide Filter, Fast Load, Free Drain Following 2 hr Sed. With Fixed PAC Dosing (Year 1)

Figure 7 – Turbidity Results for Non-Mechanized Filtration Following Sedimentation With PAC

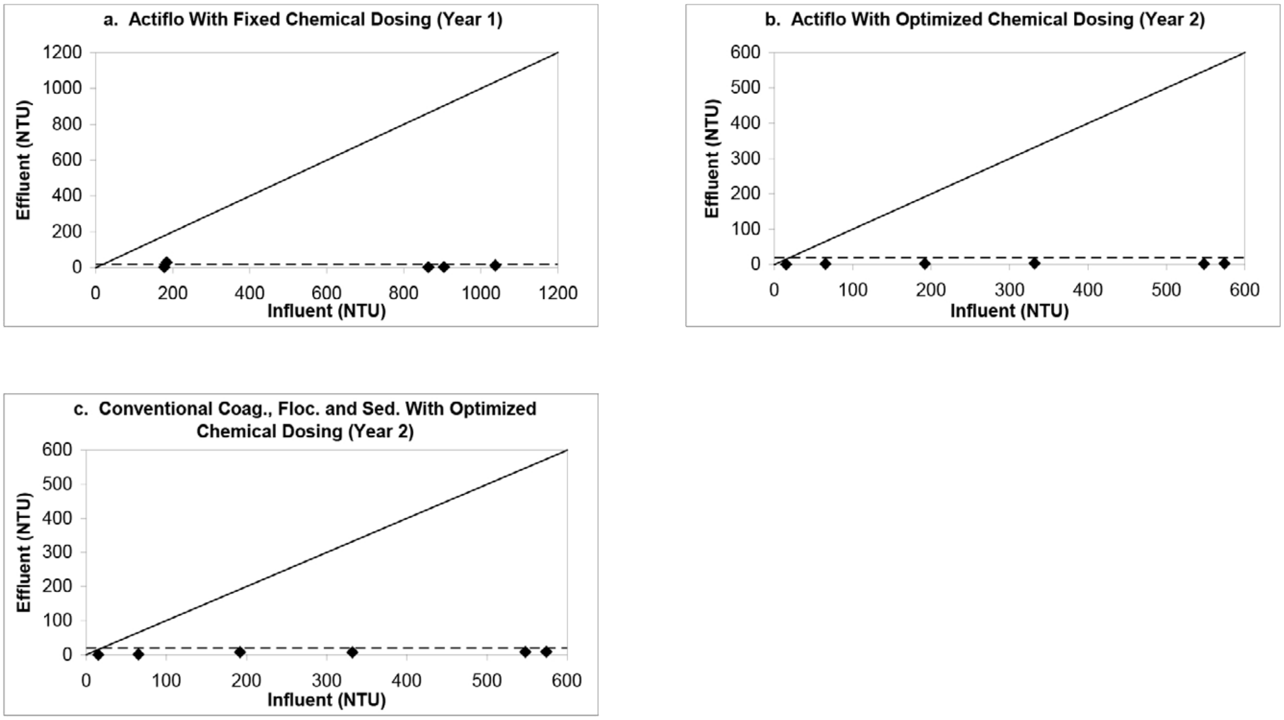


Figure 8 – Turbidity Results for Mechanized Coagulation, Flocculation, and Sedimentation

PHOSPHORUS REMOVAL

As noted in Table 1, the average total phosphorus concentration in Lake Tahoe area highway runoff is 2.1 mg/L, while the effluent limit for discharge to surface waters is 0.1 mg/L. In the paragraphs that follow, the phosphorus removal results for the various types of treatment units are presented. Throughout the presentation, the performance of each treatment unit is illustrated in graphical form similar to the graphs used for the turbidity plots. In the following plots, however, dotted lines were added parallel to both the vertical and horizontal axes to indicate the analytical reporting limit (usually 0.03 mg/L). Laboratory results at or below the reporting limit are shown on the reporting limit line. In considering the experimental results, it is helpful to realize that the dissolved fraction of influent total phosphorus in Year 1 almost always exceeded 0.1 mg/L, sometimes substantially, and was considerably lower in Year 2, never exceeding 0.1 mg/L.

Non-Mechanized Sedimentation With and Without Chemical Assistance

Total phosphorus treatment performances for the non-mechanized sedimentation systems tested in Years 1 and 2 are shown in Figure 9. Sedimentation without chemical assistance is shown in Figures 9a through 9d. Sedimentation with chitosan is shown in Figure 9e and sedimentation with PAC is shown in Figures 9f (constant dose of 100 mg/L) and 9g (dose optimized for each run).

As with the turbidity results, sedimentation without chemicals (Figures 9a through 9d) was ineffective at reducing total phosphorus. In contrast, all of the chemical-assisted systems produced substantial total phosphorus removals. Sedimentation after treatment with a 1 mg/L dose of liquid chitosan (Figure 9e) and with PAC doses based on jar testing for the individual runs (Figure 9g) were effective at meeting the regulatory limit in almost all runs. Passive dosing of solid chitosan using the tea bag approach, liquid chitosan at a dose of 0.5 mg/L, and nonoptimized constant PAC dose of 100 mg/L were less effective. Although proper dosing was most likely a factor contributing to the treatment results for the better-performing systems, since side-by-side testing of different dosing schemes on the same storm water was not completed, this conclusion can not be firmly made from the data presented.

Non-Mechanized Filtration Without Sedimentation

Total phosphorus results for the various fast-load, free-drain filters tested with and without chemical addition in Year 1 are shown in Figure 10. As indicated in the figure, none of the filters were able to meet the regulatory total phosphorus limit, though the activated alumina filter (Figure 10d) and the fine sand filter with PAC (Figure 10f) provided somewhat better performance than the other units. These results generally mirror the turbidity results, except for the fine sand filter with PAC. In this case, turbidity removal (Figure 5f) was better than phosphorus removal, probably reflecting the fact that a substantial fraction of the influent phosphorus in Year 1 was in dissolved form.

Non-Mechanized Filtration Following Sedimentation Without Chemicals

Total phosphorus treatment results for these systems are shown in Figure 11. All of the data shown are from Year 2, except for the concrete sand filter, which was tested in Year 1. As previously discussed, different sedimentation times and filter configurations were tested in Year 2, and these are noted on the graphs in Figure 11. Generally speaking, the effects of different sedimentation times and filtration conditions on phosphorus removal are similar to those on turbidity removal (Figure 6) and similar comments could be repeated here. These observations are consistent with the influent data showing that the majority of the influent phosphorus in Year 1 and almost all of the phosphorus in Year 2 was in particulate form. The key observations to be made here are that the shale and activated alumina filters (Figures 11g and 11j) consistently met or nearly met the 0.1-mg/L regulatory limit for total phosphorus. The limestone filter performance (Figure 11h) was similar, except for one run. Sand filters (without chemical addition) did not come close to meeting the total phosphorus limit regardless of how they were operated.

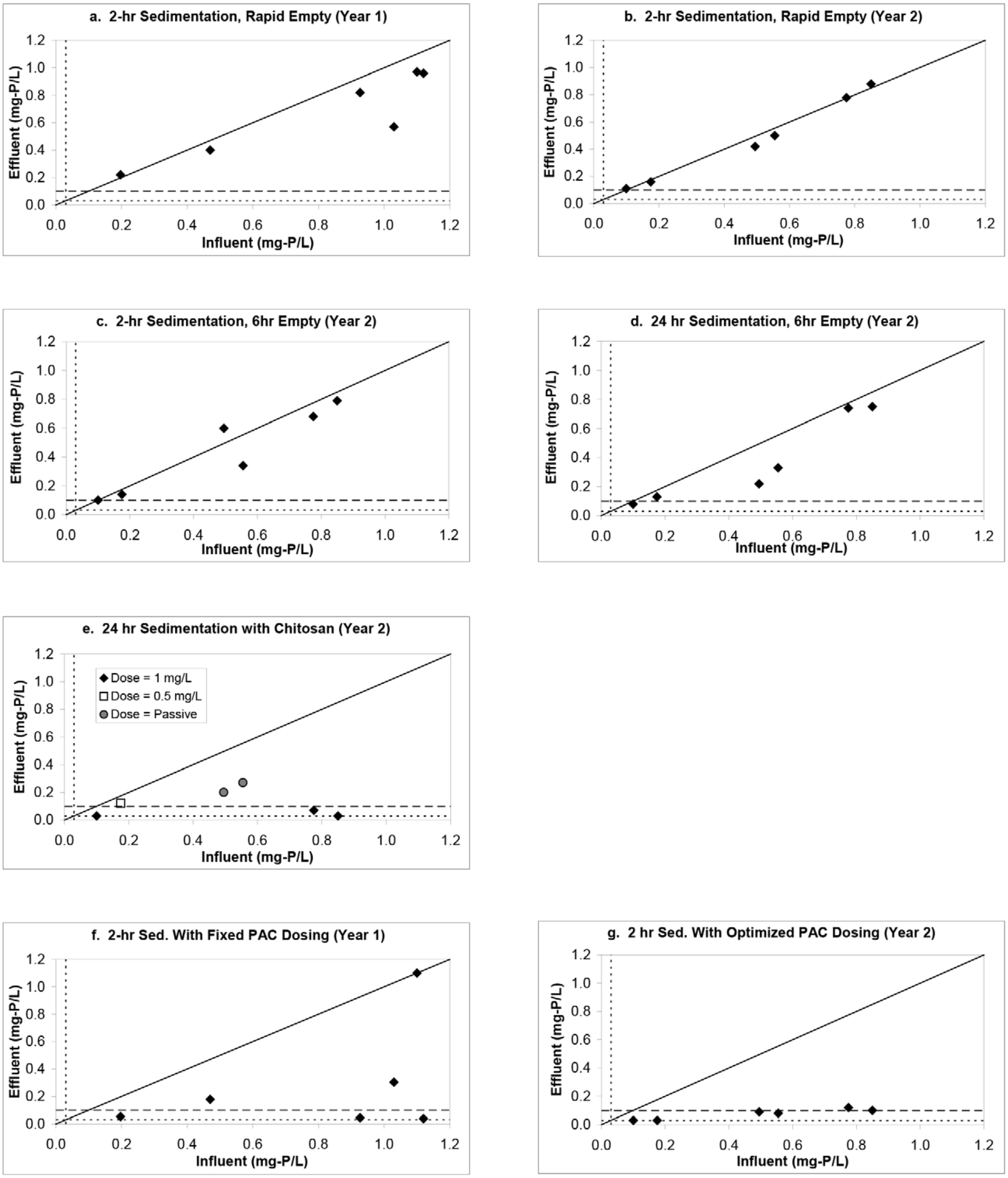


Figure 9 – Total Phosphorus Results for Non-Mechanized Sedimentation Systems

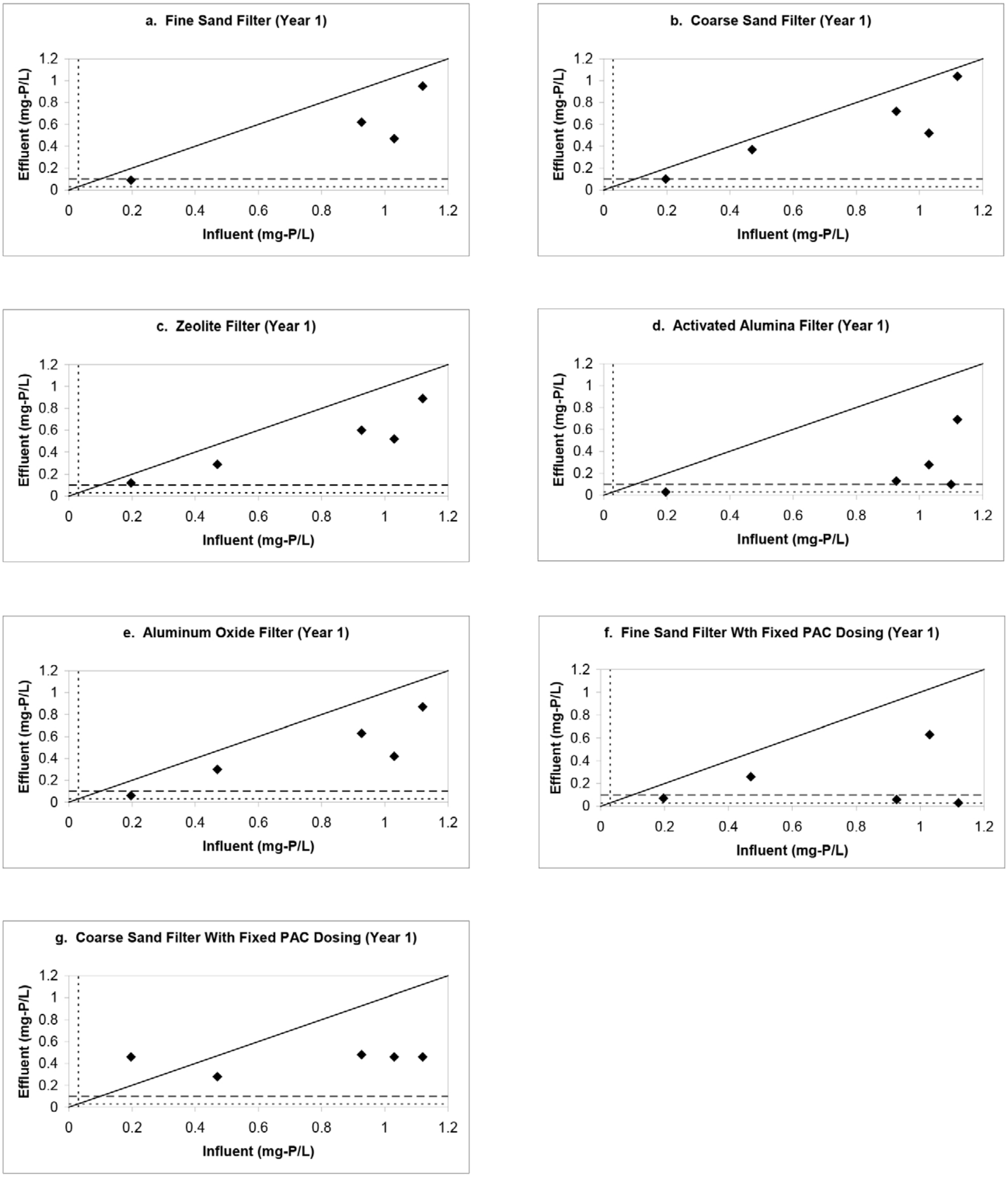


Figure 10 – Total Phosphorus Results for Non-Mechanized Filtration Systems Without Sedimentation

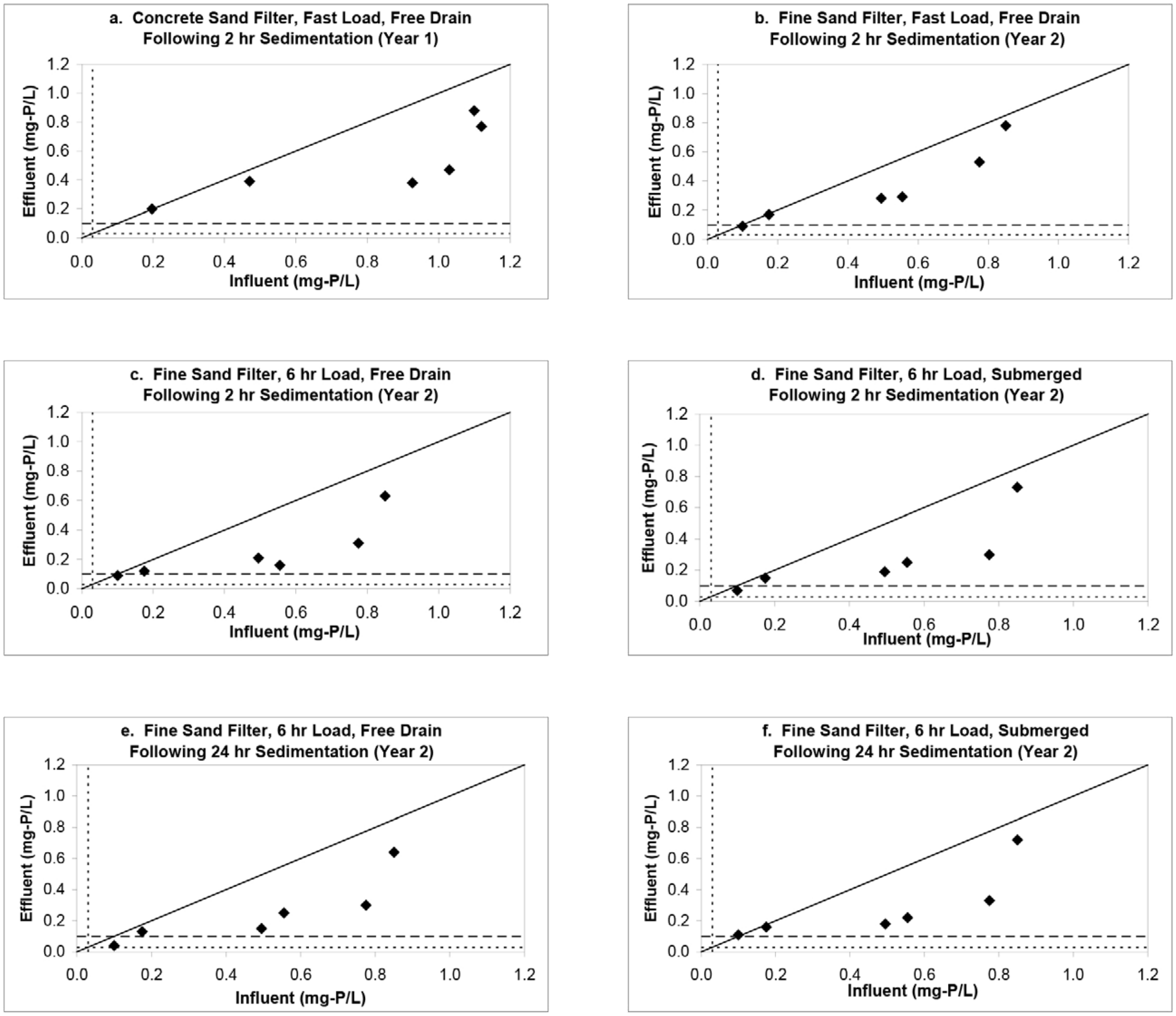


Figure 11 (Part 1) – Total Phosphorus Results for Non-Mechanized Filtration Following Sedimentation Without Chemicals

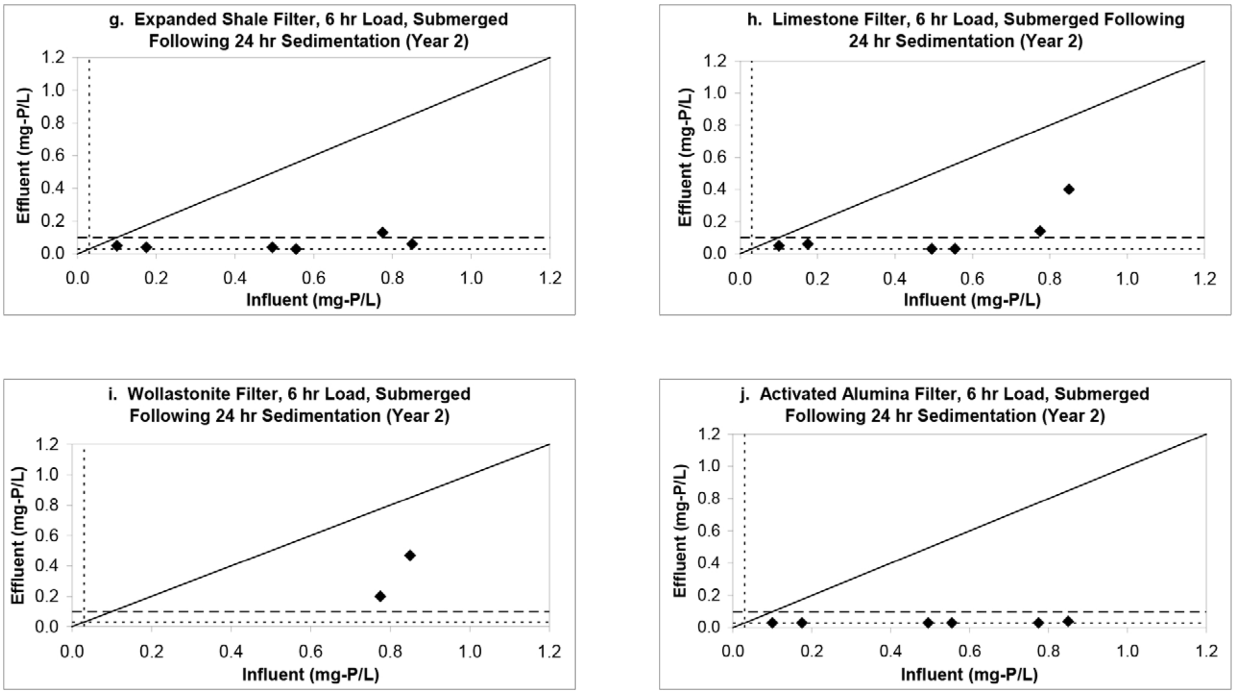


Figure 11 (Part 2) – Total Phosphorus Results for Non-Mechanized Filtration Following Sedimentation Without Chemicals

Non-Mechanized Filtration Following Sedimentation With Chemicals

Total phosphorus results for these systems, all using PAC as a coagulant, are shown in Figure 12. All of the experiments shown in this figure occurred in Year 1 except for the fine sand with slow loading and optimized PAC dosing (Figure 12b). As can be seen, this was the only system that met the 0.1-mg/L total phosphorus limit in all runs. Three features differentiate the fine sand system in Year 2 (Figure 12b) from that in Year 1 (Figure 12a): optimized vs. constant dosing, slow vs. fast loading, and different storm waters. How much each factor contributed to the improvement in performance cannot be distinguished from these data.

All of the other systems tested were successful in accomplishing substantial phosphorus removals. Although the results were similar for all the non-sand media tested in Year 1, the activated alumina and aluminum oxide filters performed slightly better than the other two, meeting the regulatory limit in four of five experimental runs.

In comparing the Year 1 fine sand filter system (12a) with the other Year 1 systems (12c through 12f), it should be noted that the fine sand filter system was operated for six runs, whereas the other systems were operated for only five runs. The worst performance for this unit (the high point in Figure 12a) was in the sixth run when the other units were not operated. Whether this result is due to a deficiency in the sand filter, or whether it reflects some special characteristic of the influent that would have prevented the other filters from treating it effectively, cannot be ascertained. Therefore, this data point should not be considered in comparing the systems.

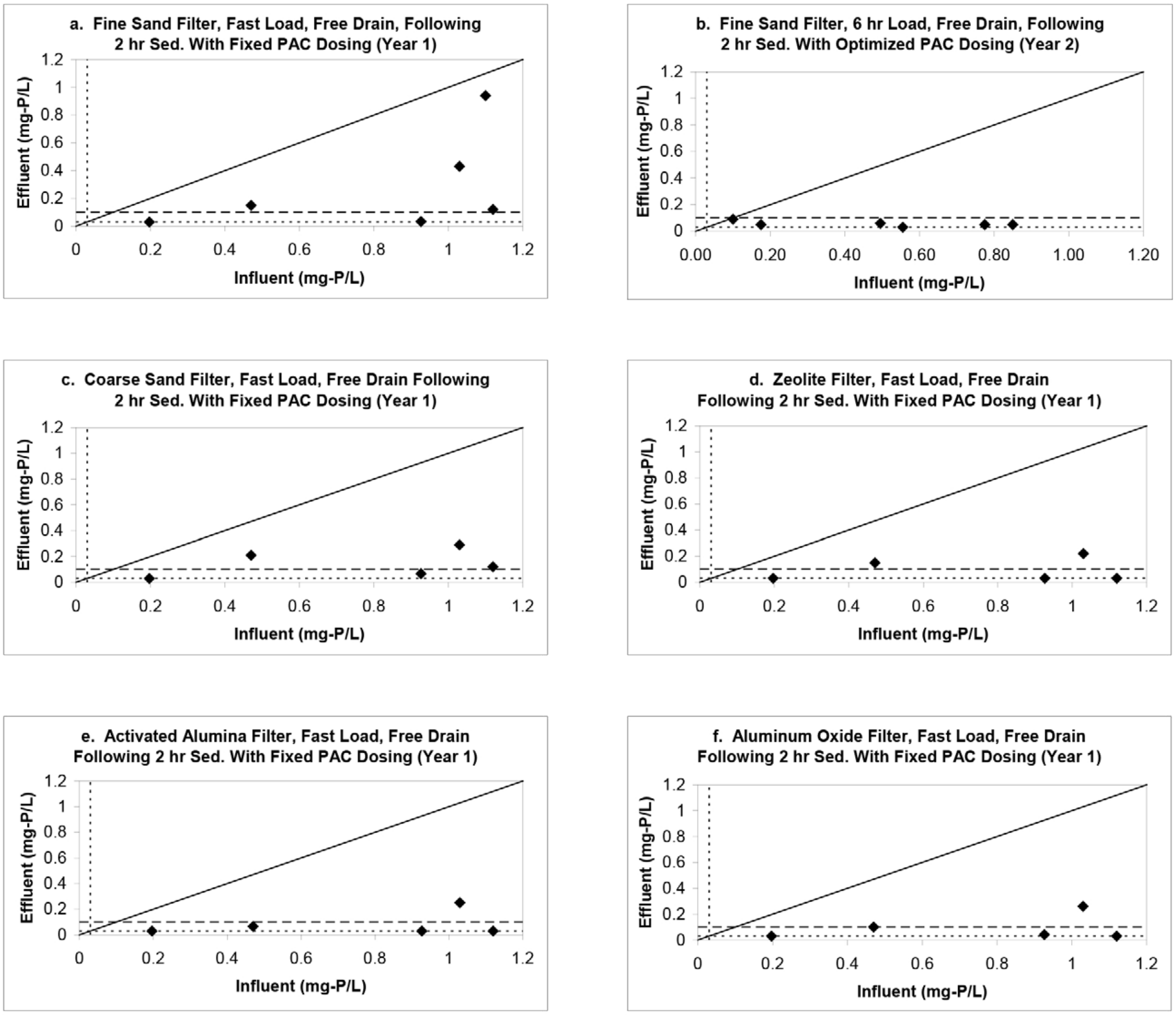


Figure 12 – Total Phosphorus Results for Non-Mechanized Filtration Following Sedimentation With PAC

Mechanized Treatment Systems

Total phosphorus results for the mechanized treatment systems tested in Years 1 and 2 are shown in Figure 13. In Year 2, both the Actiflo® and the conventional coagulation, flocculation, and sedimentation systems produced effluents with total phosphorus below the reporting limit in all six runs. Results for the downstream filters and ion exchange units for Year 2 are irrelevant and are not shown.

In Year 1, the only mechanized coagulation, flocculation, and sedimentation system tested was the Actiflo® system. In that year, the total phosphorus limit was not met by Actiflo® treatment in two of the five runs completed. Furthermore, for those two runs (Runs 1 and 6), subsequent treatment by the filters and ion exchange units still failed to meet the limit (the pressure sand filter was not operated in Run 6). Only five ion exchange results are shown in Figure 13d because the ion exchange effluents for both the Fuzzy Filter® and the pressure sand filter were composited together before the sample was sent out for laboratory analysis. The specific influent characteristics or other factors that prevented adequate treatment in Runs 1 and 6 are unknown. In Run 1 the dissolved fraction of the influent was about 0.1 mg/L and never declined as the water moved through the treatment processes. In Run 6, the influent dissolved phosphorus was an unusually high 0.68 mg/L, and even though it declined substantially as the water moved through the treatment processes, the drop in dissolved concentration wasn't enough to cause the total phosphorus in the effluent to drop below 0.1 mg/L.

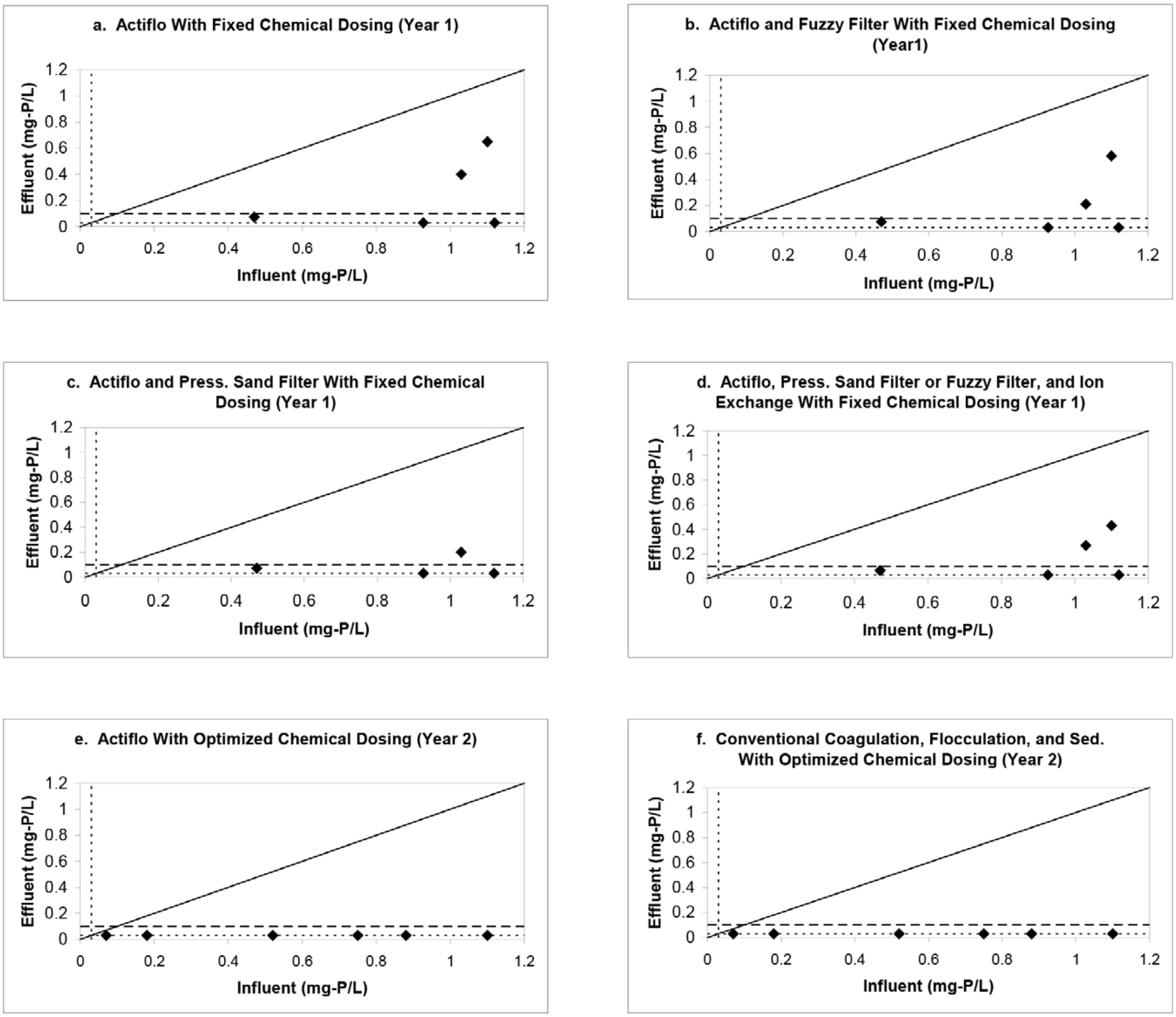


Figure 13 – Total Phosphorus Results for Mechanized Treatment Systems

OTHER CONSTITUENTS

Although turbidity and phosphorus are the most important constituents in terms of effects on Lake Tahoe, legal restrictions have been placed on nitrogen, iron, and oil and grease as well. These constituents are discussed briefly below. Also, considered in this section are impacts on dissolved aluminum and pH caused by some of the treatment systems.

Total Nitrogen

None of the non-mechanized or mechanized treatment systems tested in Year 1 was successful at consistently removing total nitrogen to meet the regulatory limit of 0.5 mg/L. Analysis of the influent characteristics revealed that in most experimental runs, soluble organic nitrogen plus nitrite and nitrate exceeded 0.5 mg/L. Because none of the experimental treatment processes except ion exchange were designed to remove dissolved forms of nitrogen, their ineffectiveness is not surprising. In Year 2, several systems appeared to be successful. These results are, however, inconclusive because the influent concentrations were significantly lower than average highway runoff values. As shown in Table 1, highway runoff averaged 2.7 mg/L total nitrogen, while the small-scale influent concentrations never exceeded 1.5 mg/L and were often below 1 mg/L. As in Year 1, a significant fraction of the influent nitrogen was dissolved. Details on the forms of nitrogen observed and the relative effectiveness of various systems can be found in Caltrans 2003b and 2003c.

Total Iron

The regulatory limit for total iron in storm water discharged to surface waters in the Lake Tahoe basin is 0.5 mg/L. Influent storm water concentrations in the pilot testing program were always substantially higher, with a median value around 10 mg/L and a high around 33 mg/L. Despite this, all the mechanized systems and the non-mechanized systems employing chemicallyenhanced sedimentation and filtration either met or almost met the limit in the majority of experimental runs. The activated alumina and expanded shale filters following sedimentation were the only successful systems without chemical addition. Non-mechanized systems without chemicals involving sedimentation alone, filtration alone, and sedimentation followed by sand filtration (all three types of sand tested) were ineffective. Details on the performance of the various treatment systems with regard to total iron removals can be found in Caltrans 2003b and 2003c.

Oil and Grease

As indicated in Table 2, the average oil and grease concentration for Lake Tahoe storm water is 18 mg/L. In the small-scale pilot testing program, though, oil and grease were often not detected above the reporting limit in influent samples, and when it was above the reporting limit, concentrations were in the range of only 5 to 11 mg/L. These low values may be due to partial treatment in the detention basins from which the experimental storm water was obtained and/or may be due to oil and grease adhering to the surfaces of tanks and piping during transport and storage. Generally, all of the mechanized treatment systems and most of the non-mechanized sedimentation/filtration combinations were successful at consistently removing oil and grease to the 2 mg/L regulatory limit. Sedimentation without chemical assistance was almost never successful at meeting the regulatory limit. Conclusions based on these results should be considered very preliminary because of the low influent concentrations and the fact that the legal limit is right at the reporting limit for laboratory analysis of this constituent. Details regarding oil and grease removal can be found in Caltrans 2003b and 2003c.

Aluminum

Although total aluminum concentrations decreased as a result of treatment, dissolved aluminum concentrations in the effluents of activated alumina, aluminum oxide, and expanded shale filters exceeded the influent values, which were almost always below the reporting limit of 25 µg/L. Average effluent concentrations from the filter media indicated ranged from about 230 to 690 µg/L. The US EPA chronic water quality objective for aluminum is 87 µg/L and the acute toxicity criterion is 750 µg/L (Brooke and Stephan, 1988). Applicable regulatory requirements are unclear at the present time. Neither aluminum objective is included in the California Toxics Rule (USEPA, 2000), though existing narrative regulations prohibit toxicity (LRWQCB, 1994).

pH

In the Lake Tahoe basin, it is required that storm water discharges must not depress receiving water pH values below 6.5 or raise them above 8.5 (LRWQCB, 1994). Several of the filter media tested resulted in pH increases above 8.5 in the filter effluent. Filtration with activated alumina resulted in effluent pH values typically in the range of about 9.0 to 9.5. Wollastonite filtration resulted in a pH of 9.1 (though only two runs were conducted). Expanded shale filtration resulted in the greatest pH increase, with effluent pH values ranging from 10.9 to 11.5. Because of the low alkalinity of Tahoe storm water, PAC tended to depress the pH of the storm water, sometimes resulting in effluent pH values near or slightly below 6.5 in both the nonmechanized and mechanized treatment systems. It is not clear how such effluents might be regulated, given that the water quality objective applies to receiving waters.

DISCUSSION

In evaluating the results of this study, it is helpful to be mindful of its goals. Although Caltrans' long-term goal is to develop treatment technologies to meet applicable water quality regulations, this study is just the first step of that process. It should be viewed as a scoping study in which the boundaries of the problem and possible solutions are explored.

One identified boundary is that conventional storm water treatment BMPs (Best Management Practices) won't be adequate to meet the Tahoe water quality requirements. Sedimentation alone and sand filtration following sedimentation were tested. These simulated detention basins and conventional "Austin-style" sand filters. Extending sedimentation time was observed to improve performance, though with diminishing marginal benefits. Filter performance was improved by controlling hydraulic loading rate and submerging the media. Despite these improvements, neither approach was successful in consistently meeting the discharge limits.

Another identified boundary is that at least some of the discharge limits could be met using mechanized treatment systems. Both the conventional coagulation, flocculation, and sedimentation system and the Actiflo® process were able to consistently meet the surface water discharge limits for both turbidity and phosphorus (except two runs in Year 1) even without subsequent filtration or ion exchange. This level of technology is not dissimilar to that used in drinking water treatment plants, but is considerably more sophisticated than what has generally been applied to storm water systems.

Between the boundaries indicated above, some of the non-mechanized systems with chemical enhancement and/or adsorptive filter media provided promising results. As a general rule, chemical addition greatly enhanced treatment results for the non-mechanized systems. Adding chemicals (optimized doses of PAC or a liquid chitosan dose of 1 mg/L) so improved the performances of sedimentation alone and sand filtration following sedimentation that in Year 2, these systems met or nearly met the discharge limits for turbidity and phosphorus. While chemical addition was found to be necessary for sand filters, other types of media showed potential for meeting discharge limits without chemicals. In particular, expanded shale and activated alumina filters following sedimentation without chemicals consistently met or nearly met the surface water discharge limits for both turbidity and phosphorus. These media were not without problems, though; they both increased dissolved aluminum concentrations and pH values, which raises potential toxicity concerns.

Based on the results of this study, reliable conclusions can be made concerning which systems did not work. Conclusions about which systems did work must, however, be considered

preliminary. One issue is the representativeness of the influent characteristics. For instance, influent total phosphorus concentrations for the experimental runs were relatively low, often well below the 2.1 mg/L mean value for Tahoe Basin highway runoff. A second issue, particularly related to non-mechanized filters, is the relatively small volume of water applied to the test systems. In this study, a maximum of 11 m (36 ft) of water were applied to the test filters, while in the field, the application rate is expected to be 27 to 91 m (90 to 300 ft) per year. Thus, a filter that operated successfully in the study, might not continue to operate successfully with loadings expected to occur in the field. Finally, it should be noted that none of the systems tested met the nitrogen discharge limits. Although turbidity and phosphorus are thought to be the more important parameters affecting lake quality, there is a legal requirement to remove nitrogen that has yet to be met.

FUTURE STUDIES

From the results of this study and in consideration of the issues faced by Caltrans, two major areas of future research have been identified. The first is related to chemically-enhanced sedimentation. Future research should include testing the effectiveness of additional chemicals, evaluating chemicals for aquatic toxicity, and developing methods to predict and deliver optimum doses. The second major area of research should be in the direction of adsorptive media filtration without chemicals, because such systems are probably best suited for roadside applications, particularly where power may not be available. Future research should include testing the effectiveness of additional media, determining design parameters such as media depth and hydraulic loading rates, and evaluating filter performance under long-term loading. Finally, field trials of both approaches will be necessary to demonstrate effectiveness under a variety of storm water flows and characteristics.

Whether the treatment technologies tested will be affordable or practical in full-scale applications in the Tahoe Basin is unclear at this time. Unfortunately, less expensive and more compact alternatives that can meet the legal requirements for surface water discharge are not readily available.

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