Day 5: Case Studies Monitoring Stormwater in Industrial Areas

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And Many Graduate Students!

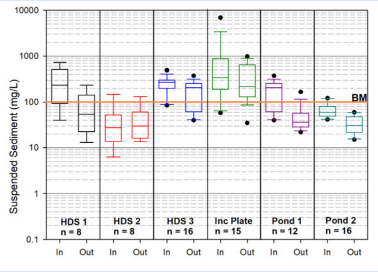
Outline of Presentation

- Overview of Industrial Stormwater Treatment Performance
- Case study of heavy industrial site monitoring and treatment research
- Additional examples of stormwater monitoring and sampling
- Ranking methodology to select treatment locations at large historical industrial site

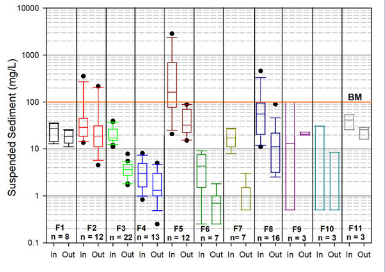
Overview of Industrial Stormwater Treatment

Suspended Sediment: Unit Operation Evaluation for Industrial Stormwater Treatment Systems

Sedimentation Devices



Filtration Systems



- Hydrodynamic separators may not meet benchmark (BM) when influent exceeds BM.
- Filtration systems better able to meet BM, but limited data for influents above BM.

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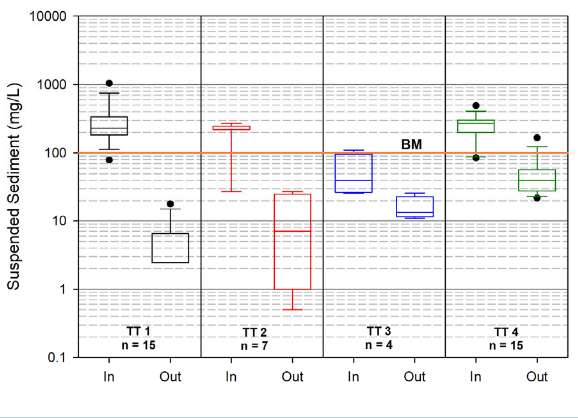
Suspended Sediment: Improving Performance Using Treatment Trains for Industrial Stormwater Treatment



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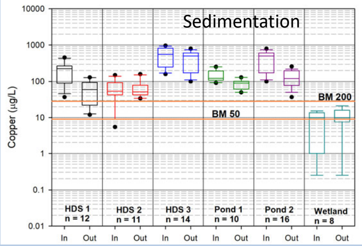
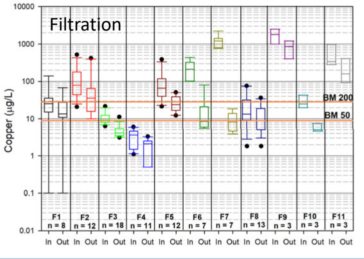
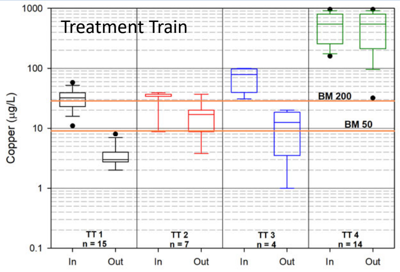
Copper: BM Based on Receiving Water Hardness







- Sedimentation alone not effective
- Certain filters, but not all filters, can meet soft-water BM
- Treatment trains can meet hard-water BM
  - TT1 has sand-peat filter and can meet soft-water BM

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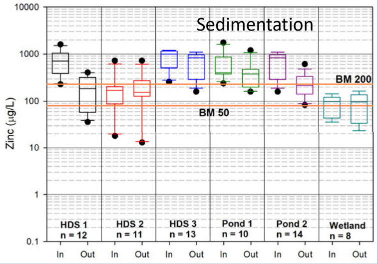
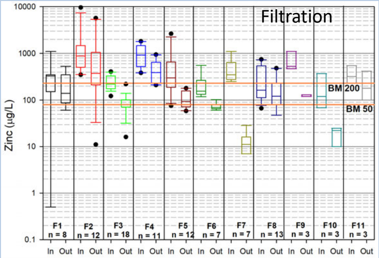
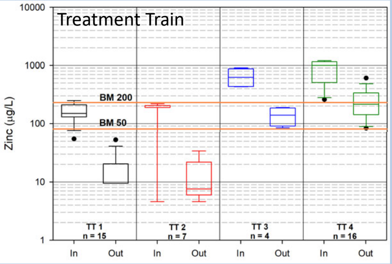
Zinc: BM Based on Receiving Water Hardness







- Sedimentation alone not effective
- Certain filters, but not all filters, can meet soft-water BM
- Treatment trains can meet hard-water BM

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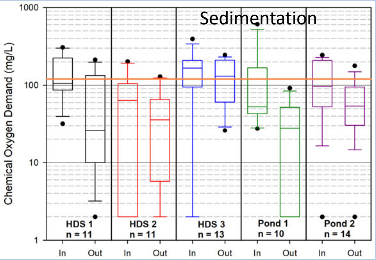
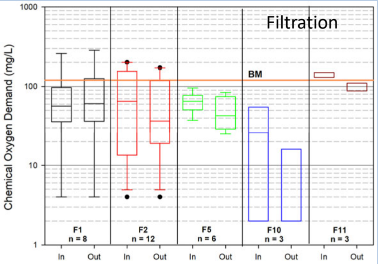
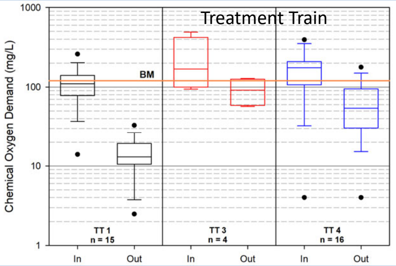
Chemical Oxygen Demand







- Sedimentation alone not effective
- Evaluating filtration not possible due to few samples exceeding BMs.
- Treatment trains generally can meet BM concentrations.

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Overview Industrial Stormwater Treatment Conclusions

- Summary of Solo Unit Operations:
  - Sedimentation devices problematic in meeting benchmark concentrations for several pollutants (TSS, Cu, Zn, COD, Al, Fe).
  - Filtration devices may be able to meet benchmarks for TSS, Zn.
    - Soft-water benchmark for copper difficult to meet.
    - COD had limited data for evaluation
- Treatment trains improve performance and introduce redundancy into system.
  - More storm events had effluent concentrations that met benchmark concentrations

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Industrial Stormwater Treatment Conclusions (cont.)

- Understanding of on-site processes necessary to improve prediction ability of models.
  - Particle size association drives effectiveness of sedimentation and filtration.
  - Influent concentrations may be "too clean" to achieve desired percent removals.
  - Device size relative to drainage area size (loading ratio) increases can improve pollutant removal up to treatment system area that is 5 – 10% of drainage area.
- Good housekeeping and maintenance is vital to reduce influent concentrations and improve likelihood of meeting benchmarks.

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Industrial Site Stormwater Monitoring (Heavy Industrial Site, Southeastern US)

The research was conducted in three stages

- Stage I
  - Land use characterization and drainage analysis of the test site
  - Continuous hydrologic and water quality monitoring and sample collection
- Stage II
  - SSC and PSD analyses of influent and effluent samples (pollutant concentrations based on particle size)
  - PSD analyses of sediment samples (pollutant concentrations based on particle size)
  - Soil sample analyses to analyze vertical migration of metals in dry pond liner, supplemented with water quality fate modeling, to evaluate their mobility
- Stage III
  - Statistical and graphical analyses to determine the performance of different treatment control practices

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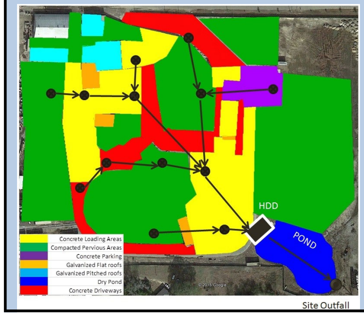
Site Characteristics

- Approximately 21 acres in size (15 acres drain inwards into the site)
- Heavy industrial land use with several buildings (galvanized metal roofs), driveways, loading docks, and highly compacted pervious areas



Site Land Use Information	
Total Drainage Area (acres):	15
Streets, parking lots and roof areas (acres):	5.25
Compacted soil area (acres)	8.13
Special areas (acres)	0.86
Pond area (acres)	0.72

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Hydrologic and Water Quality Monitoring

Hydrologic Monitoring

- ISCO 674 tipping bucket rain gage: Rain depths and intensities
- ISCO 4250 area-velocity sensors: Monitor flow rates in the effluent pipes at pre-treatment unit and dry infiltration pond

Water Quality Monitoring

- ISCO 674 tipping bucket rain gage: sample trigger
- ISCO 4250 area-velocity sensors: sampling pacing
- ISCO 6712 automatic samplers: automatic sample collection (with 20 Liter HDPE Containers)

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Sample and Data Collection Methodology

Continuous monitoring of hydrologic conditions at treatment devices

- Area velocity flow sensors - to monitor runoff volume and flow rates
- Auto samplers - for sample collection

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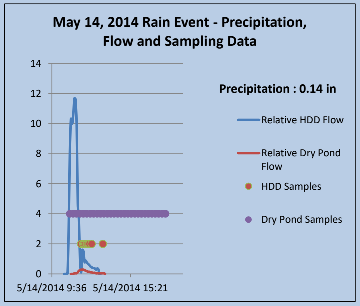
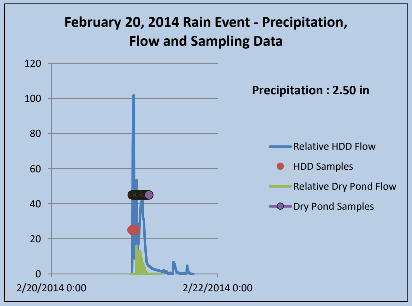
Example Precipitation and Flow Data

Seventeen runoff events were monitored with precipitation ranging from 0.15 to 2.5 inches





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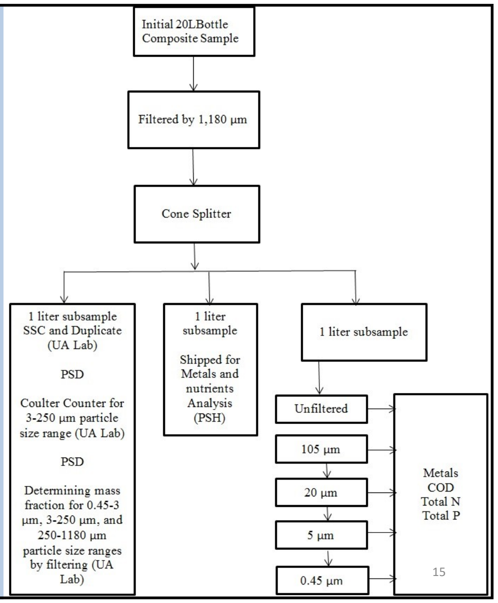
Sample Handling and Water Quality Analyses



Initial 20LBottle Composite Sample

Filtered by 1,180 µm

Cone Splitter

1 liter subsample SSC and Duplicate (UA Lab)

PSD

Coulter Counter for 3-250 µm particle size range (UA Lab)

PSD

Determining mass fraction for 0.45-3 µm, 3-250 µm, and 250-1180 µm particle size ranges by filtering (UA Lab)

1 liter subsample

Shipped for Metals and nutrients Analysis (PSH)

1 liter subsample

Unfiltered

105 µm

20 µm

5 µm

0.45 µm

Metals
COD
Total N
Total P

15

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Observations from Influent Water Quality Analyses

- Heavy metals were present in all the samples collected during the monitoring period (except arsenic was only detected in six of the seventeen sampled events)
- Iron and aluminum exhibited higher concentrations compared to other metals
- Only copper and zinc were detected in the filtered samples for all of the monitored events
- The high concentrations of the metals at the site were associated with exposed metal materials stored on the site
- The literature indicated that different factors such as the nature of the industrial activity, seasonality of precipitation, and amount of exposed material on site and hydrologic transport efficiencies of eroded materials, all affect the characteristics of the chemical runoff constituents from industrial facilities
- This study examined these factors potentially affecting site water quality and treatability

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Multivariate Analyses

- ➢ Study the relationships between different hydrologic and water quality parameters involved in the study and to predict group memberships
  - Pearson Correlation Analyses: To determine simple associations between different pairs of parameters
  - Cluster Analyses: To examine more complex associations between different parameters
  - Principal Component Analyses: To identify groupings of parameters with similar characteristics to explain the variability in the data

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Pearson Correlation Analyses

Variables	Rain Depth (in)	Runoff Depth (in)	Average Rain Intensity (in/hr)	Peak 5 min intensity (in/hr)	Inter-Event time (days)	Median particle size (um)	SSC	Al	Cu	Pb	Fe	Mn	Ni	Zn	Cd	COD	NH3	NO3	PO4	TN	TP	BiCarb	Carb
Runoff Depth (in)	**1.00**																						
Average Rain Intensity (in/hr)	0.59	**0.61**																					
Peak 5 min intensity (in/hr)	**0.75**	**0.77**	**0.78**																				
Inter-Event time (days)	0.48	0.49	0.26	**0.70**																			
Median particle size (um)	-0.10	-0.12	-0.26	-0.32	-0.45																		
SSC	0.57	0.58	**0.65**	**0.69**	0.49	-0.46																	
Al	0.36	0.37	0.54	0.51	0.25	-0.38	**0.93**																
Cu	0.37	0.37	0.44	**0.64**	0.48	-0.29	**0.75**	**0.72**															
Pb	0.29	0.29	0.40	0.51	0.33	-0.29	**0.87**	**0.92**	**0.86**														
Fe	0.36	0.37	0.52	0.53	0.27	-0.35	**0.92**	**0.99**	**0.76**	**0.94**													
Mn	0.40	0.42	**0.70**	0.47	0.08	-0.40	**0.87**	**0.89**	0.46	**0.69**	**0.87**												
Ni	0.39	0.39	0.46	0.52	0.30	-0.47	**0.91**	**0.96**	**0.81**	**0.94**	**0.97**	**0.81**											
Zn	0.30	0.29	0.39	0.50	0.36	-0.38	**0.87**	**0.90**	**0.91**	**0.98**	**0.92**	**0.67**	**0.95**										
Cd	0.37	0.37	0.52	0.51	0.33	-0.50	**0.92**	**0.95**	**0.83**	**0.91**	**0.94**	**0.81**	**0.97**	**0.95**									
COD	0.53	0.50	0.07	0.20	0.19	-0.08	0.49	0.41	0.59	0.45	0.43	0.28	0.54	0.56	0.56								
NH3	-0.22	-0.22	-0.11	-0.29	0.15	-0.15	-0.25	-0.37	-0.29	-0.40	-0.43	-0.29	-0.37	-0.33	-0.21	-0.06							
NO3	0.14	0.13	0.34	0.20	0.03	-0.01	0.55	**0.64**	0.51	0.50	**0.64**	0.59	0.55	0.56	**0.63**	0.45	-0.24						
PO4	0.19	0.19	-0.19	0.30	**0.84**	-0.54	0.20	0.03	0.27	0.10	0.04	-0.17	0.14	0.19	0.16	0.24	0.26	-0.02					
TN	-0.41	-0.41	-0.36	-0.14	0.01	0.00	0.15	0.40	0.25	0.52	0.43	0.08	0.38	0.42	0.27	-0.16	-0.39	0.12	0.07				
TP	0.17	0.15	0.27	0.46	0.47	-0.17	0.22	0.09	0.57	0.25	0.14	-0.06	0.17	0.35	0.29	0.22	-0.05	0.34	0.37	-0.15			
BiCarb	-0.02	-0.01	0.07	0.03	-0.11	0.06	0.45	0.52	0.30	0.45	0.55	0.52	0.45	0.45	0.40	0.30	-0.46	**0.62**	-0.15	0.29	-0.17		
Carb	0.32	0.34	0.43	0.22	0.07	0.04	0.43	0.39	-0.18	0.12	0.36	**0.63**	0.18	0.04	0.19	-0.11	-0.11	0.39	-0.18	-0.06	-0.31	0.42	
Total Alk	-0.02	0.00	0.07	0.03	-0.11	0.06	0.45	0.52	0.30	0.45	0.55	0.52	0.45	0.45	0.40	0.30	-0.46	**0.62**	-0.15	0.29	-0.17	**1.00**	0.43

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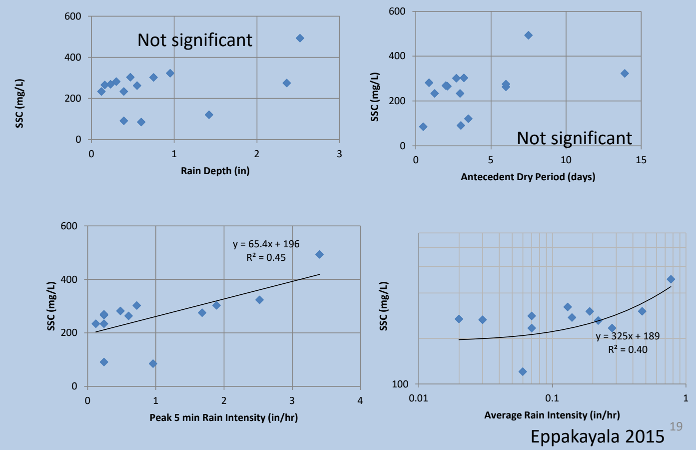
Relationships among hydrologic parameters and suspended sediment



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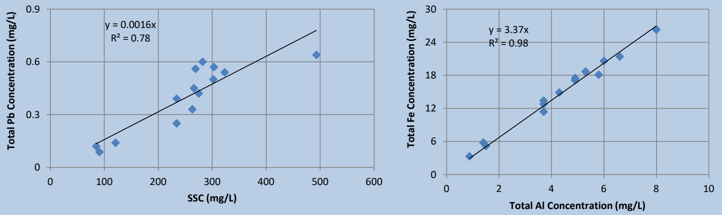
Relationships among SSC and other pollutants



- ➢ SSC was highly correlated with all the metal constituents
- ➢ All the metals were strongly correlated with each other
- ➢ COD, Total N and Total P didn't show any positive correlations with any other parameters or constituents

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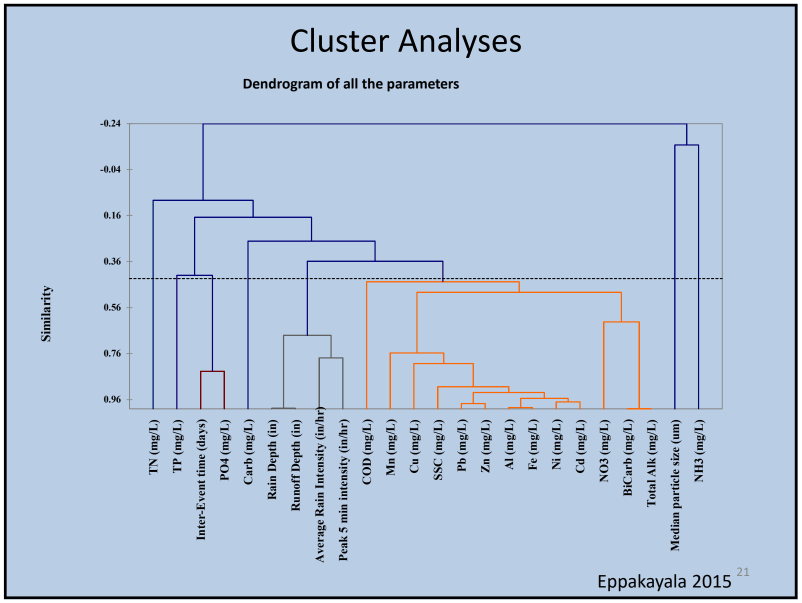

Cluster Analyses

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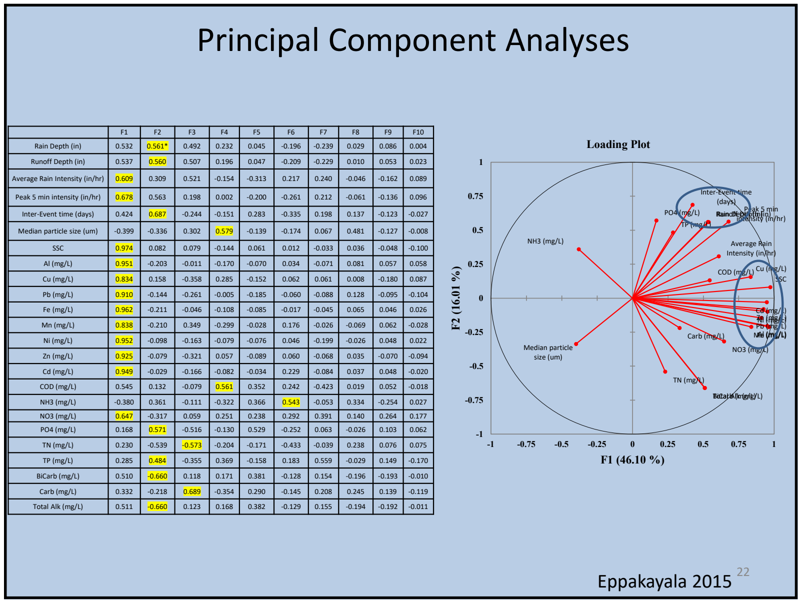

Principal Component Analyses

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Rain Depth (in)	0.532	0.561*	0.492	0.232	0.045	-0.196	-0.239	0.029	0.086	0.004
Runoff Depth (in)	0.537	0.560	0.507	0.196	0.047	-0.209	-0.229	0.010	0.053	0.023
Average Rain Intensity (in/hr)	0.609	0.309	0.521	-0.154	-0.313	0.217	0.240	-0.046	-0.162	0.089
Peak 5 min intensity (in/hr)	0.678	0.563	0.198	0.002	-0.200	-0.261	0.212	-0.061	-0.136	0.096
Inter-Event time (days)	0.424	0.687	-0.244	-0.151	0.283	-0.335	0.198	0.137	-0.123	-0.027
Median particle size (um)	-0.399	-0.336	0.302	0.579	-0.139	-0.174	0.067	0.481	-0.127	-0.008
SSC	0.974	0.082	0.079	-0.144	0.061	0.012	-0.033	0.036	-0.048	-0.100
Al (mg/L)	0.951	-0.203	-0.011	-0.170	-0.070	0.034	-0.071	0.081	0.057	0.058
Cu (mg/L)	0.834	0.158	-0.358	0.285	-0.152	0.062	0.061	0.008	-0.180	0.087
Pb (mg/L)	0.910	-0.144	-0.261	-0.005	-0.185	-0.060	-0.088	0.128	-0.095	-0.104
Fe (mg/L)	0.962	-0.211	-0.046	-0.108	-0.085	-0.017	-0.045	0.065	0.046	0.026
Mn (mg/L)	0.838	-0.210	0.349	-0.299	-0.028	0.176	-0.026	-0.069	0.062	-0.028
Ni (mg/L)	0.952	-0.098	-0.163	-0.079	-0.076	0.046	-0.199	-0.026	0.048	0.022
Zn (mg/L)	0.925	-0.079	-0.321	0.057	-0.089	0.060	-0.068	0.035	-0.070	-0.094
Cd (mg/L)	0.949	-0.029	-0.166	-0.082	-0.034	0.229	-0.084	0.037	0.048	-0.020
COD (mg/L)	0.545	0.132	-0.079	0.561	0.352	0.242	-0.423	0.019	0.052	-0.018
NH3 (mg/L)	-0.380	0.361	-0.111	-0.322	0.366	0.543	-0.053	0.334	-0.254	0.027
NO3 (mg/L)	0.647	-0.317	0.059	0.251	0.238	0.292	0.391	0.140	0.264	0.177
PO4 (mg/L)	0.168	0.571	-0.516	-0.130	0.529	-0.252	0.063	-0.026	0.103	0.062
TN (mg/L)	0.230	-0.539	-0.573	-0.204	-0.171	-0.433	-0.039	0.238	0.076	0.075
TP (mg/L)	0.285	0.484	-0.355	0.369	-0.158	0.183	0.559	-0.029	0.149	-0.170
BiCarb (mg/L)	0.510	-0.660	0.118	0.171	0.381	-0.128	0.154	-0.196	-0.193	-0.010
Carb (mg/L)	0.332	-0.218	0.689	-0.354	0.290	-0.145	0.208	0.245	0.139	-0.119
Total Alk (mg/L)	0.511	-0.660	0.123	0.168	0.382	-0.129	0.155	-0.194	-0.192	-0.011

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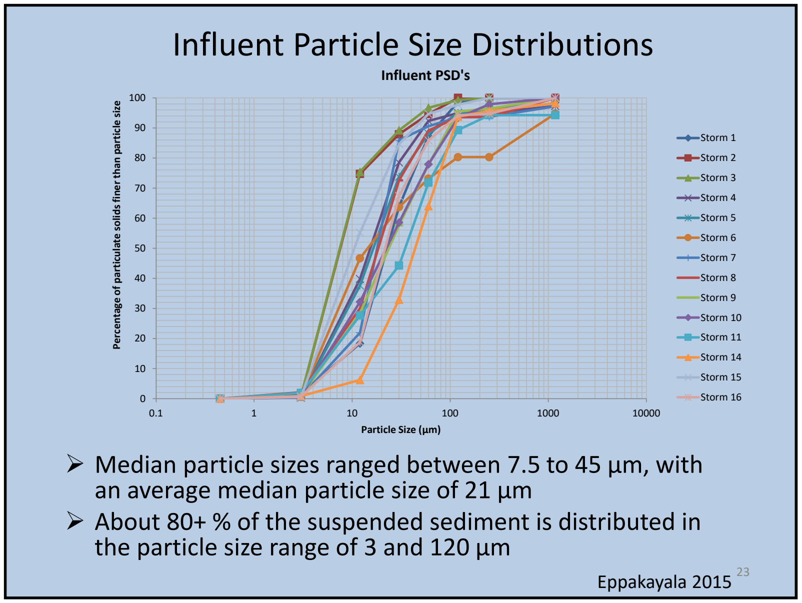

Influent Particle Size Distributions

- Median particle sizes ranged between 7.5 to 45 µm, with an average median particle size of 21 µm
- About 80+ % of the suspended sediment is distributed in the particle size range of 3 and 120 µm

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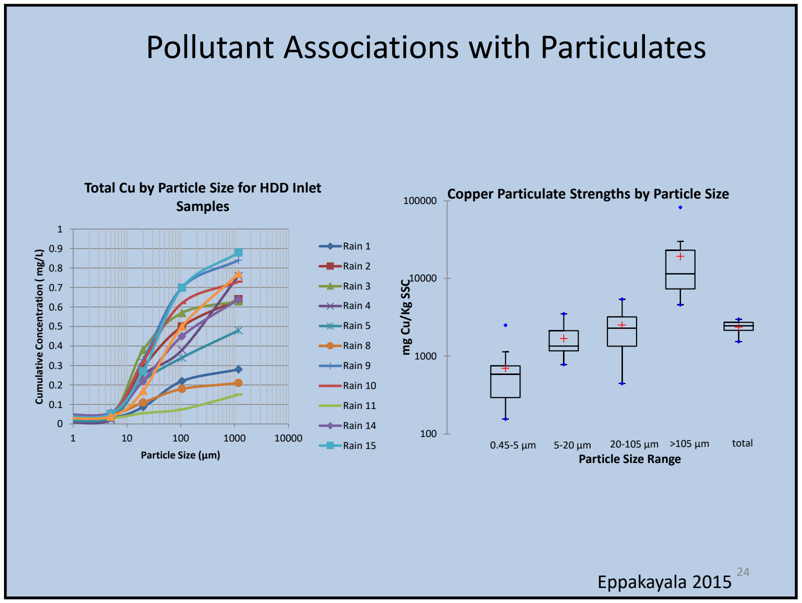

Pollutant Associations with Particulates

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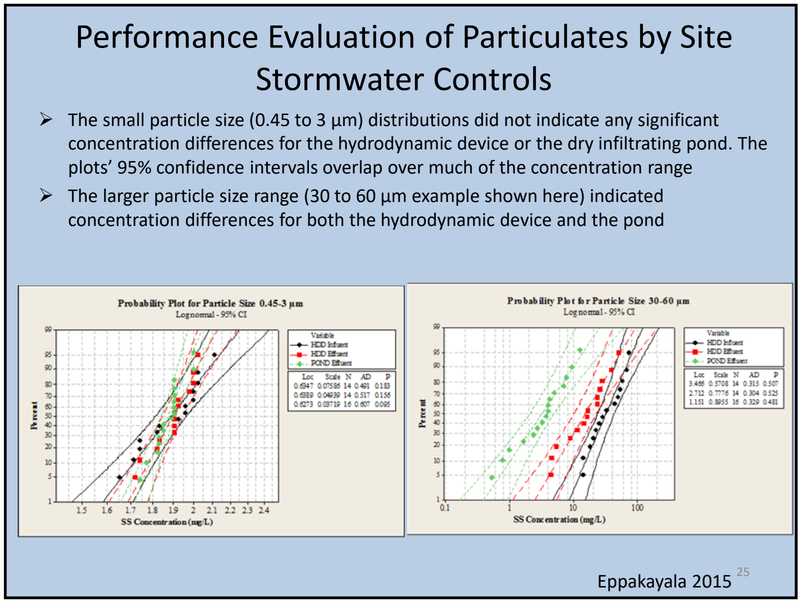

Performance Evaluation of Particulates by Site Stormwater Controls

- ➢ The small particle size (0.45 to 3 µm) distributions did not indicate any significant concentration differences for the hydrodynamic device or the dry infiltrating pond. The plots' 95% confidence intervals overlap over much of the concentration range
- ➢ The larger particle size range (30 to 60 µm example shown here) indicated concentration differences for both the hydrodynamic device and the pond

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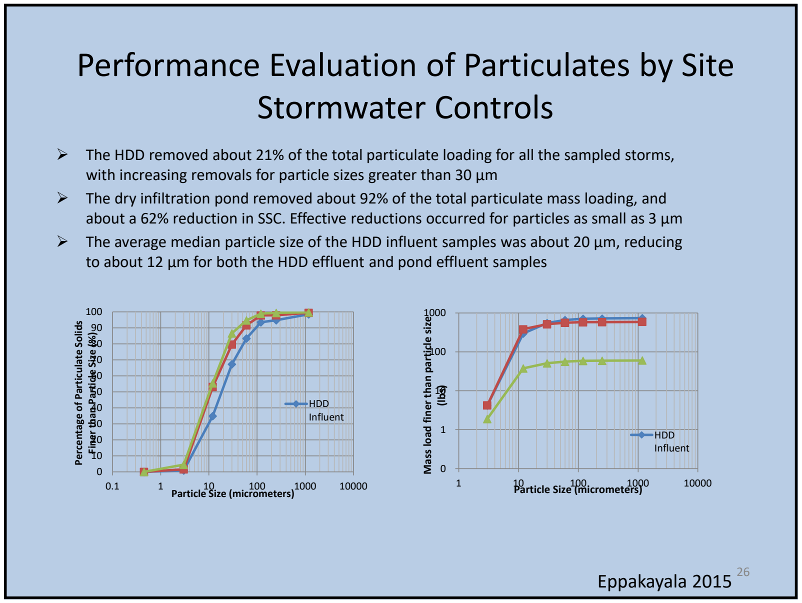

Performance Evaluation of Particulates by Site Stormwater Controls

- ➢ The HDD removed about 21% of the total particulate loading for all the sampled storms, with increasing removals for particle sizes greater than 30 µm
- ➢ The dry infiltration pond removed about 92% of the total particulate mass loading, and about a 62% reduction in SSC. Effective reductions occurred for particles as small as 3 µm
- ➢ The average median particle size of the HDD influent samples was about 20 µm, reducing to about 12 µm for both the HDD effluent and pond effluent samples

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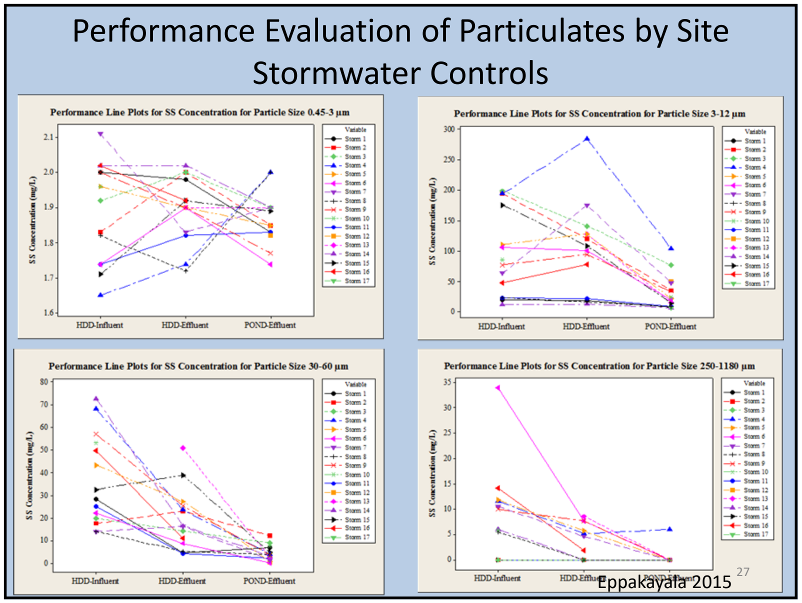

Performance Evaluation of Particulates by Site Stormwater Controls

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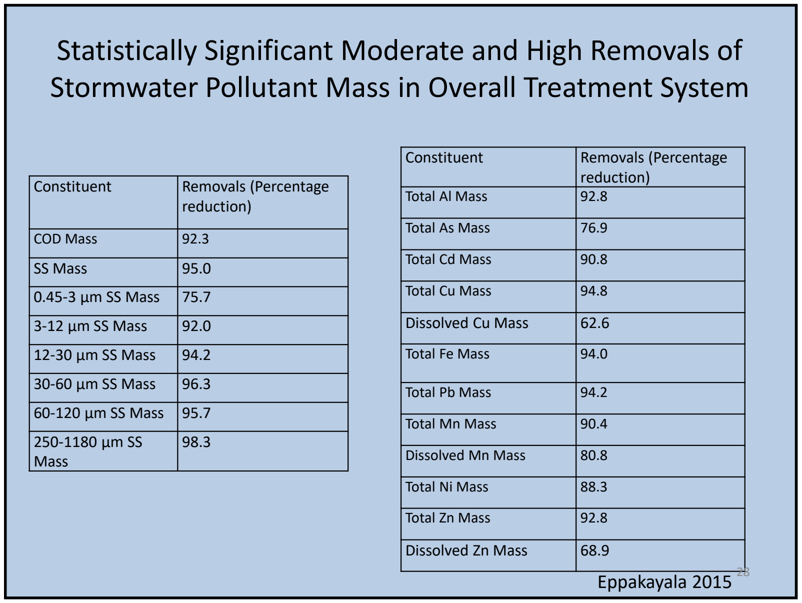

Statistically Significant Moderate and High Removals of Stormwater Pollutant Mass in Overall Treatment System

Constituent	Removals (Percentage reduction)
COD Mass	92.3
SS Mass	95.0
0.45-3 µm SS Mass	75.7
3-12 µm SS Mass	92.0
12-30 µm SS Mass	94.2
30-60 µm SS Mass	96.3
60-120 µm SS Mass	95.7
250-1180 µm SS Mass	98.3

Constituent	Removals (Percentage reduction)
Total Al Mass	92.8
Total As Mass	76.9
Total Cd Mass	90.8
Total Cu Mass	94.8
Dissolved Cu Mass	62.6
Total Fe Mass	94.0
Total Pb Mass	94.2
Total Mn Mass	90.4
Dissolved Mn Mass	80.8
Total Ni Mass	88.3
Total Zn Mass	92.8
Dissolved Zn Mass	68.9

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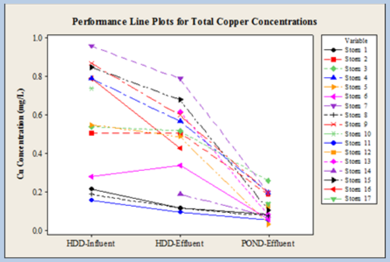
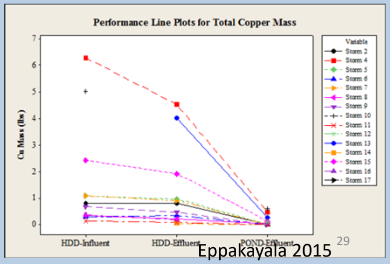
Performance Evaluation of Metals and Nutrients by Site Stormwater Controls

- Low reductions of metal concentrations and mass were observed for the HDD and moderate to high reductions for the dry infiltrating pond
- Higher removals in the dry pond can be related to higher reductions of particulate solids and associated particulate-bound pollutants and the infiltration of stormwater and associated pollutants
- Nonparametric Wilcoxon signed ranked test indicated significant reductions for concentrations and mass for total Cu, Pb, Zn for the HDD and total Al, Cu, Fe, Pb, Zn for the dry infiltration pond
- No significant reductions were observed for nutrients in either device





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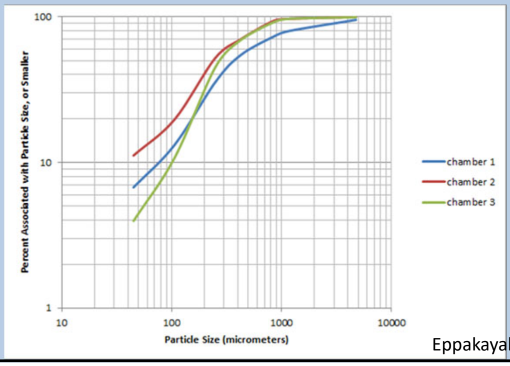
Sediment Accumulation in the Hydrodynamic Separator Device

- Sediment grab samples were collected in each of the four chambers of the HDD. No sediment was found in the fourth chamber (outlet)
- Most of the sediment captured in the chambers was greater than 45 µm
- About 80 - 90% of the particles captured in the chambers were larger than 100 µm



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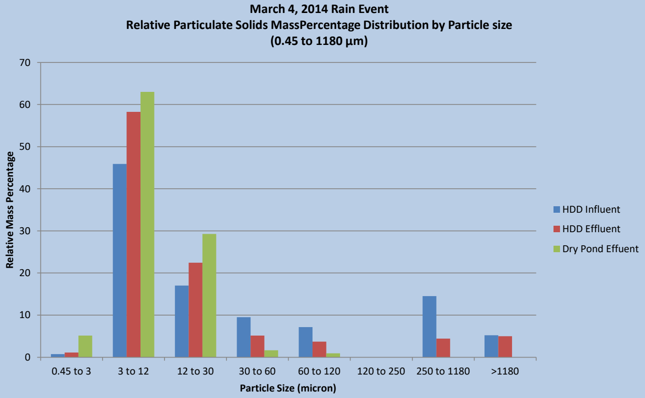
Example Relative Particulate Solids Mass Percentage Distribution by Particle Size



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Dry Pond Infiltration Characteristics

- Infiltration tests were performed in 6 different locations within the pond
- Observed average infiltration rate was about 5 in/hr

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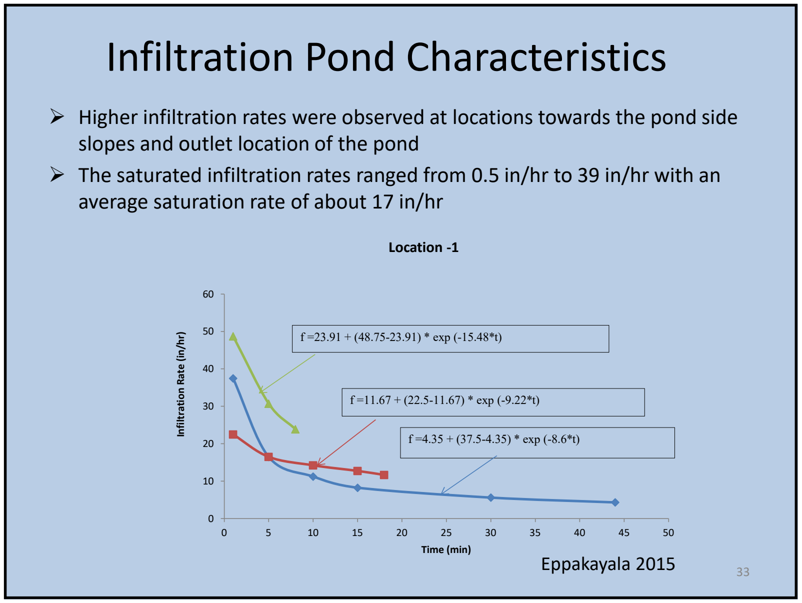

Infiltration Pond Characteristics

- Higher infiltration rates were observed at locations towards the pond side slopes and outlet location of the pond
- The saturated infiltration rates ranged from 0.5 in/hr to 39 in/hr with an average saturation rate of about 17 in/hr

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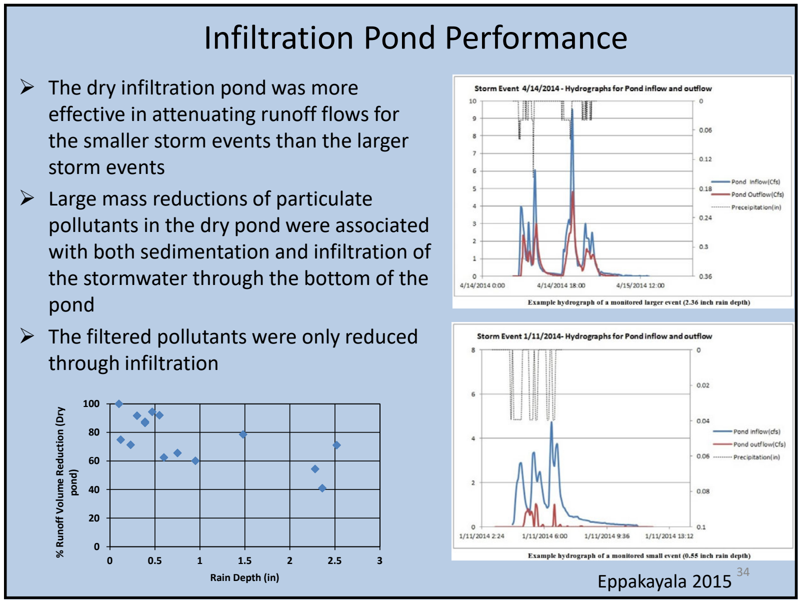

Infiltration Pond Performance

- The dry infiltration pond was more effective in attenuating runoff flows for the smaller storm events than the larger storm events
- Large mass reductions of particulate pollutants in the dry pond were associated with both sedimentation and infiltration of the stormwater through the bottom of the pond
- The filtered pollutants were only reduced through infiltration

Example hydrograph of a monitored larger event (2.36 inch rain depth)

Example hydrograph of a monitored small event (0.55 inch rain depth)

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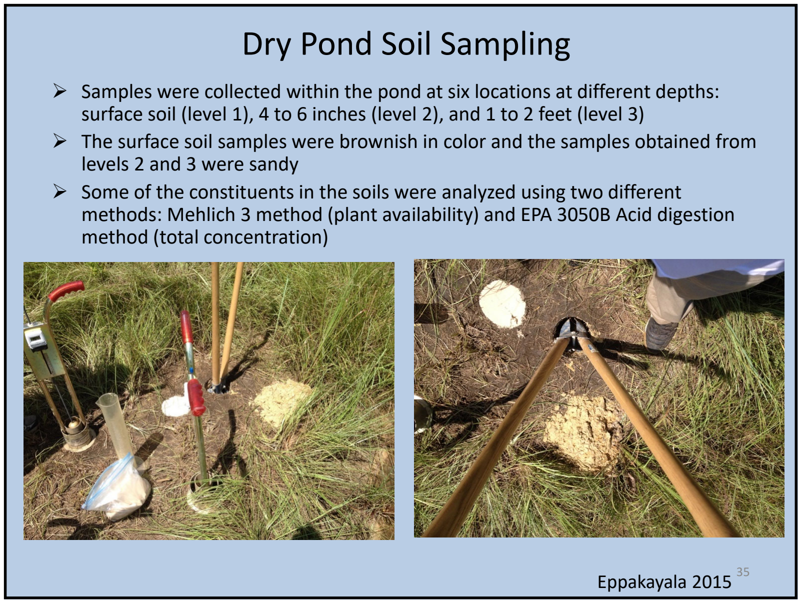

Dry Pond Soil Sampling

- Samples were collected within the pond at six locations at different depths: surface soil (level 1), 4 to 6 inches (level 2), and 1 to 2 feet (level 3)
- The surface soil samples were brownish in color and the samples obtained from levels 2 and 3 were sandy
- Some of the constituents in the soils were analyzed using two different methods: Mehlich 3 method (plant availability) and EPA 3050B Acid digestion method (total concentration)

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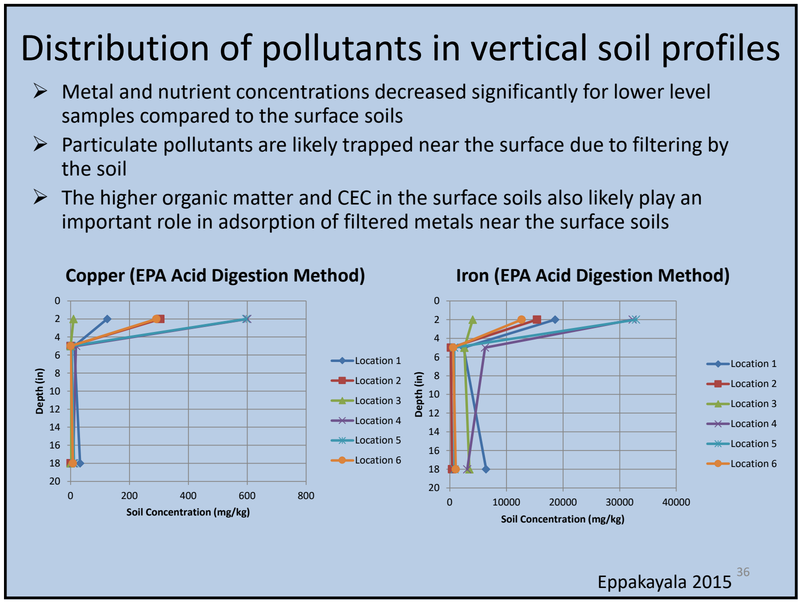

Distribution of pollutants in vertical soil profiles

- Metal and nutrient concentrations decreased significantly for lower level samples compared to the surface soils
- Particulate pollutants are likely trapped near the surface due to filtering by the soil
- The higher organic matter and CEC in the surface soils also likely play an important role in adsorption of filtered metals near the surface soils

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Multivariate Analyses of Soil Contaminant Data

Identify the relationships between different soil parameters and pollutant concentrations and predict group memberships

- Pearson Correlation Analyses: To determine simple linear associations between different pairs of parameters
- Cluster Analyses: To examine more complex relationships between different parameters
- Principal Component Analyses: To identify groupings of parameters with similar characteristics to explain the variability in the data

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Pearson Correlation Analyses of Soil Contaminant Data

Variables	Soil pH	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	% Org Matter	% Nitrogen	% Carbon	Acidity (meq/100g)	CEC (meq/100g)	S (mg/kg)	Mg (mg/kg)	Al (mg/kg)	As (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Ni (mg/kg)
P (mg/kg)	-0.17																		
K (mg/kg)	0.08	0.39																	
Ca (mg/kg)	0.23	0.10	**0.82**																
% Org Matter	0.16	0.05	**0.77**	**0.90**															
% Nitrogen	0.19	0.11	**0.80**	**0.91**	**0.98**														
% Carbon	0.22	0.21	**0.84**	**0.90**	**0.97**	**0.98**													
Acidity (meq/100g)	**-0.93**	-0.01	-0.23	-0.34	-0.28	-0.32	-0.35												
CEC (meq/100g)	0.06	0.26	**0.88**	**0.88**	**0.78**	**0.78**	**0.82**	-0.17											
S (mg/kg)	**-0.51**	-0.08	0.36	0.21	0.25	0.20	0.21	0.43	0.36										
Mg (mg/kg)	0.14	0.02	**0.84**	**0.96**	**0.89**	**0.88**	**0.86**	-0.27	**0.86**	0.36									
Al (mg/kg)	-0.03	-0.02	**0.74**	**0.91**	**0.92**	**0.89**	**0.87**	-0.08	**0.84**	0.42	**0.90**								
As (mg/kg)	0.17	0.08	**0.79**	**0.94**	**0.96**	**0.98**	**0.95**	-0.32	**0.79**	0.21	**0.92**	**0.92**							
Cd (mg/kg)	0.23	-0.05	**0.75**	**0.94**	**0.95**	**0.96**	**0.92**	-0.35	**0.76**	0.17	**0.92**	**0.91**	**0.99**						
Cu (mg/kg)	0.24	-0.10	**0.75**	**0.95**	**0.92**	**0.92**	**0.88**	-0.36	**0.80**	0.20	**0.95**	**0.92**	**0.96**	**0.99**					
Fe (mg/kg)	0.15	0.12	**0.83**	**0.95**	**0.95**	**0.97**	**0.96**	-0.29	**0.84**	0.27	**0.93**	**0.92**	**0.99**	**0.97**	**0.95**				
Pb (mg/kg)	0.24	-0.01	**0.76**	**0.94**	**0.97**	**0.97**	**0.94**	-0.36	**0.80**	0.18	**0.92**	**0.93**	**0.99**	**0.99**	**0.98**	**0.98**			
Mn (mg/kg)	0.16	-0.04	**0.77**	**0.95**	**0.93**	**0.93**	**0.90**	-0.28	**0.81**	0.30	**0.97**	**0.94**	**0.96**	**0.97**	**0.97**	**0.97**	**0.96**		
Ni (mg/kg)	0.22	-0.04	**0.75**	**0.94**	**0.96**	**0.96**	**0.93**	-0.34	**0.79**	0.20	**0.93**	**0.93**	**0.99**	**1.00**	**0.99**	**0.98**	**1.00**	**0.97**	
Zn (mg/kg)	0.24	-0.03	**0.78**	**0.95**	**0.95**	**0.96**	**0.93**	-0.36	**0.81**	0.21	**0.94**	**0.93**	**0.99**	**0.99**	**0.99**	**0.98**	**1.00**	**0.97**	**1.00**

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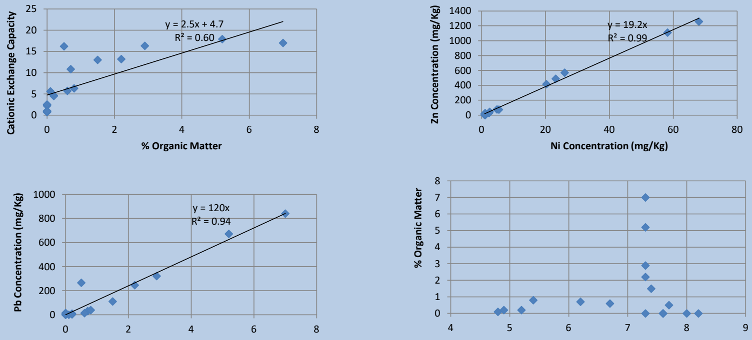
Relationships among different soil parameters

- Strong correlations were observed between different metal concentrations retained in the soil
- All the parameters in the study showed weak correlations with pH
- CEC and organic matter content showed strong correlations with potassium, calcium, magnesium, nitrogen, carbon and the metal concentrations



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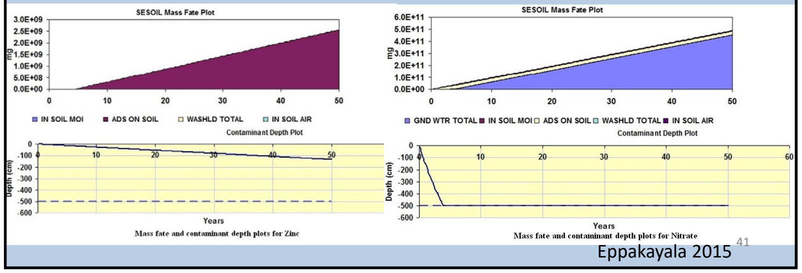
Migration of Pollutants in Vadose Zone under Dry Pond

- The SESOIL model was used to predict the migration potential of the filtered constituents in the vadose zone underneath the dry pond
- SESOIL uses soil, chemical, and meteorological values as input information
- The monitored effluent from HDD was used to describe the pollutant loads available for infiltration and were loaded into the model as a monthly load (mass per unit area)
- Rainfall hydrologic parameters were selected from SESOIL's climatic database
- Soil parameters were selected from SESOIL's soil database and site measurements
- The pollutants modeled were filtered copper, filtered zinc, filtered iron, filtered manganese, and nitrate

Parameter	Site Values
pH	7
% Organic matter	3
Intrinsic permeability	10^{-8} cm^2
Bulk density	1.7 g/cm^3

Migration of Pollutants in Vadose Zone under Dry Pond

- The migration depths of metals stayed under 1.5 m for a simulation period of 50 years, ignoring site runoff entering the pond, which is well above the water table for the study site although nitrate reached the maximum simulated depth within about 3 years
- The additional site runoff may increase these depths by about 10 times, potentially reaching the water table after 50 years of operation
- The mobility for the metals, while low, was ranked as follows: Zn > Mn > Cu > Fe



Mass fate and contaminant depth plots for Zinc

Mass fate and contaminant depth plots for Nitrate

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Variations in pollutant migration with different site conditions – Full Factorial Analyses

- Full factorial analyses were performed for zinc to examine the effects of rainfall, intrinsic permeability, organic matter content, and their interactions on migration depth
- High and low values for rainfall and soil parameters were selected from the NRCS database included in SESOIL, and the high and low values for zinc were selected from the NSQD data base for residential and industrial land uses

Factor	High (+)	Low (-)
Zinc concentration (μg/L) (A)	500	50
Rainfall (cm/yr) (B)	154 (West Palm Beach, FL)	19.9 (Phoenix, AZ)
Intrinsic permeability (cm^2) (C)	1.00E-07	1.00E-10
% Organic matter (D)	3	0.5

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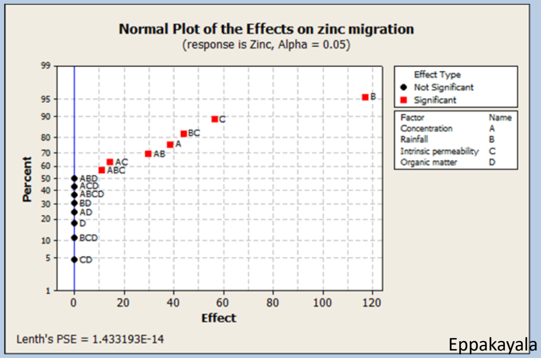
Variations in pollutant migration with different site conditions – Full Factorial Analyses

- Rainfall and intrinsic permeability were the most important factors, while concentration, and their interactions, also showed significant effects on zinc migration in the vadose zone
- No significant effect was associated with organic matter content



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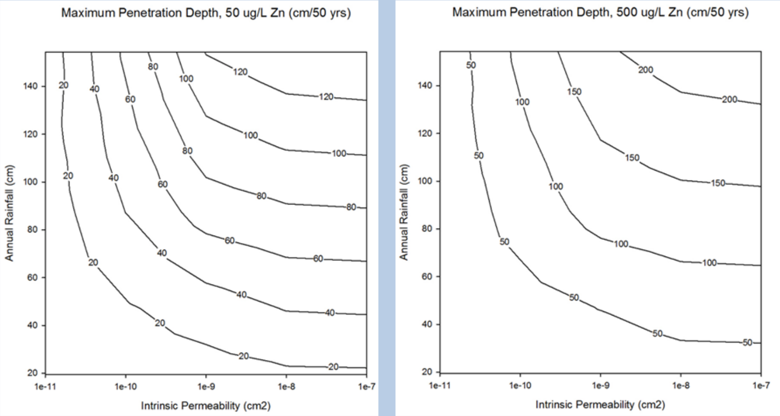
Variations in pollutant migration with different site conditions – Response Surface Analyses



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Heavy Industrial Site Monitoring Conclusions

Pre-treatment hydrodynamic devices are effective in removing larger particles, but less effective for smaller particles

- PSD analyses indicated the average median particle size of the HDD influent samples was about 20 µm, while the effluent sample median particle size was about 12 µm, indicating preferential removal of the larger particles
- Wilcoxon signed rank tests only indicated significant removals for concentrations and mass for SSC and for particle sizes greater than 12 µm
- Median particle size of the sediment captured in the HDD was about 250 µm, with 90% of the sediment mass greater than 45 µm

The dry infiltration pond was very effective in reducing the runoff volumes for monitored storm events, along with associated pollutant mass reductions, and with small to moderate pollutant concentration reductions

- The pond hydrographs indicated high runoff reductions for smaller storm events compared to the larger storm events
- Wilcoxon signed rank tests showed statistically significant reductions for concentrations and masses for particle sizes greater than 3 µm, COD, and unfiltered heavy metals
- Medium to high removals were observed for heavy metal concentrations (>45%) and high removals for masses of the metals (>90%)

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Heavy Industrial Site Monitoring Conclusions (cont.)

- Influent sample analyses showed that suspended sediment concentrations (SSC), COD, nutrients, and heavy metals were commonly found in the runoff, some at potentially problematic levels
- A full factorial analyses on median particle size, SSC, and metals to examine the effects of rain depth, peak rain intensity, and the their interactions showed no significant effects in relation of these factors, and their interactions to the pollutant concentrations
- Concentration variations of pollutants in the pond indicated increased surface concentrations in areas along the main flow pathway and where the water pooled
- Infiltrating stormwater could reach the water table from <3 years (nitrates) to 50 years (metals)

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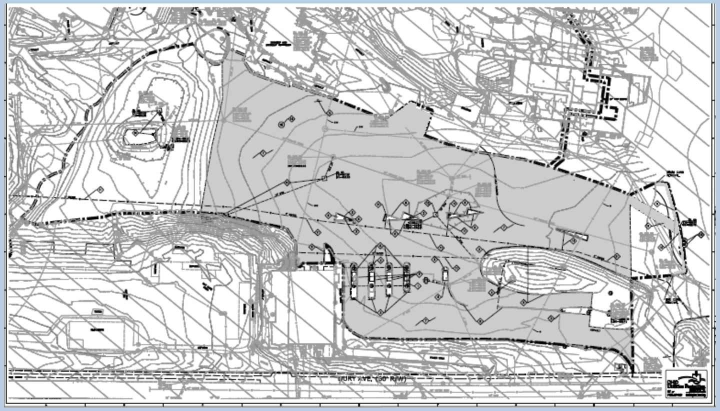
Sampling Plan for Stormwater Control Effectiveness at Cincinnati Zoo

Talebi and Pitt 2013

- The prior land cover of the Cincinnati Zoo consisted of various paved areas (including parking lot and exhibit areas), open space areas, and steep wooded hillsides.
- Stormwater runoff originally flowed in a northeastern direction into catchbasins and storm sewers which were directly rerouted to the Mitchell Avenue Regulator combined sewer system upstream from combined sewer overflow (CSO) 482.
- Retro-fitted controls included:
  - Replacement of pavement with pervious pavers and enhanced turf and vegetation
  - Bioretention areas and tree wells
  - Rainwater harvesting, storage and reuse system
  - Storm sewer separation and roof leader collection

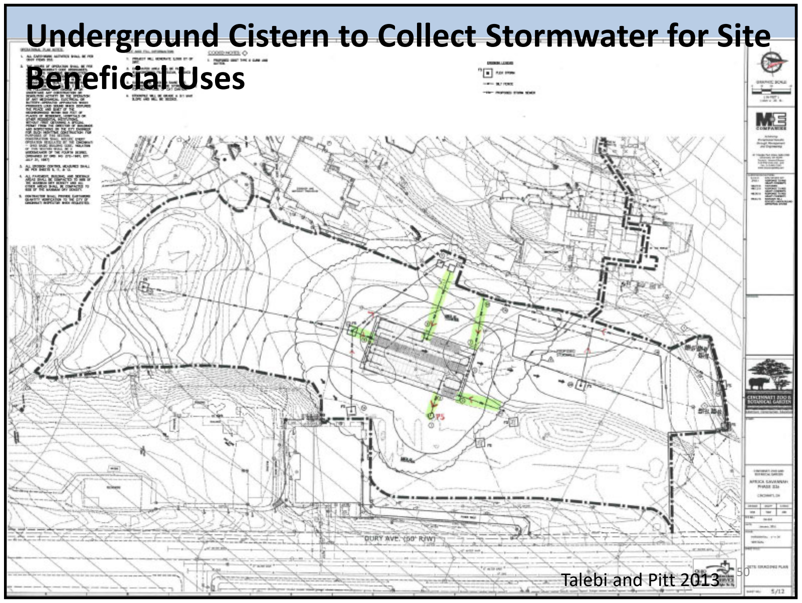
Talebi and Pitt 2013

Asphalt Removal



Talebi and Pitt 2013

Underground Cistern to Collect Stormwater for Site Beneficial Uses



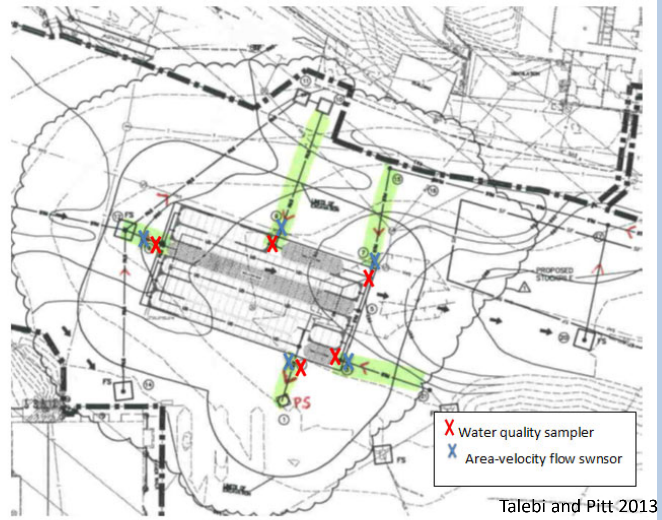
Talebi and Pitt 2013

Stormwater Beneficial Uses

- Irrigation; (4,240,000 gallons annually)
  - The Zoo is a heavy irrigator (close to 2"/week) due to high display quality. The industry standard is 1"/week. Within the Africa Savannah project there is 4 acres of irrigated area.
- Providing water for filling Swan Lake; (10 months each year and will be able at accept 8,000,000 gallons annually)
  - Swan Lake has a surface area of 50,000 sf. It is generally at the highest elevation of the Zoo and actually receives very little surface water. The lake is was filled with a 2" domestic water line. The pond requires 6-9" of make-up water 12 months out of the year.
- Providing water for the bear ponds; (5,230,000 gallons each year)
  - The existing bear moat requires between 400,000 to 500,000 gallons of "make-up" domestic. water on a monthly basis. This translates to 13,350 to 16,600 ft^3 per week. The Zoo constructed a pump and filtration system that directs 10 gpm of water to the moat (24/7).

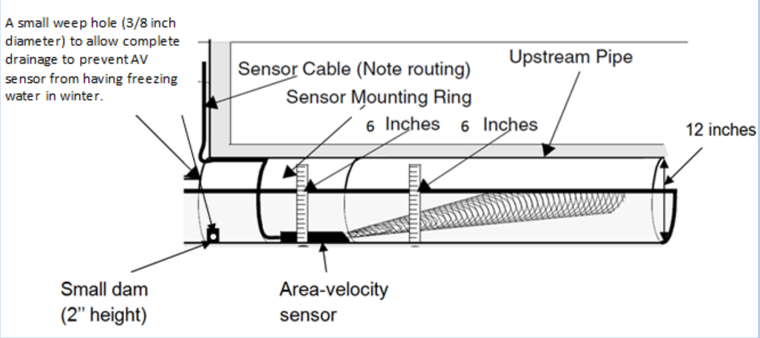
Talebi and Pitt 2013

Flow sensor and sampling locations



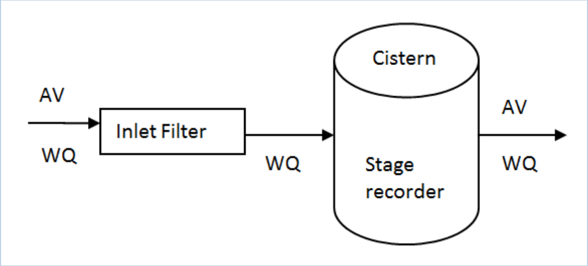
Talebi and Pitt 2013

Area-velocity flow sensor in 12 inch pipe



Talebi and Pitt 2013

Mass Balance Monitoring Components for Cistern



Talebi and Pitt 2013

Summary of Stormwater Sampling and Monitoring Efforts at Cincinnati Zoo

- Inlet pipes
  - 4 inlet automatic water sampler and 4 inlet flow monitor (one for each pipe)
- Outlet pipe
  - 1 outlet automatic water sampler and 1 outlet flow monitor
- Cistern
  - 1 water level recorder in the cistern
  - 4 inlet automatic water sampler after filter and before tank (because we have four inlet pipes)
- Therefore, a total of 9 automatic samplers ($27k), 5 flow monitors ($17k), and 1 water level recorders ($0.65k) was be needed at this location.

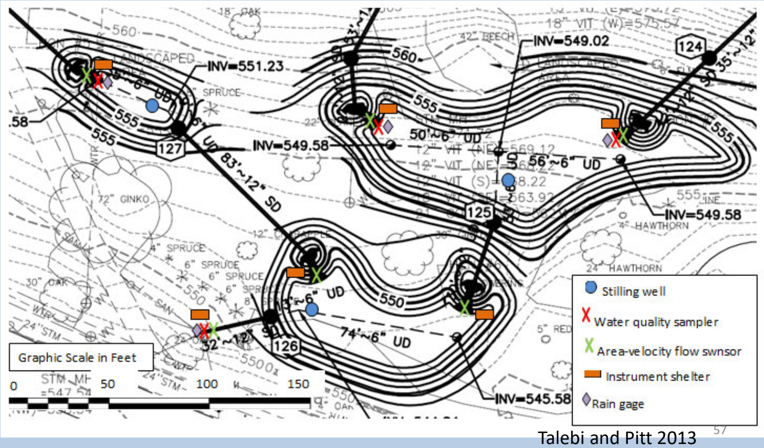
Talebi and Pitt 2013

Cincinnati State Technical and Community College

- ✓ The site is located along Ludlow Avenue east of the intersection of Ludlow Avenue and Central Parkway.
- ✓ Total Drainage Area: 11.7 acre
- ✓ Located in two combined sewer areas. Runoff from the southern half of campus flows south into CSO 12, runoff from the northern half of campus flows north into CSO 21.

Talebi and Pitt 2013

Stormwater Sampling and Monitoring Locations at Large Bioinfiltration System



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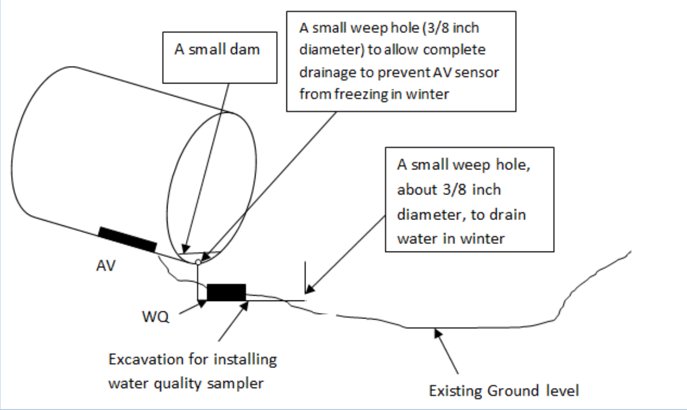
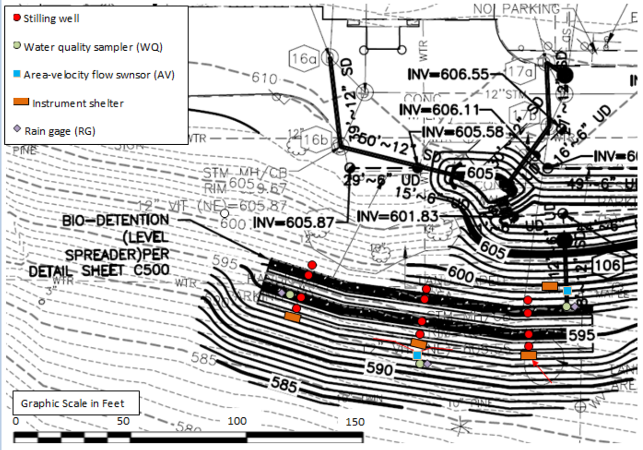
Water Quality Sampler and Flow Meters at Inlets to Bioinfiltration System



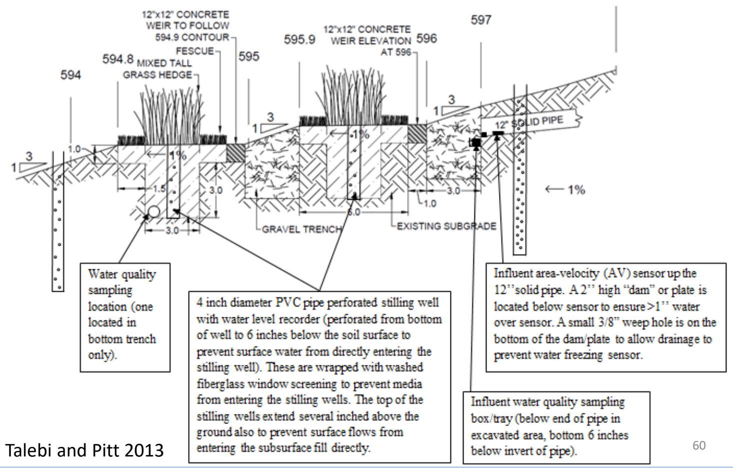
Talebi and Pitt 2013

Monitoring and Sampling Locations at Level Spreader Infiltration System



Talebi and Pitt 2013

Cross-Section of Level Spreader Infiltration System



Water quality sampling location (one located in bottom trench only).

4 inch diameter PVC pipe perforated stilling well with water level recorder (perforated from bottom of well to 6 inches below the soil surface to prevent surface water from directly entering the stilling well). These are wrapped with washed fiberglass window screening to prevent media from entering the stilling wells. The top of the stilling wells extend several inched above the ground also to prevent surface flows from entering the subsurface fill directly.

Influent area-velocity (AV) sensor up the 12'' solid pipe. A 2'' high "dam" or plate is located below sensor to ensure >1'' water over sensor. A small 3/8" weep hole is on the bottom of the dam/plate to allow drainage to prevent water freezing sensor.

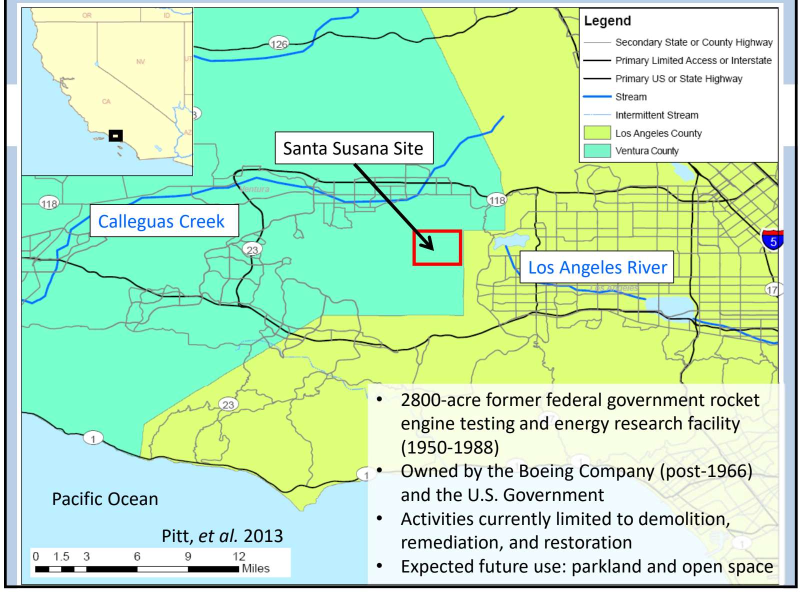
Influent water quality sampling box/tray (below end of pipe in excavated area, bottom 6 inches below invert of pipe).

Talebi and Pitt 2013

Site Ranking Methodology:

Statistical consideration of permit limits, natural background levels, number of samples, and exceedance frequency to identify the best locations for stormwater controls at an industrial location

Pitt, *et al.* 2013



- 2800-acre former federal government rocket engine testing and energy research facility (1950-1988)
- Owned by the Boeing Company (post-1966) and the U.S. Government
- Activities currently limited to demolition, remediation, and restoration
- Expected future use: parkland and open space

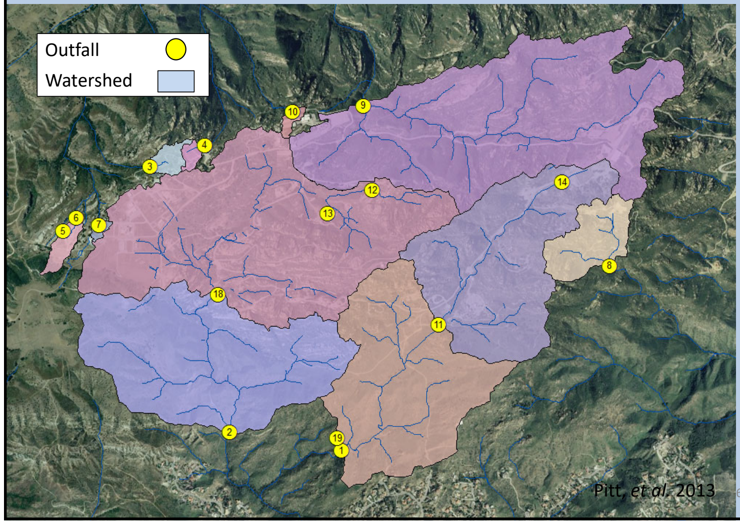
Pitt, *et al.* 2013

Regulation of Santa Susana Field Laboratory Stormwater

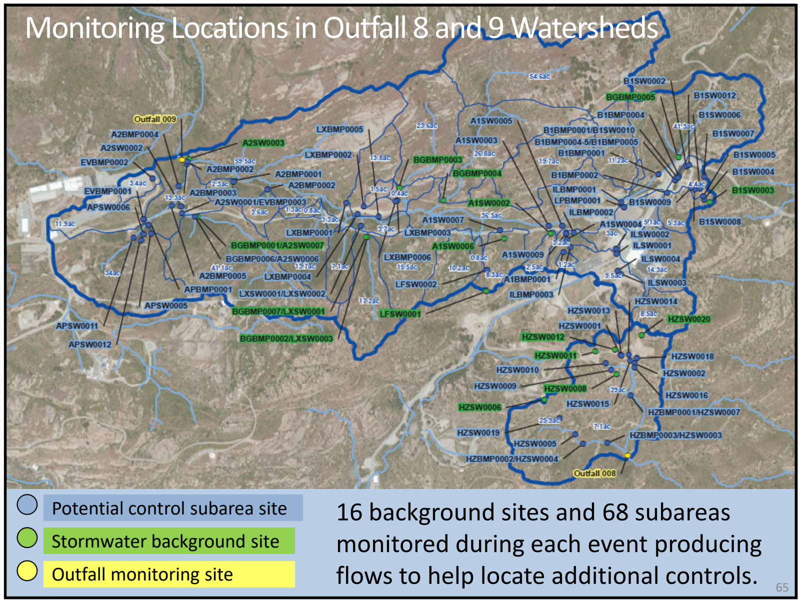
- Stormwater discharges are regulated by the Los Angeles RWQCB through an individual NPDES permit
- All outfalls monitored for all runoff producing events.
- Permit includes Numeric Effluent Limits (NELs) for a wide range of constituents (about 50) including:
  - Dioxins (TCDD TEQ): 2.8×10^{-8} µg/L
  - Total Lead: 5.2 µg/L
  - Total Copper: 14 µg/L

Pitt, *et al.* 2013

NPDES Regulated Outfall Watersheds



Pitt, *et al.* 2013



Monitoring Locations in Outfall 8 and 9 Watersheds

○ Potential control subarea site
🟩 Stormwater background site
🟨 Outfall monitoring site

16 background sites and 68 subareas monitored during each event producing flows to help locate additional controls.

Stormwater Control Site Ranking Methodology

Historical use of site (including testing of rocket engines for moon landing missions)

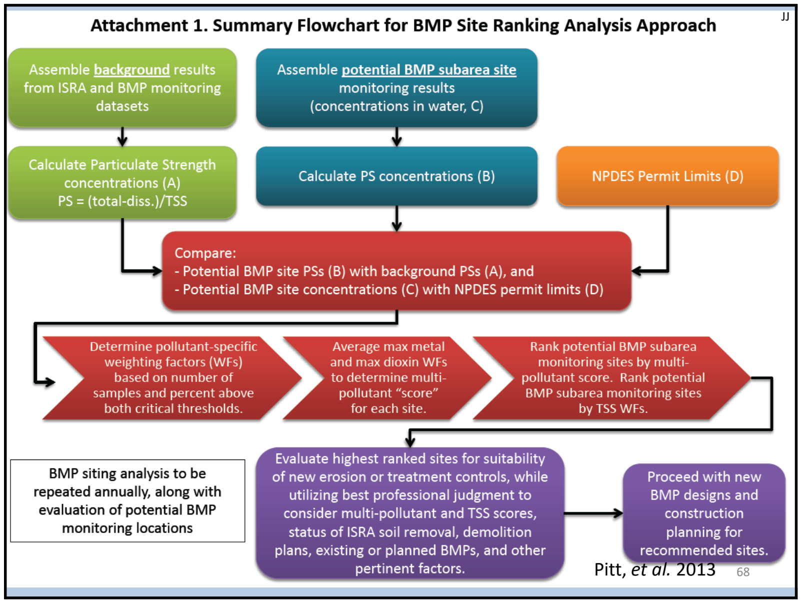
Current site conditions (site sustained devastating wild fires in 2005 and 2018)

Pitt, *et al.* 2013

Overview of Ranking

- Innovative, statistically rigorous approach
- Rank potential control subarea monitoring sites based on comparisons of:
  - Stormwater subarea concentrations with NPDES permit limits
  - Stormwater subarea particulate strengths with stormwater background particulate strengths
- Monitoring locations were scored based on number and percent of samples above NPDES permit limits and/or background
- Locations then ranked based on scores, and top locations identified
- Process repeated annually

Pitt, *et al.* 2013



Attachment 1. Summary Flowchart for BMP Site Ranking Analysis Approach

JJ

Assemble background results from ISRA and BMP monitoring datasets

Assemble potential BMP subarea site monitoring results (concentrations in water, C)

Calculate Particulate Strength concentrations (A)
PS = (total-diss.)/TSS

Calculate PS concentrations (B)

NPDES Permit Limits (D)

Compare:
- Potential BMP site PSs (B) with background PSs (A), and
- Potential BMP site concentrations (C) with NPDES permit limits (D)

Determine pollutant-specific weighting factors (WFs) based on number of samples and percent above both critical thresholds.

Average max metal and max dioxin WFs to determine multi-pollutant "score" for each site.

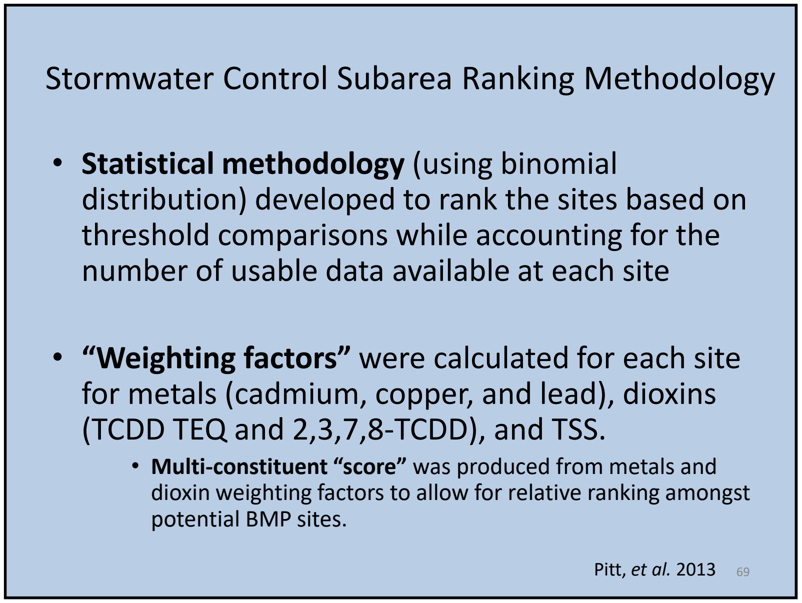
Rank potential BMP subarea monitoring sites by multi-pollutant score. Rank potential BMP subarea monitoring sites by TSS WFs.

BMP siting analysis to be repeated annually, along with evaluation of potential BMP monitoring locations

Evaluate highest ranked sites for suitability of new erosion or treatment controls, while utilizing best professional judgment to consider multi-pollutant and TSS scores, status of ISRA soil removal, demolition plans, existing or planned BMPs, and other pertinent factors.

Proceed with new BMP designs and construction planning for recommended sites.

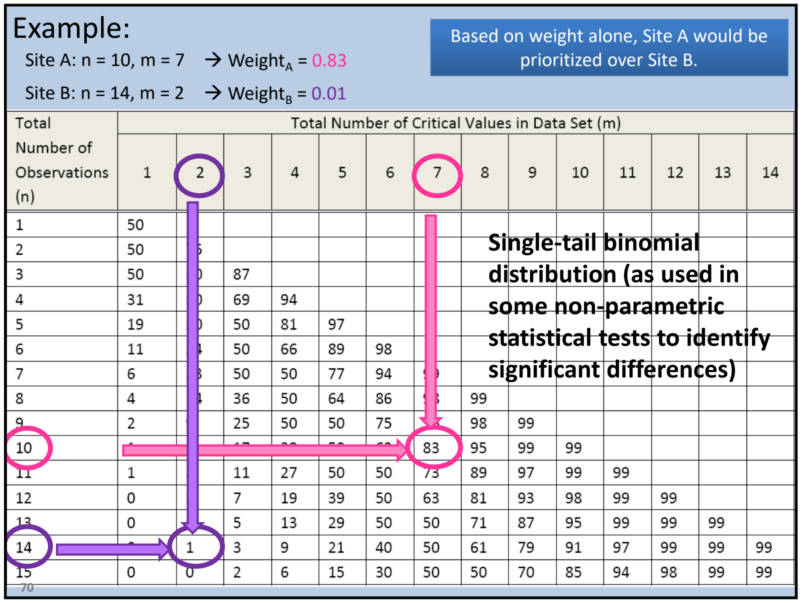
Pitt, *et al.* 2013



Stormwater Control Subarea Ranking Methodology

- **Statistical methodology** (using binomial distribution) developed to rank the sites based on threshold comparisons while accounting for the number of usable data available at each site
- **"Weighting factors"** were calculated for each site for metals (cadmium, copper, and lead), dioxins (TCDD TEQ and 2,3,7,8-TCDD), and TSS.
  - **Multi-constituent "score"** was produced from metals and dioxin weighting factors to allow for relative ranking amongst potential BMP sites.

Pitt, *et al.* 2013



Example:

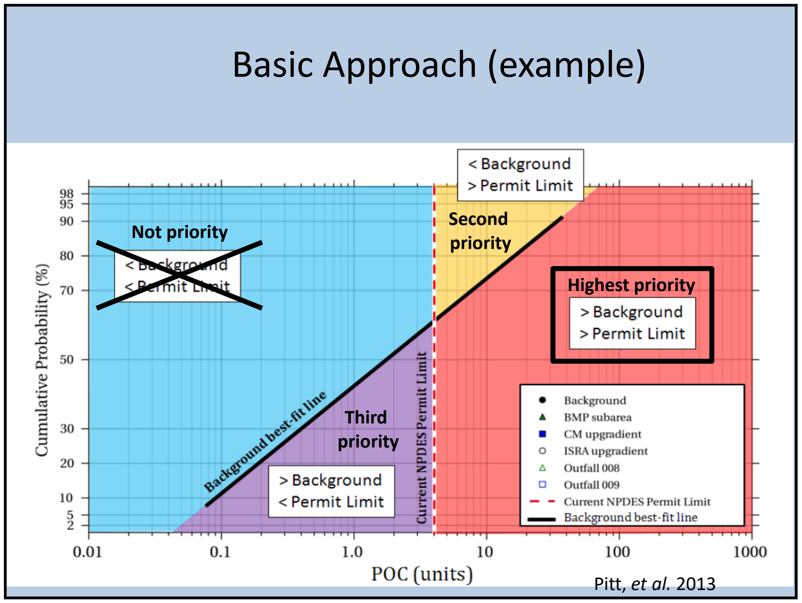
Site A: n = 10, m = 7 → Weight_A = 0.83

Site B: n = 14, m = 2 → Weight_B = 0.01

Based on weight alone, Site A would be prioritized over Site B.

Total Number of Observations (n)	Total Number of Critical Values in Data Set (m)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	50													
2	50	[illegible]												
3	50	[illegible]	87											
4	31	[illegible]	69	94										
5	19	[illegible]	50	81	97									
6	11	[illegible]	50	66	89	98								
7	6	[illegible]	50	50	77	94	[illegible]							
8	4	[illegible]	36	50	64	86	[illegible]	99						
9	2	[illegible]	25	50	50	75	[illegible]	98	99					
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	83	95	99	99				
11	1	[illegible]	11	27	50	50	73	89	97	99	99			
12	0	[illegible]	7	19	39	50	63	81	93	98	99	99		
13	0	[illegible]	5	13	29	50	50	71	87	95	99	99	99	
14	[illegible]	1	3	9	21	40	50	61	79	91	97	99	99	99
15	0	0	2	6	15	30	50	50	70	85	94	98	99	99

Single-tail binomial distribution (as used in some non-parametric statistical tests to identify significant differences)



Basic Approach (example)

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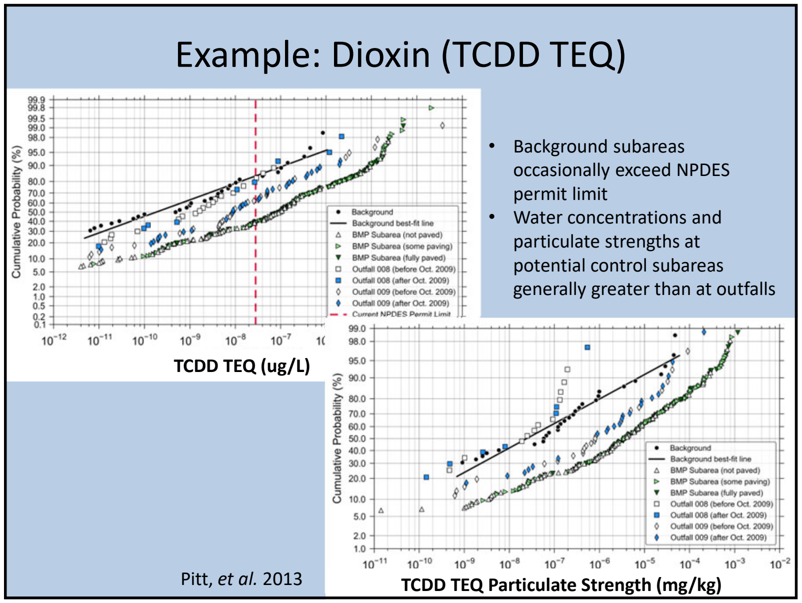

Example: Dioxin (TCDD TEQ)

- Background subareas occasionally exceed NPDES permit limit
- Water concentrations and particulate strengths at potential control subareas generally greater than at outfalls

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Example 2012/2013 Ranking Results

Rank	Potential BMP Subarea (Co-locations)	Description	BMP Status	Approximate Upgradient Drainage Area (ac)	Multi-Constituent Score	Rank from Maximum Metal Weighting	Rank from Maximum Dioxin Weighting	Total Number of Events Sampled
1	**ILBMP0002**[a]	Road runoff to CM-9	Addressed by current BMP; Influent site	2.5	0.95	1[c]	6	9
2	**EVBMP0003** (A2SW0001)[a]	CM-1 upstream west	Addressed by current BMP; Influent site	11.8	0.94	3[c]	1	17
3	EVBMP0001-A[b]	ELV culvert inlet (helipad road and ELV ditch, composite)	Will be addressed by BMP; discontinued	2.5	0.67	17.5	7	5
4	**EVBMP0002**[a b]	Helipad (pre-sandbag berms)	Addressed by current BMP	4.1	0.66	15.5	10	10
5.5	**EVBMP0005**[b]	2012/13 ELV drainage ditch (pre-ELV-1C ISRA)	Will be addressed by BMP	11	0.63	21	9	2
5.5	**A1SW0009-A**	CM-9 downstream-underdrain outlet (post-A1LF asphalt removal, pre-filter fabric over weir boards)	BMP site has since been improved (old site)	16.4	0.63	4	21	1
7	**EVBMP0004**[b]	2012/13 Lower Helipad Road	Will be addressed by BMP	1.8	0.62	2	31.5	3
8	**APBMP0001**[b]	Ashpile culvert inlet/ road runoff	NA	34	0.60	5	21	2
9	**ILBMP0001**[b]	Lower lot 24" stormdrain outlet	Addressed by current BMP and planned building demolition	23	0.57	23	8	16
10	B1BMP0004 (B1SW0015, B1BMP0004-5)	B-1 media filter north	Addressed by current BMP; Influent site	3.7	0.53	29	2	6
14.5	LPBMP0001-A	Lower lot sheetflow (post-gravel bag berms)	Addressed by current BMP; discontinued	5.1	0.50	37.5	3	6
14.5	B1SW0002[a]	Woolsey Canyon Road runoff	Addressed by current BMP; Influent site; discontinued	1.3	0.50	10	21	2

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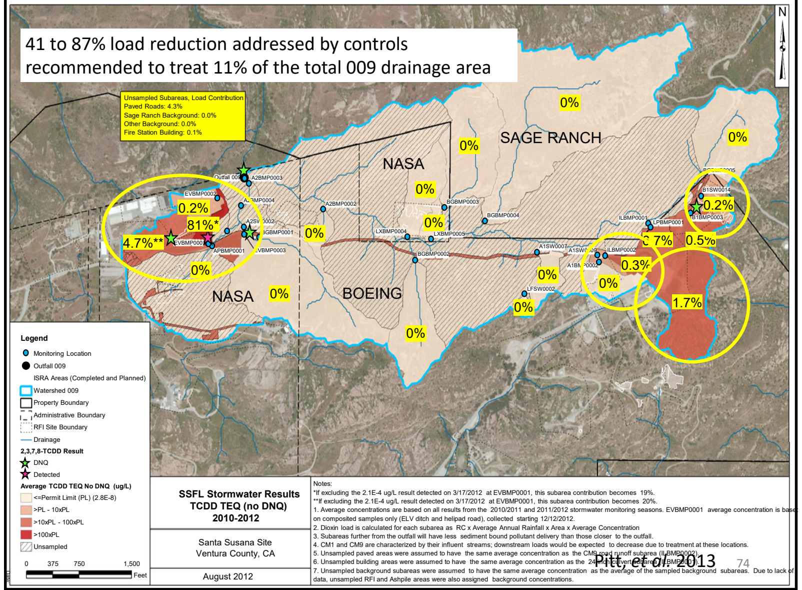
41 to 87% load reduction addressed by controls recommended to treat 11% of the total 009 drainage area



SSFL Stormwater Results
TCDD TEQ (no DNQ)
2010-2012

Santa Susana Site
Ventura County, CA

August 2012

Notes:
*If excluding the 2.1E-4 ug/L result detected on 3/17/2012 at EVBMP0001, this subarea contribution becomes 19%.
**If excluding the 2.1E-4 ug/L result detected on 3/17/2012 at EVBMP0001, this subarea contribution becomes 20%.
1. Average concentrations are based on all results from the 2010/2011 and 2011/2012 stormwater monitoring seasons. EVBMP0001 average concentration is based on composited samples only (ELV ditch and helipad road), collected starting 12/12/2012.
2. Dioxin load is calculated for each subarea as RC x Average Annual Rainfall x Area x Average Concentration
3. Subareas further from the outfall will have less sediment bound pollutant delivery than those closer to the outfall.
4. CM1 and CM9 are characterized by their influent streams; downstream loads would be expected to decrease due to treatment at these locations.
5. Unsampled paved areas were assumed to have the same average concentration as the CM9 road runoff subarea (ILBMP0002).
6. Unsampled building areas were assumed to have the same average concentration as the 24-inch culvert subarea (ILBMP0001).
7. Unsampled background subareas were assumed to have the same average concentration as the average of the sampled background subareas. Due to lack of data, unsampled RFI and Ashpile areas were also assigned background concentrations.

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Example of Some of the Distributed Stormwater Controls at the Santa Susana Field Laboratory

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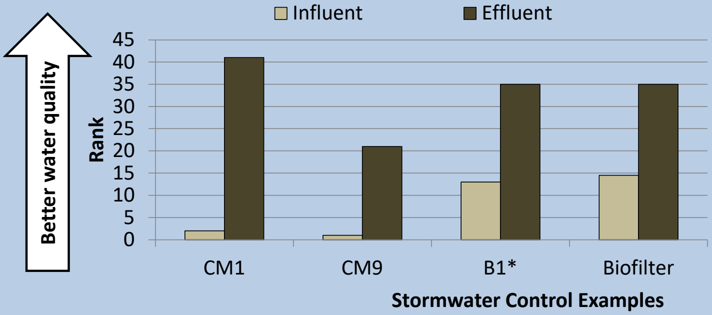
Water Quality Improvements with Site Distributed Controls

- Demonstrated by increasing ranks (decreasing importance) comparing influent and effluent.



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Conclusions

- Industrial stormwater can be highly contaminated with metals and organics
- Because of highly variable stormwater quality, many samples are needed to characterize industrial area stormwater and to develop the most effective management plan
- Treatment trains using both sedimentation and filtration have been shown to be very robust
- Need to identify the most significant sources of contaminants on a site for control

Main References used in Presentation

- Clark, S.E. *Treating Industrial Stormwater to Meet Effluent Concentration Requirements*. Seminar at Tsinghua University, Sept. 2018.
- Eppakayala, V.K. *Performance Evaluation of Stormwater Treatment Controls at an Industrial Site*. Ph.D. Dissertation. University of Alabama. 2015.
- Pitt, R., B. Steets, and R. Kampalath. *BMP Site Ranking Methodology*. Presented at the California Stormwater Quality Association (CASQA). 9th Annual Conference, Lake Tahoe, CA. 2013.
- Talebi, L. and R. Pitt. *Evaluation of Retrofitted Infrastructure Controls at Cincinnati State College, the Cincinnati Zoo and Clark Montessori High School*. Prepared for the Cincinnati Metropolitan Sewer District, OH. 2013.