Report No. CDOT-2012-7
Final Report

MODELING BALLASTED TRACKS FOR POLLUTANTS

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August 2012

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

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Technical Report Documentation Page

1. Report No. CDOT-2012-7	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MODELING BALLASTED TRACKS FOR POLLUTANTS		5. Report Date August 2012 6. Performing Organization Code
7. Author(s) Albert Molinas and Amanullah Mommandi		8. Performing Organization Report No. CDOT-2012-7
9. Performing Organization Name and Address Hydrau-Tech, Inc. 333 W. Drake Road, Suite 40 Fort Collins, CO 80526		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 107.00
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the US Department of Transportation, Federal Highway Administration. Dr. Aziz Khan was the Project Manager of the study.

16. Abstract

In this study, the Regional Transportation District's (RTD's) light rail operations were examined for pollutant production and runoff. To accomplish this, a laboratory study utilizing a rainfall-runoff facility was conducted. Input to this laboratory model was provided by using RTD's design criteria, data from existing installations, and a field study to sample surface materials along ballasted tracks. A rainfall-runoff physical model of the light rail system was constructed at the Colorado State University Hydraulics Laboratory to study the effectiveness of the as-built ballasted tracks in the railroad environment. This model was subjected to Denver hydrology and environmental conditions using the available local rainfall information and pollution data. A 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. A rainfall simulator was designed to vary rainfall duration and intensity. The model had the capability of capturing all of the runoff for volumetric measurement of the quantity and quality of the runoff.

Potential sources of pollutants from a light rail system are: i) metal introduced from track abrasion; ii) metal from wheel abrasion; iii) material from disk brakes; and iv) material from overhead power lines, etc. These quantities were computed using RTD's maintenance records for wheel truing, brake rotor maintenance, track replacement, copper power line replacement, and field sampling of light rail tracks. For field measurements, toe regions of tracks near the most heavily travelled sections of the light-rail system were sampled at RTD's Broadway Light Rail Station. The measured iron and aluminum concentrations from the field samples were introduced into the laboratory ballasted-track model and were subjected to various rainfall events. Runoff water and soil samples collected during and after different frequency events were analyzed to trace the effectiveness of ballasted tracks for capturing pollutants.

Conclusions from the study:

- Water leaving ballasted tracks carries only a small fraction of the heavy metals that are introduced into tracks from the light rail operations.
- Heavy metal concentrations at the most heavily travelled light rail station showed that pollutant concentrations were far below the regulatory limits.

Implementation:

It is recommended that the CDOT use the findings of the study in the CDOT Drainage Design Manual.

17. Keywords light rail, stormwater management, MS4 permits, National Pollution Discharge Elimination Program (NPDES), Colorado Discharge Permit System (CDPS), best management practices (BMPs), rainfall-runoff models, heavy metals, Denver hydrology	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov or CDOT's Research Report website http://www.coloradodot.info/programs/research/pdfs

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	56	

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FINAL REPORT

MODELING BALLASTED TRACKS FOR POLLUTANTS

FOR

COLORADO DEPARTMENT OF TRANSPORTATION

DENVER, COLORADO

BY

ALBERT MOLINAS

AND

AMANULLAH MOMMANDI

REPORT NO. CDOT-2012-7

AUGUST 2012

ACKNOWLEDGEMENTS

This study was jointly sponsored by the Colorado Department of Transportation (CDOT) and the Regional Transportation District, FASTRACKS, Denver. Authors Albert Molinas (Hydrau-Tech, Inc.) and Amanullah Mommandi (CDOT's Hydraulics Program Manager) gratefully acknowledge Randy Jensen (CDOT's Region 6 Transportation Director), CDOT's Structures Research Oversight Team, CDOT's Research Implementation Council, and RTD's support during the course of this study.

Authors also wish to acknowledge the support from Jake Kononov (CDOT's Director of Applied Research and Innovation Branch) and John Shonsey (Senior Manager of Engineering/Chief Engineer, RTD-FASTRACKS) and thank them for their guidance throughout the project, refinement of the project goals, and the review of the final report.

The authors would like to thank all the study panel members including Jeffrey Anderson, Mike Banovich, Keith Powers, Mohan Sagar, Dave Wieder, C.K. Su, Roberto DeDios, Fred Schultz, Aziz Khan, and Matt Greer for their support, expertise, and advice during the project. Special thanks go to the numerous individuals, who participated in the planning, scope of work development, conducting laboratory experiments, soil analysis, and the review of the final report. These individuals included:

CDOT, RTD, UDFCD and Cities

Gary Gonzales (CDOT-FASTRACKS Liaison)

Jim Paulmeno (CDOT-FASTRACKS Liaison)

Tom Boyce (CDOT, DTD Environmental)

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EXECUTIVE SUMMARY

In this study, the Regional Transportation District's (RTD's) light rail operations were examined for pollutant production and runoff. In order to accomplish this, a laboratory study utilizing a rainfall-runoff facility was conducted. The input to this laboratory model was provided by using RTD's design criteria, data from existing installations, and a field study to sample surface materials along ballasted tracks.

The study was directed to answer the questions:

1. What is the state of runoff in regards to inflows? What is the water quality properties following an event?

2. If there are minor pollutants entering the system, what are their amounts and their fate?

A rainfall-runoff physical model of the light rail system was constructed at the Colorado State University (CSU) Daryl B Simons Hydraulics Laboratory to study the effectiveness of the as-built ballasted tracks in the railroad environment. This model was subjected to Denver hydrology and environmental conditions using the available local rainfall information and pollution data.

A 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. This model was placed in the CSU rainfall simulator that was designed to vary rainfall duration and intensity. The model had the capability of capturing all of the runoff for volumetric measurement of the quantity and quality of the runoff. Potential sources of pollutants from a light rail system are: i) metal introduced from track abrasion; ii) metal from wheel abrasion; iii) material from disk brakes; and iv) material from overhead power lines, etc. These quantities were computed by using RTD's maintenance records for wheel truing, brake rotor maintenance, track replacement, copper power line replacement, etc. and by field sampling of light rail tracks. For field measurements, toe regions of tracks near the most heavily travelled sections of the light-rail system were sampled at RTD's Broadway Light Rail Station. The measured iron and aluminum concentrations from the field samples were introduced into the laboratory ballasted-track model and were subjected to various rainfall events. Runoff water and soil samples collected during and after different frequency events were analyzed to trace the effectiveness of ballasted tracks for capturing pollutants.

Conclusions from the study:

a. The state of runoff in regards to inflows was determined. The water leaving ballasted tracks carries minute amounts of heavy metals that are introduced into tracks from light rail operation.

b. The minor pollutants entering the system were determined and quantified from a field sampling program. The heavy metals concentrations at the most heavily travelled light rail station showed that pollutant concentrations were far below the regulatory limits.

EXPECTED BENEFITS

A rainfall-runoff physical model of the light rail system was developed to analyze the effectiveness of the as-built ballasted tracks in the railroad environment. This model was developed based on Denver hydrology and environmental conditions using the available local rainfall information, weather information, pollution data, etc. Measured concentrations of metals from light rail operations were introduced into the laboratory model and were subjected to rainfall events; the runoff quantities of these pollutants were measured to quantify the water quality properties of runoff leaving the ballasted track boundaries.

This study answered the following questions:

- What are sources of pollutants in light rail systems?
- How effectively can the pollutants be removed from stormwater?
- What is long-term effectiveness for ballasted tracks in retaining pollutants within light rail operational boundaries?
- Magnitude of pollutants --how clean is the water?

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1 INTRODUCTION

The Environmental Protection Agency (EPA) requires that discharges from regulated small municipal separate storm sewer systems (MS4s) must be covered under the National Pollutant Discharge Elimination System (NPDES) program. The Colorado program is referred to as the Colorado Discharge Permit System, or CDPS, instead of NPDES. In accordance with the NPDES regulations, all RTD Light Rail Systems in Denver are required to file NPDES permit applications. It was found urgent to conduct a research study to investigate the impact of ballasted track system on stormwater quality and quantity under local Denver railroad environment.

The NPDES requirements demand dischargers to reduce the discharge of pollutants from their MS4 to the maximum extent practicable (*MEP*), to protect water quality, and to satisfy the appropriate water quality requirements of the Colorado Water Quality Control Act and the Colorado Discharge Permit Regulations through the development of CDPS Stormwater Management Program. The management program must include program areas covering: 1) public education and outreach; 2) public involvement/participation; 3) illicit discharge detection and elimination; 4) construction site stormwater runoff control; 5) post-construction stormwater management; and 6) pollution prevention/good housekeeping for municipal operations.

It is believed that Best Management Practices (BMPs) are all that will be necessary to control water quality impacts. The Federal Clean Water Act requires that NPDES permits for discharges from MS4s "shall require controls to reduce the discharge of pollutants to the maximum extent practicable, including management practices, control techniques, and system, design, and engineering methods."

RTD has built and is operating light rails through the southeast and southwest of Denver within CDOT right-of-way. However, all railroads need to apply for stormwater NPDES/CDPS permit. RTD believes that its operations do not produce any negative environmental impacts; it desires to identify and quantify potential sources of pollutants from its operations and determine the fate of these pollutants within is operational boundaries.

In this study, the RTD's light rail operations are examined for pollutant production and runoff. In order to accomplish this, a laboratory study utilizing a rainfall-runoff facility was conducted. The input to this laboratory model was provided using RTD design criteria, data from existing installations, and a field study sampling surface materials along tracks.

2 STUDY OBJECTIVES

The statistics related to RTD's light rail operations are summarized as:

- Locale: Denver-Aurora Metropolitan Area
- Transit type: Light Rail
- Number of lines: 5
- Number of stations: 36
- Daily ridership: 54,779
- Operation Began: October 7, 1994
- Operator(s): Regional Trans. District (RTD)
- System length: 39.4 miles
- Electrification: Overhead lines

RTD believes that its operations do not produce any negative environmental impacts; it desires to identify and quantify potential sources of pollutants from its operations and determine the fate of these pollutants within is operational boundaries. A scientific, impartial study is needed to examine the environmental impacts of ballasted tracks and quantify such impacts. There is a lack of information on ballasted track systems and water quality. This study will determine ballast impacts on water quality and if needed, what the appropriate BMPs to use with these systems.

In this research study, a hydrologic laboratory model was used. A 1 to 1 scale of a typical railroad segment was constructed; this model was subjected to Denver rainfall conditions in order to examine effectiveness of ballasted tracks to meet NPDES requirements of reducing the discharge of pollutants from RTD's MS4 to the maximum extent practicable (*MEP*), to protect water quality, and to satisfy the appropriate water quality requirements of the Colorado Water Quality Control Act.

The study was directed to answer these questions:

- What is the state of runoff in regards to inflows? What is the water quality properties following an event (sediment and heavy metal concentrations)?
- If there are minor pollutants entering the system, what are their amounts and their fate?
- How long is the detention time in the ballast for the runoff?

As a philosophy, the study uses a conservative worst-case approach to support its findings. Since the driving force in the pollutant runoff is the water flow, the infiltration losses into the subgrade are minimized in the experiments by introducing an epoxy-coated plywood surface for simulating the subgrade. Similarly, rather than choosing a reach that represents average light rail traffic and average age of the system, the soil sampling was conducted the most heavily travelled reach of the ballasted track that has been in service the longest was chosen. Also, the soil sampling was concentrated at the toe region of the tracks (6 to 8 feet from tracks) where after 15 years of operation, it is believed to have the highest levels of pollutant concentrations. Finally, at the light rail station where 5 different lines converged, soil sampling was made in the direction of braking in order to observe the most metal abrasion. It was decided on the outset that if the system was found to not have any pollution problems under worst-case conditions, then conclusions could be extended to the entire light-rail system using the same technology.

3 RESEARCH APPROACH

Elements of the light rail tracks are:

- Ballast
- Sub-ballast
- Rail
- Sleepers (ties)
- Electrification Mast

A rainfall-runoff physical model of the light rail system was constructed at the Colorado State University (CSU) Daryl B Simons Hydraulics Laboratory to study the effectiveness of the as-built ballasted tracks in the railroad environment. This model was subjected to Denver hydrology and environmental conditions by using the available rainfall information and pollution data.

1. A 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. The rainfall-runoff physical model of the light rail system was constructed at the CSU Hydraulics Laboratory. A rainfall simulator was designed to accurately vary rainfall duration and intensity. The model also was designed to capture all of the runoff for accurate volumetric measurement of the quantity and quality of the runoff.

2. Drainage characteristics of the ballast and sub-ballast are affected by the grinding of gravel through time. Even though the light rail design criteria tries to minimize the adverse effects of introducing finer sediments by proper selection of material, an existing light rail installation that has been in operation for 15 years was sampled for fine materials and pollutants from light rail operations. The objective of the field sampling was to quantify the finer materials (if found in larger quantities) and pollutants and introduce them into the ballasted track experiments to simulate their fate.

3. Potential sources of pollutants from a light rail system are: i) metal introduced from track abrasion; ii) metal from wheel abrasion; iii) material from disk brakes; and iv) material from overhead power lines, etc. These quantities were computed by using RTD's maintenance records for wheel truing, brake rotor maintenance, track replacement, copper power line replacement, etc. and by field sampling of light rail tracks. For field measurements, toe regions of tracks near the most heavily travelled sections of the light-rail system were sampled at RTD's Broadway Light Rail Station. The measured iron and aluminum concentrations from the field samples were introduced into the laboratory ballasted-track model and were subjected to various rainfall events. Runoff water and soil samples collected during and after different frequency rainfall events were analyzed to trace the effectiveness of ballasted tracks for capturing pollutants.

4 LABORATORY MODELING OF POLLUTANT TRANSPORT

4.1 Laboratory Model of Ballasted Tracks

For the laboratory experiments, a 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. The concrete railroad ties, steel tracks and other hardware used in the model were supplied by RTD and are currently being used in RTD's existing installations.

Figure 1 below shows half of a double-track ballasted section constructed for the experiments. By using a half-model, the runoff collection system is greatly simplified eliminating a major source of error. The runoff from the track is collected by a gutter at the toe and discharged into a runoff catchment box. According to RTD's design criteria for the ballasted tracks, the slope of the subgrade is 2.5%. In the model, the compacted clay subgrade was simulated by a painted plywood surface. This arrangement provided a more conservative runoff characteristic since it allowed no infiltration losses in the system.

A rainfall simulator with 4 spray nozzles was placed 14ft above the 8-foot railroad segment to provide uniform distribution of rainfall. The selection of 4 nozzles was to attain a more uniform cover and was made after trials with 1-nozzle and 2-nozzle systems and after sensitivity testing. Figures 2 through 5 provide views of the laboratory model and rainfall simulator. In Figure 2, the overall model is shown during a rainfall simulation event. Figure 3 shows the runoff catchment box with two compartments; Figures 4 and 5 show various elements of the rainfall simulation model. In order to have similar antecedent conditions, a drying period of 7 to 10 days between runoff experiments were implemented.

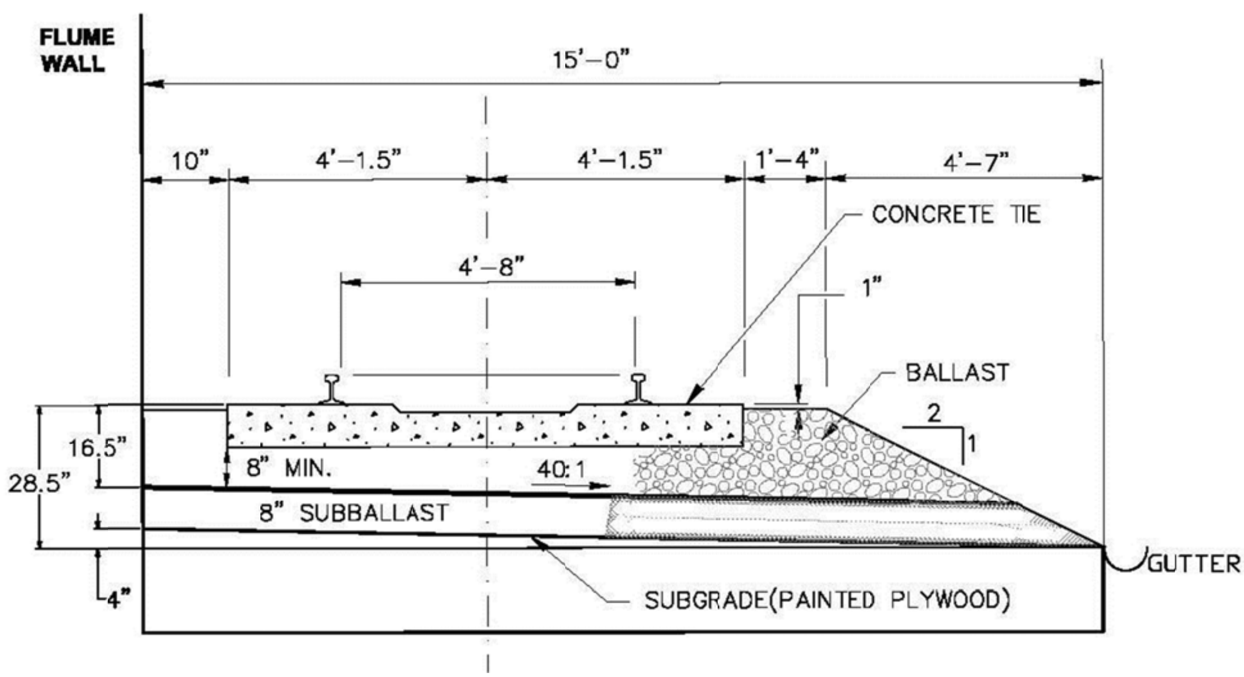


Figure 1. Half of a double-track ballasted section used in the laboratory modeling study.

Figure 2. The overall model during a rainfall simulation event.

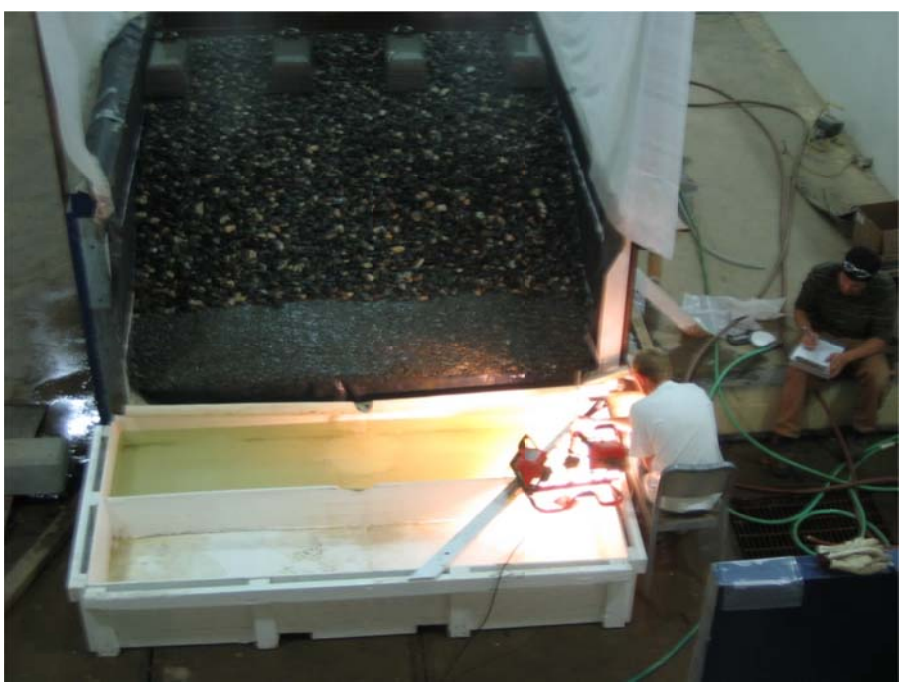


Figure 3. Runoff collection system and the catchment box with two compartments.

Figure 4. The rainfall simulator with 4 spray nozzles.

Figure 5. Pressure regulator and flow meter to measure inflow into the rainfall simulator.

4.2 Sediment Characteristics

The ballast and sub-ballast materials used in the experiments were acquired from a main RTD supplier. The size gradation characteristics of these sediments are given in Table 1 below and shown in Figure 6. As shown in Table 1, the ballast material has a median diameter of approximately 2/3” (16mm) with almost no fine material. The median diameter of sub-ballast material is approximately 0.1” (2.36mm) with 14 percent sediments falling in the silt-clay size groups.

Table 1. Sediment size distribution for the ballast and subballast materials used in the experiments

SIZE (MM)	BALLAST-Pct Finer	SUBBALLAST-Pct Finer
75.00	100	100
63.00	100	100
50.00	100	100
37.50	100	100
25.00	100	96
19.00	72	91
12.50	28	78
9.50	11	72
4.75	2	61
2.36	2	51
0.002	1	14

4.3 Experimental Procedure

Using the experimental setup described in the preceding sections:

1. Place the pollutants generated from the light rail operations to the toe region of the model at concentrations measured from the field study.
2. Select the return frequency of the rainfall event.
3. Run the rainfall simulator at desired intensity and duration
4. Sample the runoff at desired time intervals (5 minutes, 10 minutes, 15 minutes, and 30 minutes from the start of runoff).
5. At the end of the experiment, collect the sediment accumulated in the runoff accumulation boxes.
6. Conduct laboratory analysis of water samples and accumulated sediments for pollutant concentrations.

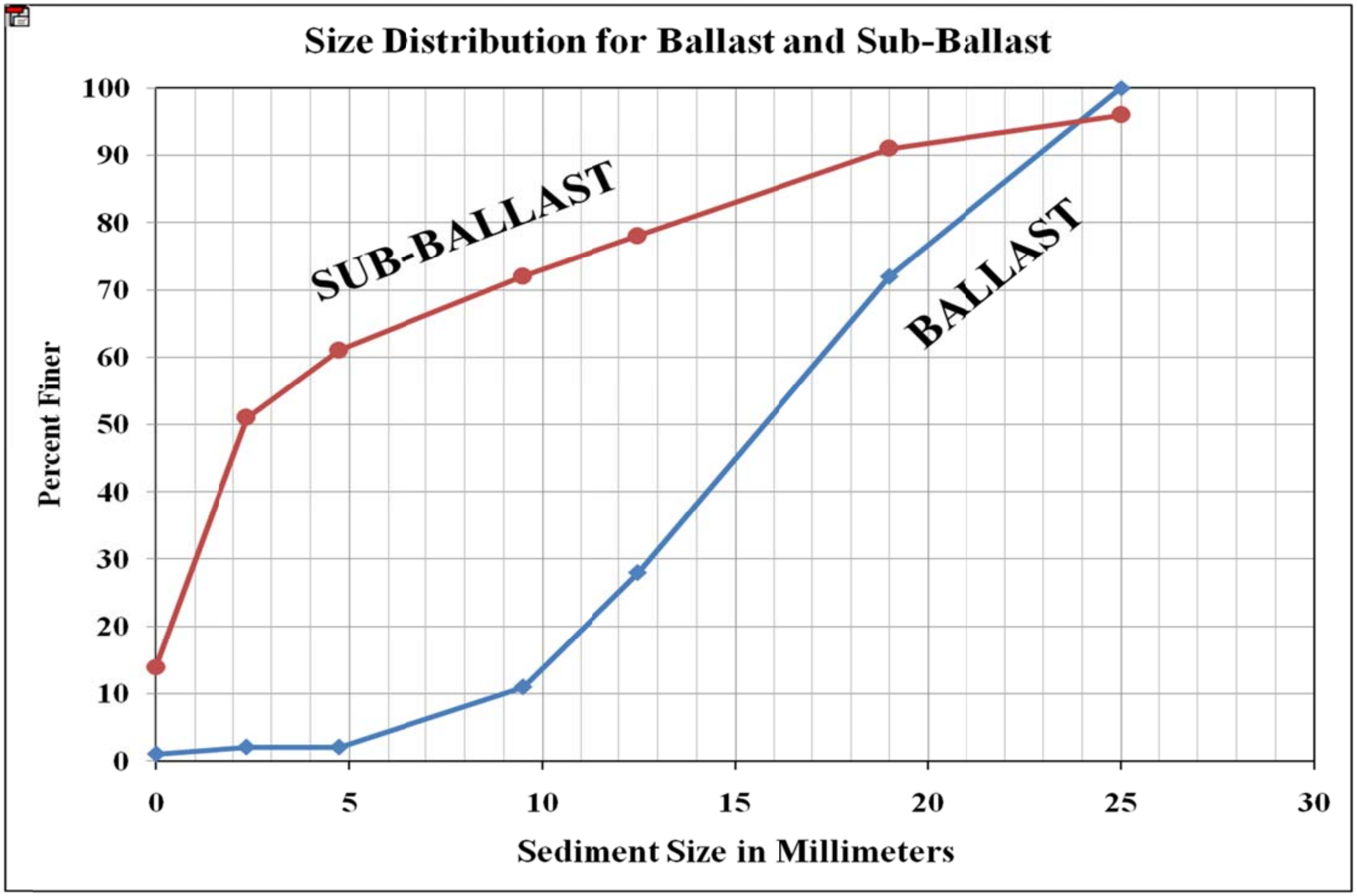


Figure 6. Sediment size distribution for the ballast and sub-ballast materials used in experiments.

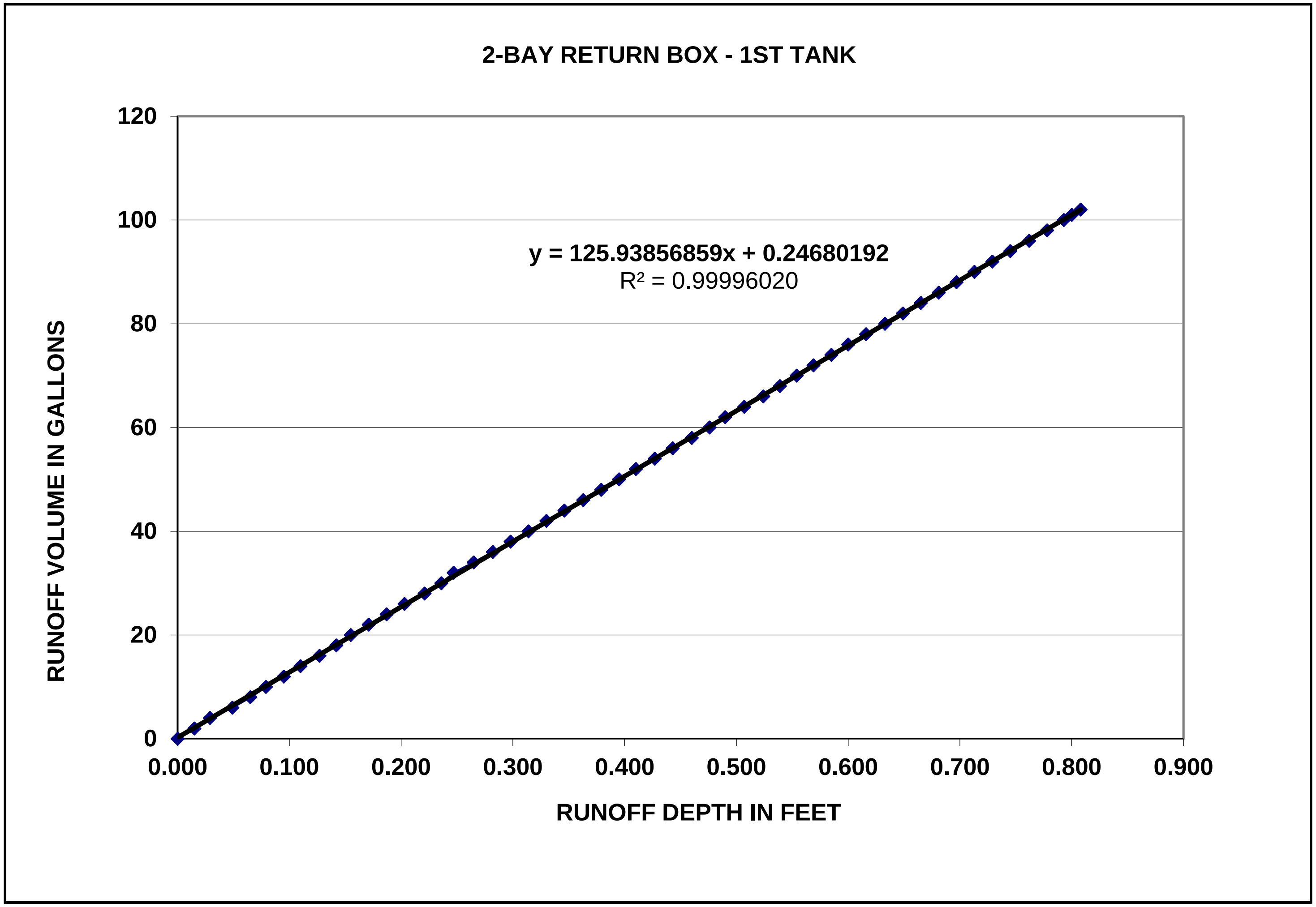


Figure 7. Depth-volume relationships for runoff catchment boxes used in experiments.

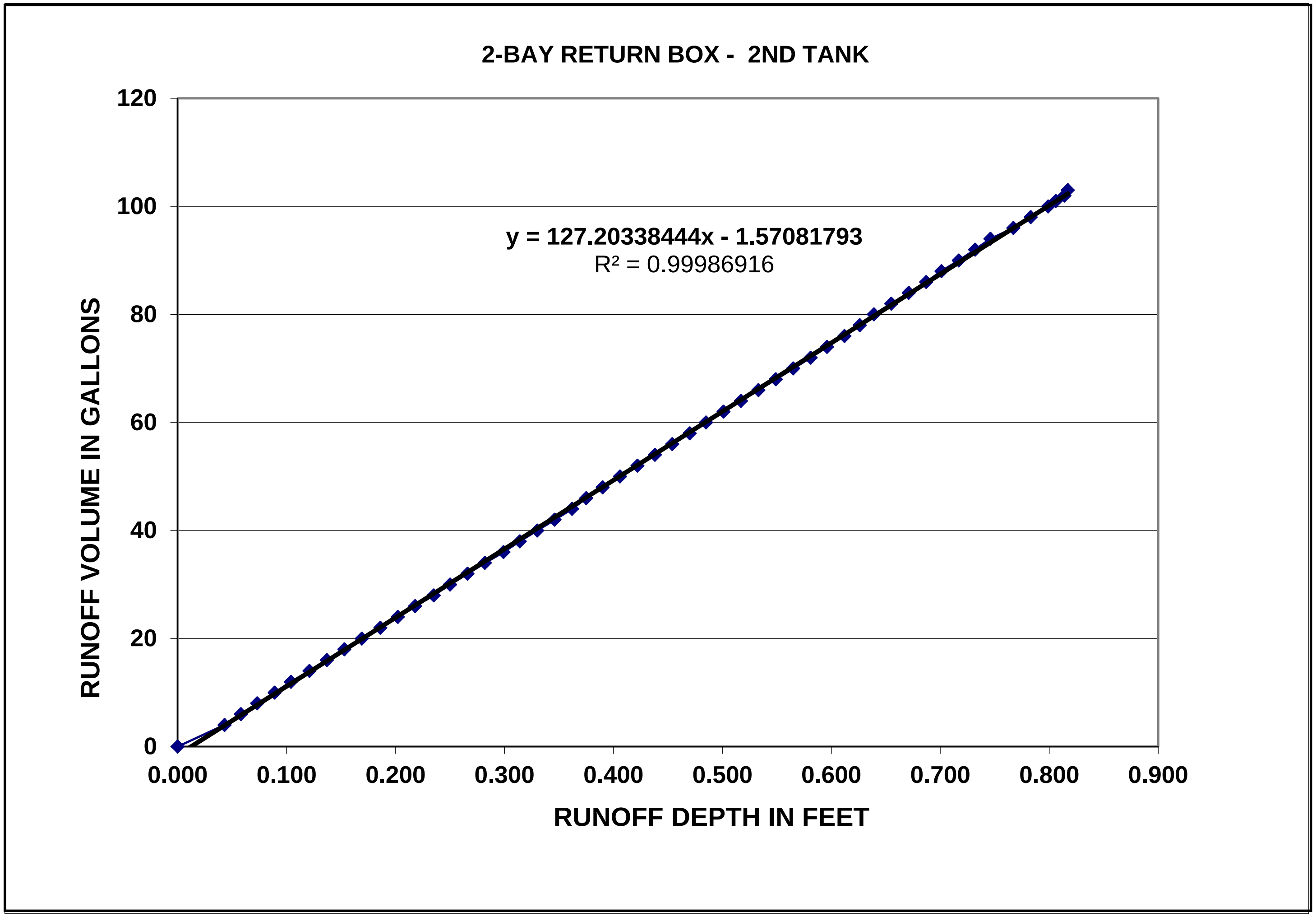


Figure 8. Depth-volume relationships for runoff catchment boxes used in experiments.

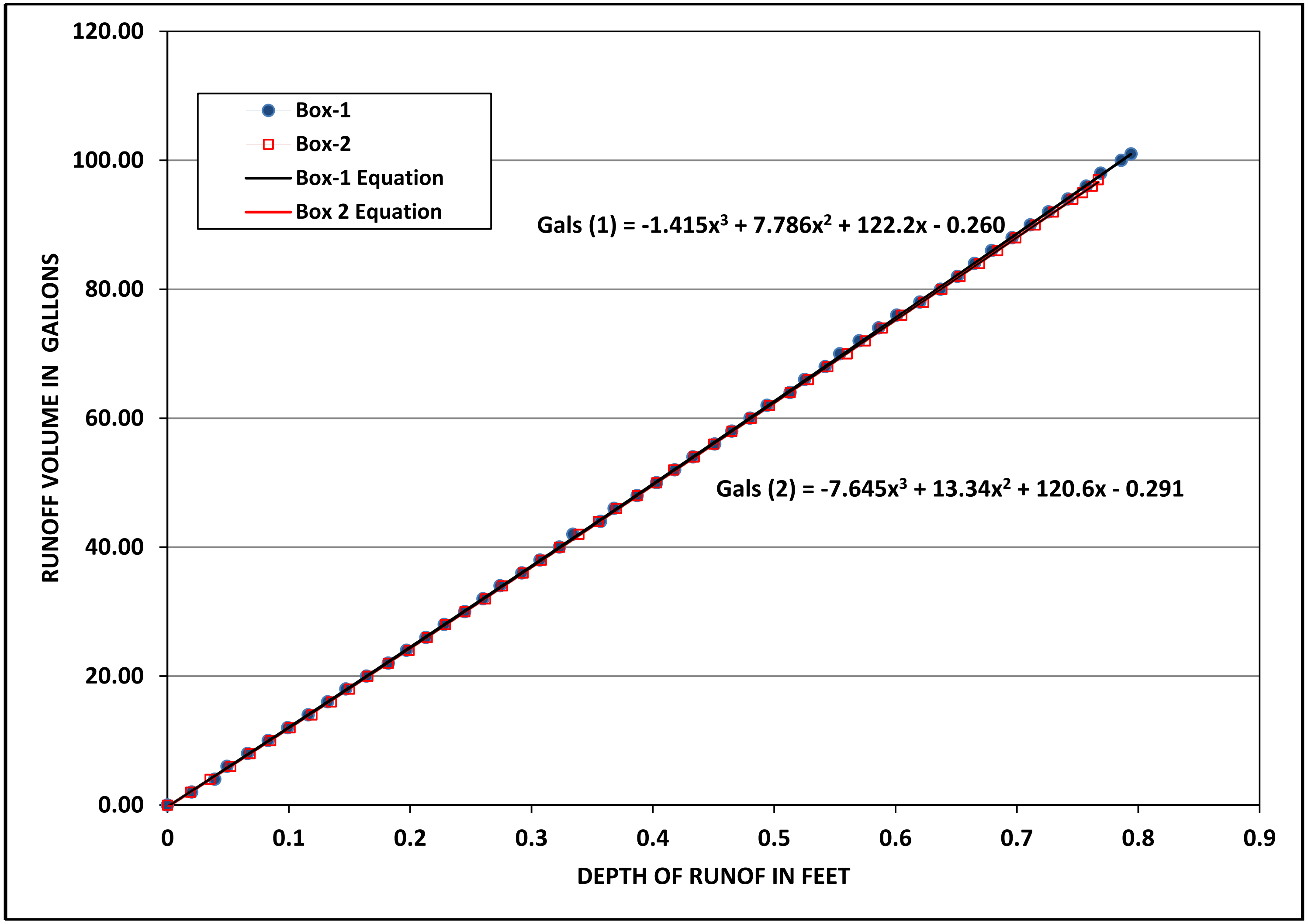


Figure 9. Depth-volume relationships for runoff catchment boxes used in experiments.

5 DETERMINATION OF POLLUTANT RUNOFF

5.1 Literature Review

Past work in estimating pollutant production along light rail tracks is very limited. The work by Burkhard, Rossi, and Boller (2008) claim to have quantified railway pollutant releases for the first time. According to this publication, the significant sources and amounts emitted by regular operation within the Swiss Federal Railways network containing approximately 4,500 miles of tracks are:

- Brakes: 1,912 T/year (73%)
- Rails: 550 T/year (21%)
- Wheels: 124 T/year (5%)
- Contact lines: 38 T/year (1%)
- Total 2,624 T/year (100%)
- Hydrocarbons: 1,357 T/year
- Herbicides: 3.9 T/year

Other past work on the topic include the study by Jian-Hua, Chun-Jie, and Bo (2009) that investigated the distribution of heavy metal emissions along a railroad in China. Variation in heavy metal emissions with distance from the edge of the railroad tracks is investigated and pollutant zones are defined. Unfortunately, even though the main conclusions of the study remains valid (pollutant concentrations vary inversely with distance and heavy pollution zone is next to the tracks) the pollutant limits established by using railroads that have been in service for 100 years are not applicable to light rail emissions.

RTD's light rail system uses newer technology. By using concrete railroad ties, the hydrocarbon releases are eliminated. Also, the braking system utilizes engine brakes rather than friction brakes at high speeds reducing the amount of metal released into the environment.

5.2 Procedure

In order to determine the pollutant production from RTD's light rail operations, two approaches can be followed:

1) Estimate quantities of various pollutants produced by light rail from maintenance records. These quantities can then be converted to average pollutant production per miles travelled per year and average pollutant production per track length per year.
2) Conduct a field data collection program where surface samples are taken from selected locations representing light rail operations and are analyzed in a soils laboratory for pollutant concentrations. These pollutant concentrations can then be converted to pollutant production per year by using the number of years the tracks have been in operation.

Next, the pollutant concentrations from the analysis are introduced into the laboratory model and selected return frequency rainfall events are applied to determine the water quality of the runoff.

In this study both approaches to determine pollutant concentrations were utilized. Light rail maintenance records were collected for annual loss of material from the wheels, brake rotors, tracks, etc. These quantities were converted to annual pollutant production per miles travelled and to annual production per track lengths. However, the resulting quantities, when averaged by the approximately 34 miles of tracks in the system, were negligible (<0.01 mg/L). Because of the newer technology using engine braking at high speeds, conventional frictional braking involving brake pads and rotors occurs only at speeds below 10 to 15 miles per hour near light rail stations. This results in localized concentrations of pollutants near light rail stations. Therefore, averaging pollutant production by the entire length of tracks does not reflect the overall system behavior and must be adjusted.

Field data collection program was revised to concentrate data collection to one of the most severe cases. If at this site the surface pollutant concentrations are within the acceptable ranges and if runoff from these areas does not contain any significant amounts of pollutants, then the RTD light rail operations can be said to have negligible impacts on pollutant production. Otherwise, data collection must be repeated at other light rail station sites and the variability must be further examined.

The severe case for pollutant production was defined as the case where:

- Heavy light rail traffic occurs causing the most wear on the tracks and moving parts;
- Heavy braking occurs causing the most wear in brake pads and rotors;
- Longest service periods causing the most pollutant amounts.

After studying the light rail system, the approach to the Broadway Light Rail Station was determined to be a proper candidate for data sampling program.

5.3 Data Collection Program

Figure 10 shows the sampling locations along the approach to the RTD's Broadway Light Rail Station. Along this 900 ft section of the light rail, in order to sample braking regions, 25 sediment samples were collected every 50 ft along two separate tracks leading to the station. This segment of the light rail has been in operation around 15 years and is the most travelled reach (5 light rail lines pass through Broadway Station). For sediment collection purposes, this segment of the light rail represented a conservative approach to estimating pollutant production since RTD maintenance records showed that in this area wear on the tracks, wheels, brake rotors and other sources of metal abrasion were well above the average experienced in other parts of the system. Also, due to the length of operation, accumulation of pollutants generated from light rail traffic is also expected to be well above a segment that is recently put in operation. Previous work in pollutant production from railroad operations indicate that the pollutant concentrations are inversely proportional to distance from tracks (greater the distance from tracks, lower the concentration). It is expected that the highest pollutant concentrations occur at the toe of the ballasted tracks. It is expected that selecting samples from the toe region of one of the oldest and most travelled segments of the light rail tracks would produce highest pollutant concentrations. Figures 11 through 26 show some of the sampling locations along the toe region of tracks. At each of the sampling locations the global coordinates of the site was recorded, photos were taken and a 1ft wide by 1 ft long surface sample from the ballast and sub-ballast regions was collected. The surface material was collected up to the compacted clay subgrade in order to capture all surface pollutants (see Figures 11, 13, 15, 17, 18, 22, 25).

Figure 10also shows that in the approach to the Broadway Station, the light rail tracks pass under the Interstate 25 Highway. Collecting samples from under the highway (samples 4 through 8), 300 to 400ft away from the railroad, represents light pollutant production conditions with minor runoff from surrounding roads and catchments.

Soil samples collected from the area immediately before and afterI-25 crossing (samples 9, 19, 20, 21) are expected to include some pollutant runoff from the Interstate traffic. Finally, highest pollutant concentrations are expected to occur near the station where most of the braking occurs (samples 11-18, 22-25).

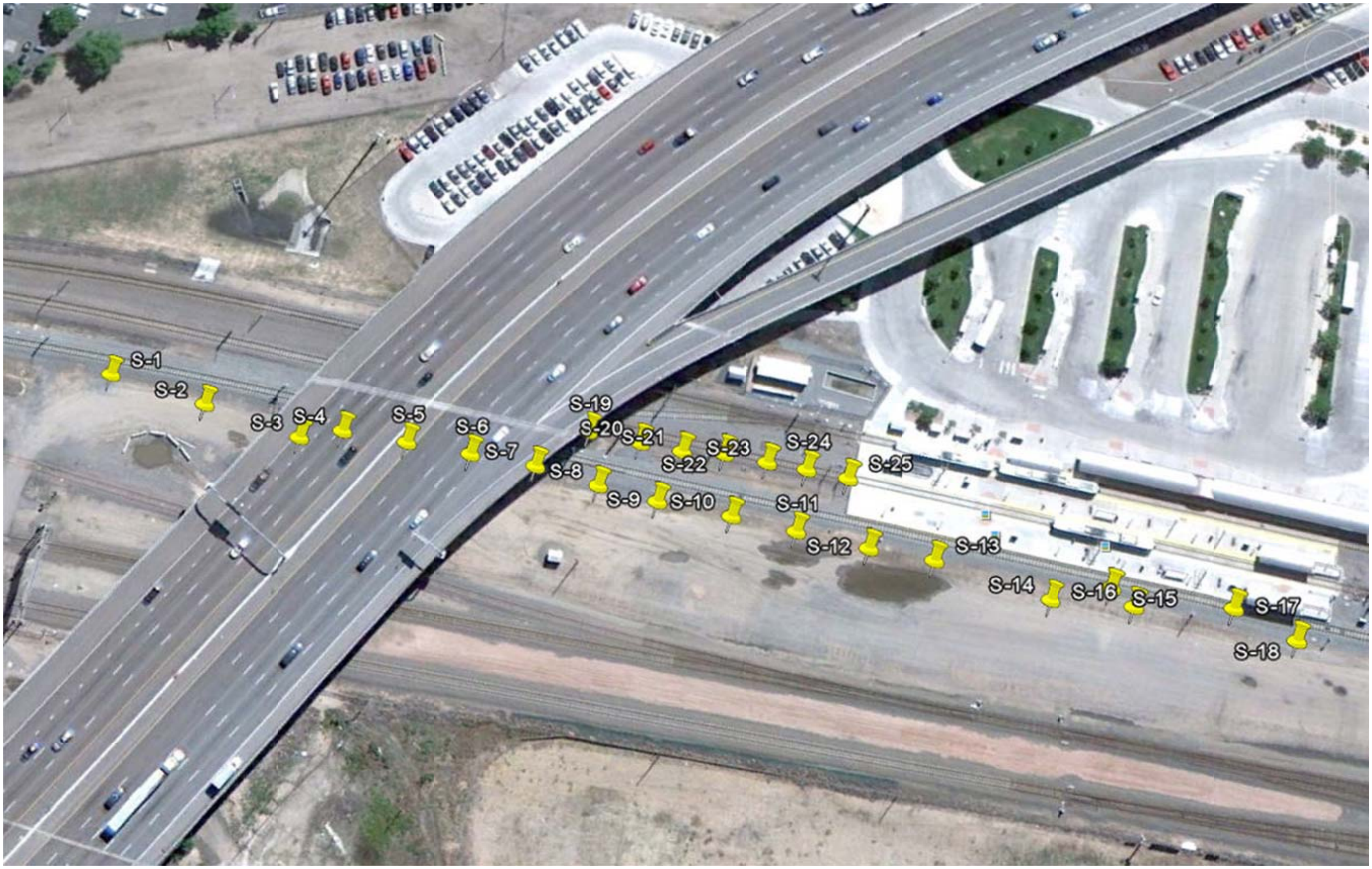


Figure 10. Soil sampling locations near RTD's Broadway Light Rail Station.

Figure 11. Soil sampling near RTD's Broadway Light Rail Station, east of I-25.

Figure 12. Soil sampling location near RTD's Broadway Light Rail Station, east of I-25.

Figure 13. Soil sampling near RTD's Broadway Light Rail Station, east of I-25.

Figure 14. Soil sampling location near RTD's Broadway Light Rail Station, east of I-25.

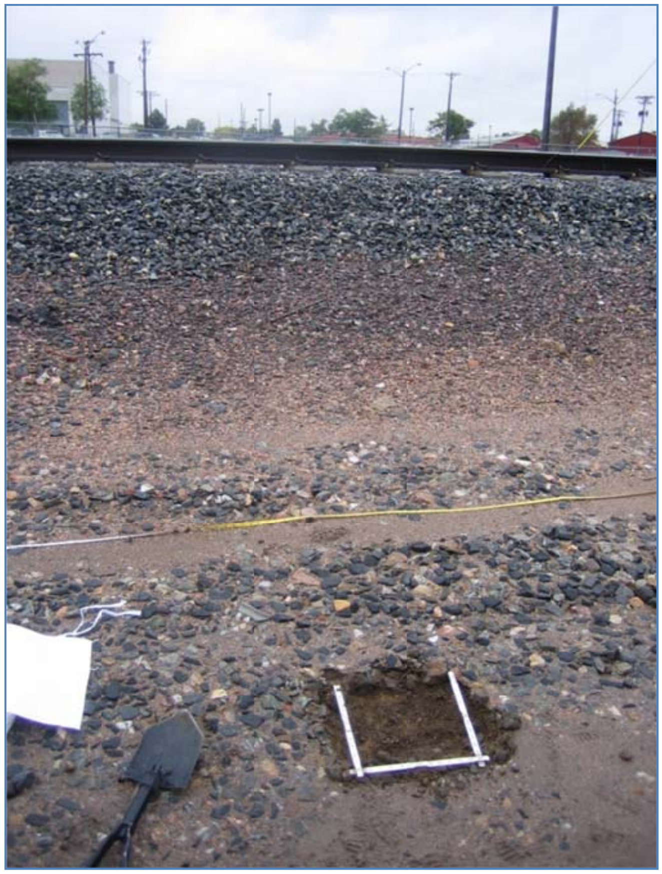


Figure 15. Soil sampling at the toe of ballasted tracks near Broadway Light Rail Station, east of I-25.

Figure 16. Soil sampling location near RTD's Broadway Light Rail Station, east of I-25.

Figure 17. Soil sampling at the toe of ballasted tracks near Broadway Light Rail Station, east of I-25.

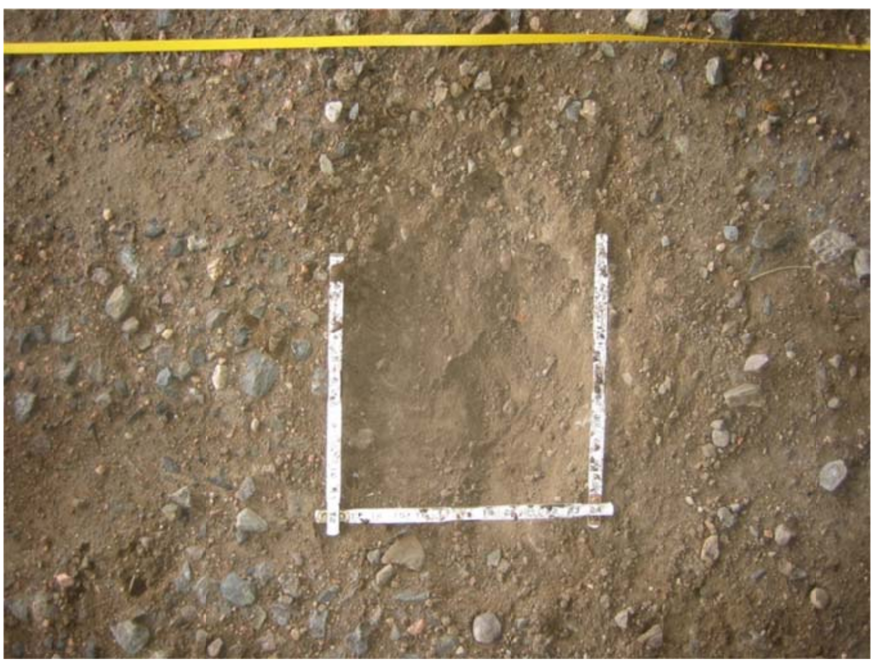


Figure 18. Soil sampling at the toe of ballasted tracks, under the Interstate Highway I-25.


Figure 19. Soil sampling at the toe of ballasted tracks under I-25.


Figure 20. Soil sampling location just west of I-25.

Figure 21. Soil sampling location just west of I-25 near Broadway Station.

Figure 22. Soil sampling just west of I-25 near Broadway Station.

Figure 23. Soil sampling location just west of I-25 near Broadway Station.

Figure 24. Soil sampling location just west of I-25 at the approach to Broadway Station.

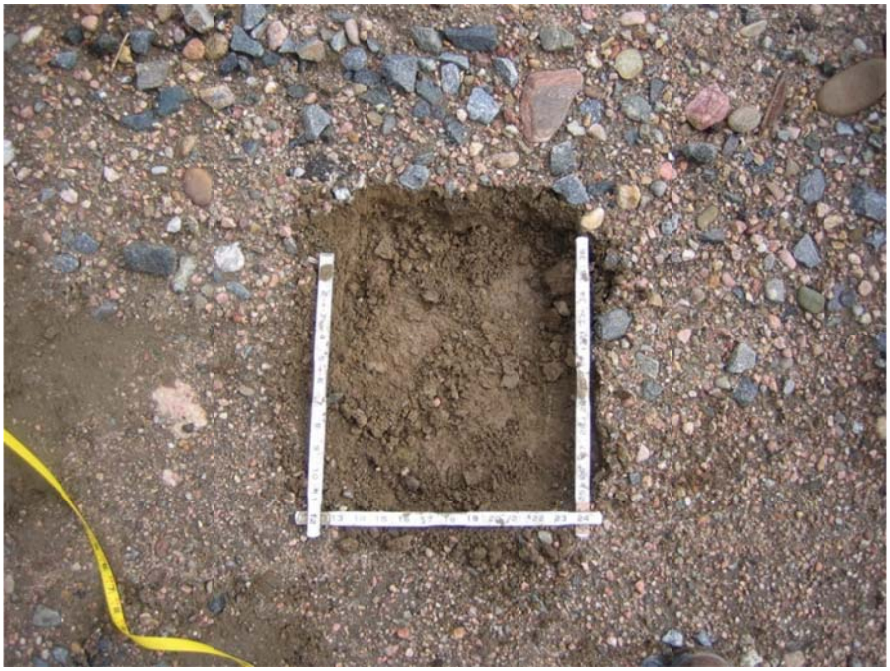


Figure 25. Soil sampling west of I-25 at the approach to Broadway Station.

Figure 26. Soil sampling west of I-25 at the approach to Broadway Station.

5.4 Results of Laboratory Analysis of Soils

The 25 soil samples collected from the Broadway Station site were analyzed at the Colorado State University Soils Laboratory. In general, 2” to 4” thick surface layer samples weighted about 20lbs to 30lbs and required the splitting of the samples into three parts for the laboratory analysis. In order not to lose any pollutants from the samples, each of these parts was analyzed separately, and the results are reported in Table 5 in separate lines. For a given mineral, the content is the average of these 3 parts. Table 5 results are summarized in Figure 27. Since the location of each site is known with respect to the light rail station (approach, under the I-25 highway, near the platform, along the platform, etc.), it was possible to make some conclusions regarding the metal concentrations. These conclusions are presented in the Summary and Conclusions.

Table 2. Colorado State University Soils Laboratory results for soil sample analysis for metal content from ballasted tracks.

Lab ID	Sample ID	Cl	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S	Sb	Se	Si	Sn	Sr	Ti	V	Zn
		mg/L																														
1552-1	1	30.7	<0.01	4987	2.21	8.2	59.0	<0.01	4091	0.171	2.6	10.2	12.4	4292	1791	2.7	1101	192	<0.01	341	3.9	226	16.1	234	<0.01	<0.01	11.0	0.41	28.9	93.4	<0.01	12.2
1552-2		29.2	<0.01	4955	1.81	8.1	58.9	<0.01	4071	0.153	2.6	10.2	12.3	4236	1809	2.7	1087	190	<0.01	338	3.9	224	16.0	225	<0.01	<0.01	10.5	0.31	28.6	92.8	<0.01	11.4
1552-3		31.8	<0.01	4910	1.90	8.2	58.6	<0.01	4010	0.184	2.6	10.0	12.3	4199	1797	2.7	1087	188	<0.01	337	4.0	223	15.9	224	<0.01	<0.01	10.6	0.29	28.0	91.7	<0.01	10.7
1553-1	2	3.15	<0.01	3242	1.40	4.1	26.6	<0.01	5015	0.089	1.9	3.1	11.0	3311	1111	1.8	1148	174	<0.01	188	2.8	233	8.6	228	<0.01	<0.01	17.3	<0.01	24.1	7.2	<0.01	<0.01
1553-2		2.89	<0.01	3247	1.41	4.1	26.8	<0.01	5099	0.091	1.9	3.2	11.0	3283	1105	1.8	1144	174	<0.01	187	2.9	233	9.0	231	<0.01	<0.01	17.9	<0.01	24.2	7.3	<0.01	<0.01
1553-3		3.25	<0.01	3293	1.35	4.2	27.2	<0.01	5189	0.078	1.9	3.3	11.1	3286	1122	1.8	1171	177	<0.01	188	2.9	239	8.8	234	<0.01	<0.01	18.3	<0.01	24.2	7.4	<0.01	<0.01
1554-1	3	6.08	<0.01	2704	1.45	3.5	34.7	<0.01	5491	0.077	1.7	3.1	6.9	2962	581	1.5	919	131	<0.01	376	2.2	259	17.3	141	<0.01	<0.01	13.2	0.03	26.1	5.6	<0.01	8.7
1554-2		5.89	<0.01	2751	1.70	3.5	35.3	<0.01	5576	0.099	1.7	3.2	7.1	2954	594	1.6	924	133	<0.01	382	2.2	265	17.5	146	<0.01	<0.01	13.1	<0.01	26.4	5.9	<0.01	8.9
1554-3		6.11	<0.01	2720	1.47	3.5	34.8	<0.01	5549	0.107	1.7	3.1	7.1	2965	594	1.6	928	132	<0.01	377	2.2	265	17.3	140	<0.01	<0.01	13.7	<0.01	26.2	5.7	<0.01	8.2
1555-1	4	45.3	<0.01	5505	1.87	7.7	61.1	<0.01	4999	0.132	2.5	5.4	11.5	3886	1148	2.5	1022	165	<0.01	336	2.9	255	17.7	128	<0.01	<0.01	1.5	0.01	42.3	79.4	<0.01	21.5
1555-2		46.2	<0.01	5455	1.77	7.8	61.5	<0.01	4938	0.144	2.5	5.3	11.6	4080	1154	2.5	997	167	<0.01	337	2.8	260	18.2	130	<0.01	<0.01	1.3	0.39	42.5	81.1	<0.01	21.8
1555-3		44.9	<0.01	5547	2.05	8.0	61.8	<0.01	5039	0.107	2.6	5.3	11.7	4075	1166	2.5	1028	169	<0.01	340	2.9	262	18.3	130	<0.01	<0.01	1.4	0.43	42.5	81.8	<0.01	22.2
1556-1	5	21.3	<0.01	5195	1.34	6.7	60.6	<0.01	4853	0.042	2.2	4.6	10.6	3851	1410	2.2	1034	147	<0.01	246	2.6	269	9.2	166	<0.01	<0.01	8.0	<0.01	40.3	136.1	<0.01	<0.01
1556-2		20.8	<0.01	5512	1.38	7.1	62.7	<0.01	5003	0.094	2.4	4.8	11.5	3893	1496	2.4	1050	156	<0.01	264	2.8	286	10.1	178	<0.01	<0.01	8.6	<0.01	42.4	144.0	<0.01	<0.01
1556-3		22.7	<0.01	5572	1.76	7.3	63.6	<0.01	5086	0.088	2.4	4.9	11.8	3921	1522	2.4	1037	157	<0.01	264	2.8	290	10.0	173	<0.01	<0.01	8.9	<0.01	42.6	146.3	<0.01	<0.01
1557-1	6	18.4	<0.01	3295	1.12	4.6	27.6	<0.01	5152	0.109	2.0	3.3	11.2	3367	1167	1.8	1179	179	<0.01	205	3.0	272	9.0	231	<0.01	<0.01	17.9	<0.01	24.2	7.6	<0.01	<0.01
1557-2		17.6	<0.01	3276	1.30	4.4	27.5	<0.01	5052	0.095	2.0	3.3	11.3	3343	1169	1.8	1190	176	<0.01	207	2.9	272	8.8	229	<0.01	<0.01	18.2	<0.01	23.7	7.6	<0.01	<0.01
1557-3		19.3	<0.01	3271	1.17	4.4	27.5	<0.01	5115	0.105	2.0	3.2	11.2	3313	1169	1.8	1163	175	<0.01	206	2.9	270	8.7	227	<0.01	<0.01	17.8	<0.01	24.2	7.6	<0.01	<0.01
1558-1	7	89.7	<0.01	5550	2.08	8.0	62.0	<0.01	5042	0.130	2.5	5.3	11.7	4059	1165	2.5	1019	167	<0.01	337	2.9	267	18.2	129	<0.01	<0.01	1.3	0.31	42.1	82.0	<0.01	21.4
1558-2		90.4	<0.01	5472	1.80	8.0	61.6	<0.01	5046	0.097	2.5	5.5	11.6	4088	1176	2.5	1020	167	<0.01	335	2.9	267	18.2	130	<0.01	<0.01	1.3	0.56	42.4	82.1	<0.01	21.4
1558-3		87.3	<0.01	5578	1.89	8.0	61.4	<0.01	5024	0.129	2.5	5.4	11.5	4013	1177	2.5	998	167	<0.01	337	2.9	267	18.0	129	<0.01	<0.01	1.5	0.26	42.4	82.0	<0.01	21.3
1559-1	8	1.72	<0.01	8177	3.82	11.2	108	<0.01	10820	0.217	3.6	5.2	13.2	8918	1574	3.0	3503	274	<0.01	437	4.5	453	22.3	200	<0.01	<0.01	272	<0.01	94.2	223.9	<0.01	13.7
1559-2		1.83	<0.01	8220	4.01	11.7	107	<0.01	10980	0.154	3.7	5.6	13.1	9206	1577	3.0	3561	283	<0.01	435	4.7	463	21.6	203	<0.01	<0.01	276	<0.01	95.2	225.7	<0.01	15.8
1559-3		1.96	<0.01	8235	2.43	11.6	108	<0.01	11040	0.197	3.6	5.8	13.2	9287	1587	3.0	3579	285	<0.01	439	4.4	465	23.8	207	<0.01	<0.01	279	<0.01	94.3	226.5	<0.01	16.2
1560-1	9	2.55	<0.01	15890	7.30	20.8	187	<0.01	23680	0.209	6.2	11.8	14.2	14410	2045	4.8	4383	440	<0.01	720	6.5	738	27.2	362	<0.01	<0.01	46.2	<0.01	178.5	464.5	<0.01	<0.01
1560-2		2.66	<0.01	15850	5.82	20.1	186	<0.01	23610	0.119	6.2	11.9	14.3	13880	2055	4.8	4363	432	<0.01	720	6.1	727	25.4	344	<0.01	<0.01	45.2	<0.01	176.3	464.4	<0.01	<0.01
1560-3		2.75	<0.01	15570	5.35	20.0	184	<0.01	23600	0.091	6.2	11.6	13.7	13880	2024	4.7	4333	426	<0.01	710	6.0	726	25.6	351	<0.01	<0.01	44.6	<0.01	171.8	454.9	<0.01	<0.01
1561-1	10	5.01	<0.01	8927	7.44	16.7	121	<0.01	7872	0.644	4.2	8.9	19.5	11190	1709	3.1	3731	325	<0.01	568	5.4	440	101	359	<0.01	<0.01	26.4	0.01	81.1	317.8	<0.01	92.1
1561-2		5.39	<0.01	8914	5.34	16.6	122	<0.01	7867	0.649	4.1	8.7	19.5	11130	1720	3.1	3720	324	<0.01	566	5.3	446	101	350	<0.01	<0.01	26.7	<0.01	81.4	319.4	<0.01	91.1

Lab ID	Sample ID	Cl	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S	Sb	Se	Si	Sn	Sr	Ti	V	Zn
		mg/L																														
1561-3		4.82	<0.01	8995	5.59	16.4	122	<0.01	7821	0.685	4.2	8.8	19.7	11090	1727	3.2	3717	325	<0.01	577	5.3	441	101	363	<0.01	<0.01	25.5	<0.01	81.2	317.4	<0.01	90.9
1562-1	11	1.79	<0.01	7627	6.82	14.3	122	<0.01	7660	1.12	3.5	4.5	33.7	10450	1615	1.9	3549	308	0.13	326	4.6	336	112	319	<0.01	<0.01	320	<0.01	67.2	288.6	<0.01	147.0
1562-2		1.77	<0.01	7510	7.64	14.2	120	<0.01	7466	1.10	3.5	4.7	33.4	10400	1622	1.9	3500	307	<0.01	322	4.5	342	108	314	<0.01	<0.01	316	0.71	65.9	285.2	<0.01	147.2
1562-3		1.93	<0.01	7617	8.21	14.5	121	<0.01	7620	1.21	3.6	4.4	33.5	10580	1659	1.9	3535	311	0.32	324	4.8	343	111	311	<0.01	<0.01	322	<0.01	67.1	290.7	<0.01	150.4
1563-1	12	4.82	<0.01	8901	44.29	21.8	194	<0.01	7124	5.70	8.5	4.6	54.9	13380	2592	2.5	4422	423	1.52	517	5.1	347	472	712	<0.01	<0.01	96.0	1.84	72.9	246.6	<0.01	550.4
1563-2		5.13	<0.01	8852	43.43	21.2	190	<0.01	7131	5.57	8.5	4.5	54.1	13260	2568	2.5	4417	419	1.57	513	5.1	340	469	674	<0.01	<0.01	93.6	1.56	71.8	246.0	<0.01	540.9
1563-3		4.75	<0.01	8695	43.72	21.4	191	<0.01	7064	5.74	8.8	4.5	54.1	13190	2566	2.5	4360	417	1.56	519	5.2	345	465	684	<0.01	<0.01	94.5	1.56	71.9	243.8	<0.01	540.2
1564-1	13	61.4	<0.01	9633	15.46	24.2	237	<0.01	6269	4.17	3.6	5.4	47.2	11360	2431	4.9	4308	331	1.61	1122	5.3	403	234	543	<0.01	<0.01	116	0.86	89.1	290.4	<0.01	183.5
1564-2		59.7	<0.01	9664	14.03	25.2	240	<0.01	6395	4.52	3.9	6.0	47.0	11840	2436	4.9	4389	346	1.66	1115	5.6	418	246	550	<0.01	<0.01	121	0.65	89.5	294.4	<0.01	198.0
1564-3		63.4	<0.01	9657	14.03	25.1	238	<0.01	6305	4.50	3.8	5.7	46.8	11750	2451	4.9	4392	342	1.55	1116	5.4	419	242	543	<0.01	<0.01	118	0.89	89.7	293.0	<0.01	193.5
1565-1	14	13.2	<0.01	9850	6.54	19.5	140	<0.01	6958	0.674	4.3	5.5	44.1	12210	3258	4.7	4920	540	<0.01	840	5.6	337	86.2	423	<0.01	<0.01	223	<0.01	63.1	342.7	<0.01	117.7
1565-2		14.8	<0.01	9870	8.11	20.0	140	<0.01	7132	0.655	4.5	5.4	43.7	12490	3272	4.7	4982	552	0.01	837	5.7	339	89.9	441	<0.01	<0.01	224	0.74	63.2	345.8	<0.01	124.4
1565-3		12.9	<0.01	9824	6.59	19.9	139	<0.01	7134	0.614	4.4	5.8	43.4	12440	3219	4.7	5080	547	0.41	831	5.6	339	89.0	435	<0.01	<0.01	220	<0.01	63.1	341.8	<0.01	123.3
1566-1	15	1.38	<0.01	10910	6.16	25.5	148	<0.01	6360	0.908	4.9	6.2	27.3	13200	2832	4.7	4934	388	<0.01	713	6.6	421	75.9	609	<0.01	<0.01	59.8	<0.01	70.3	257.1	<0.01	112.3
1566-2		1.52	<0.01	10820	6.92	23.8	148	<0.01	6221	0.848	4.5	6.3	27.7	12530	2814	4.7	4719	363	<0.01	714	5.9	403	72.0	562	<0.01	<0.01	55.9	<0.01	70.0	256.6	<0.01	97.0
1566-3		1.43	<0.01	10720	8.26	23.8	147	<0.01	6210	0.832	4.2	5.9	27.3	12450	2802	4.7	4688	361	<0.01	713	6.1	404	71.7	568	<0.01	<0.01	57.4	<0.01	70.1	253.5	<0.01	96.3
1567-1	16	15.9	<0.01	13950	5.11	17.6	116	<0.01	6508	0.162	5.4	6.1	17.2	12900	2350	5.1	4254	307	<0.01	941	5.5	449	19.6	183	<0.01	<0.01	123	<0.01	96.4	307.0	<0.01	<0.01
1567-2		15.1	<0.01	13960	5.82	18.3	117	<0.01	6465	0.181	5.5	6.2	17.3	13250	2334	5.2	4243	317	<0.01	945	6.1	461	20.7	179	<0.01	<0.01	129	<0.01	97.1	307.3	<0.01	<0.01
1567-3		16.8	<0.01	13880	4.72	18.2	116	<0.01	6568	0.176	5.4	6.3	17.2	13100	2334	5.1	4298	316	<0.01	938	5.9	457	21.4	188	<0.01	<0.01	123	<0.01	97.9	306.4	<0.01	<0.01
1568-1	17	11.8	<0.01	13750	6.63	23.5	155	<0.01	9969	0.320	4.9	12.6	41.0	15280	7425	6.7	6283	622	<0.01	580	9.4	197	25.2	2181	<0.01	<0.01	40.3	<0.01	19.2	469.0	<0.01	<0.01
1568-2		12.1	<0.01	13850	5.68	23.8	157	<0.01	10110	0.209	5.0	13.3	41.0	15770	7522	6.8	6181	631	0.14	582	9.5	196	25.6	2253	<0.01	<0.01	42.6	0.01	19.4	476.7	<0.01	<0.01
1568-3		12.9	<0.01	13790	6.59	24.1	156	<0.01	10060	0.285	5.0	12.8	41.0	15720	7561	6.8	6176	630	<0.01	584	9.6	194	25.1	2258	<0.01	<0.01	41.6	<0.01	19.2	471.7	<0.01	<0.01
1569-1	18	8.34	<0.01	13030	4.58	19.3	113	<0.01	6410	0.429	4.4	5.5	22.4	12730	3176	5.2	4956	362	<0.01	413	5.8	368	44.6	417	<0.01	<0.01	26.5	<0.01	72.4	293.4	<0.01	10.5
1569-2		8.01	<0.01	13040	5.20	19.1	113	<0.01	6368	0.434	4.4	5.5	22.5	12500	3164	5.2	4851	352	<0.01	418	5.5	360	44.3	405	<0.01	<0.01	26.3	<0.01	72.6	294.2	<0.01	8.3
1569-3		9.23	<0.01	12870	5.87	19.0	113	<0.01	6276	0.478	4.4	4.8	22.6	12510	3176	5.2	4904	353	<0.01	419	5.5	365	43.3	410	<0.01	<0.01	25.6	<0.01	72.1	290.8	<0.01	8.5
1570-1	19	101	<0.01	10870	17.28	30.4	188	<0.01	7554	3.62	4.2	7.1	43.9	12390	1859	3.8	3542	324	1.47	2084	5.9	480	173	459	<0.01	<0.01	239	0.56	103.1	318.4	<0.01	214.6
1570-2		105	<0.01	10940	15.65	30.1	186	<0.01	7463	3.49	4.2	7.1	43.2	12290	1857	3.8	3516	320	1.57	2059	6.1	476	171	457	<0.01	<0.01	239	0.53	104.5	312.6	<0.01	210.2
1570-3		95.3	<0.01	10750	16.32	29.5	184	<0.01	7419	3.63	4.1	7.2	42.6	12070	1807	3.7	3538	317	1.29	2019	5.9	470	168	427	<0.01	<0.01	223	1.11	104.3	307.1	<0.01	208.4
1571-1	20	1.05	<0.01	8273	21.19	18.6	208	<0.01	5912	5.60	4.0	6.3	56.9	10970	2147	3.3	3586	324	1.87	275	5.7	462	247	346	<0.01	<0.01	136	7.00	74.2	324.6	<0.01	234.5
1571-2		1.12	<0.01	8231	20.19	18.5	209	<0.01	6024	5.77	4.0	6.0	56.6	11030	2153	3.3	3639	326	2.26	275	5.8	473	251	348	<0.01	<0.01	142	7.94	74.4	326.5	<0.01	237.1
1571-3		1.01	<0.01	8274	19.95	18.9	210	<0.01	5976	5.76	3.9	6.4	56.8	11150	2171	3.3	3612	328	2.34	276	6.3	478	251	350	<0.01	<0.01	140	7.52	74.2	326.8	<0.01	242.0
1572-1	21	0.82	<0.01	6075	17.80	12.9	126	<0.01	3868	3.27	3.1	4.5	36.7	9074	1500	2.5	3116	224	1.08	176	5.0	339	156	259	<0.01	<0.01	21.5	1.38	53.0	249.1	<0.01	154.9

Lab ID	Sample ID	Cl	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S	Sb	Se	Si	Sn	Sr	Ti	V	Zn
		mg/L																														
1572-2		0.79	<0.01	6092	16.08	13.0	126	<0.01	3875	3.23	3.1	4.4	36.8	9117	1493	2.5	3174	224	1.30	173	4.8	342	157	263	<0.01	<0.01	21.8	0.37	53.5	250.7	<0.01	155.7
1572-3		0.85	<0.01	6074	14.56	12.9	126	<0.01	3899	3.29	3.0	4.5	36.2	9075	1491	2.5	3165	223	1.00	173	5.1	341	155	262	<0.01	<0.01	21.3	1.69	53.5	250.5	<0.01	155.5
1573-1	22	0.55	<0.01	6257	13.60	18.4	114	<0.01	3928	3.31	3.3	4.5	31.4	9926	1579	2.5	3267	242	1.14	238	5.3	395	140	294	<0.01	<0.01	273	1.26	54.8	317.8	<0.01	164.2
1573-2		0.66	<0.01	6301	14.65	18.3	113	<0.01	3860	3.33	3.3	5.0	31.6	9925	1598	2.5	3229	242	1.22	240	5.4	403	138	293	<0.01	<0.01	272	1.62	54.5	315.7	<0.01	164.1
1573-3		0.51	<0.01	6210	13.41	18.4	114	<0.01	3939	3.25	3.3	4.7	31.5	9863	1563	2.5	3254	239	1.27	240	5.3	411	138	300	<0.01	<0.01	265	1.59	54.5	314.5	<0.01	161.3
1574-1	23	0.57	<0.01	6886	5.58	12.8	98.8	<0.01	3954	1.32	2.5	2.6	24.3	9338	3065	3.3	4864	261	1.14	263	3.4	188	72.7	224	<0.01	<0.01	67.7	<0.01	26.5	319.7	<0.01	40.6
1574-2		0.63	<0.01	6908	6.73	13.3	101	<0.01	4039	1.34	2.6	2.4	24.3	9722	3084	3.3	4924	274	1.56	264	3.6	197	74.5	228	<0.01	<0.01	71.9	0.07	26.5	323.8	<0.01	46.3
1574-3		0.64	<0.01	6958	8.06	13.3	101	<0.01	4099	1.36	2.5	2.7	24.4	9798	3119	3.3	4969	278	1.42	263	3.9	196	75.8	230	<0.01	<0.01	75.5	0.34	27.0	328.9	<0.01	46.7
1575-1	24	52.7	<0.01	7230	15.37	15.3	119	<0.01	4461	3.21	3.2	4.1	32.2	10110	2136	3.1	4094	302	0.99	276	4.8	381	175	409	<0.01	<0.01	278	2.66	48.9	278.5	<0.01	172.8
1575-2		50.9	<0.01	7217	14.60	14.3	118	<0.01	4278	2.91	2.9	3.7	32.3	9557	2147	3.1	4006	284	1.05	278	4.6	363	161	385	<0.01	<0.01	273	2.30	48.1	274.8	<0.01	155.7
1575-3		53.8	<0.01	7203	13.51	14.5	118	<0.01	4282	3.03	3.0	3.8	32.3	9548	2150	3.2	4025	281	0.94	279	4.3	364	162	382	<0.01	<0.01	272	1.90	48.2	273.9	<0.01	153.6
1576-1	25	0.79	<0.01	6797	26.53	18.0	194	<0.01	5480	6.25	3.5	4.1	65.8	10310	1540	2.5	3443	273	2.90	296	6.2	422	316	464	<0.01	<0.01	196	2.08	67.7	300.2	<0.01	316.5
1576-2		0.82	<0.01	6791	28.27	18.7	198	<0.01	5502	6.41	3.6	4.6	66.2	10670	1555	2.6	3427	285	3.06	297	6.5	434	330	486	<0.01	<0.01	194	2.94	67.9	302.7	<0.01	334.9
1576-3		0.72	<0.01	6848	27.35	18.9	199	<0.01	5457	6.41	3.5	4.3	66.5	10580	1567	2.6	3431	283	2.97	302	6.7	437	329	483	<0.01	<0.01	195	2.17	67.4	302.0	<0.01	331.6

Note: Samples exceeding regulatory EPA limits are indicated in red.

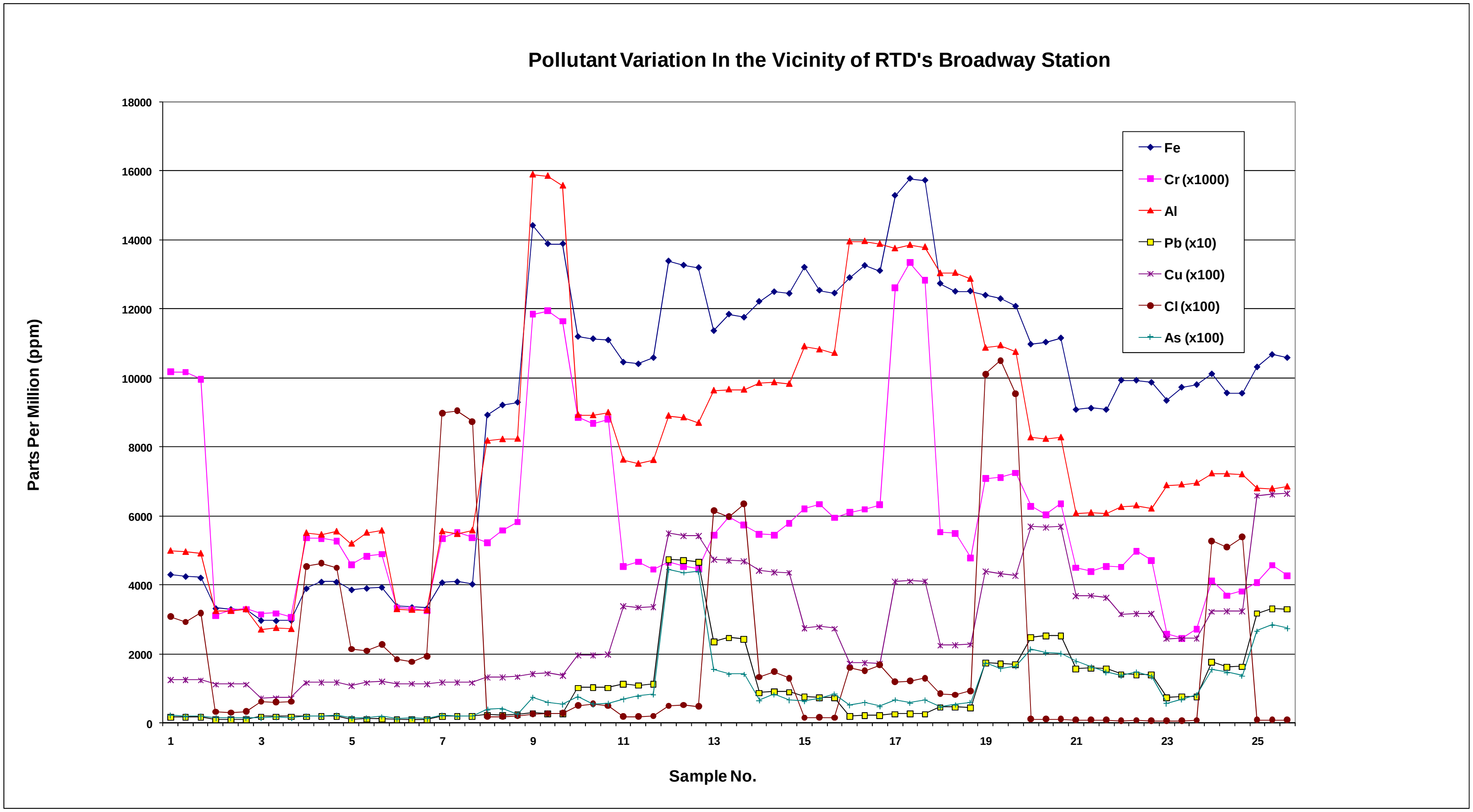


Figure 27. Variation of pollutant concentration in the vicinity of Broadway Light Rail Station.

5.5 Laboratory Study

Results of the field study are summarized in Figure 27 and show that after 15 years of operation, at the approach to the Broadway Station the metal concentrations are approximately 2 percent (mainly iron and aluminum). Using the findings from the laboratory analysis, this metal concentration was introduced into the model by replacing the original sub-ballast material at the toe region with a new mixture containing 2 percent iron and aluminum shavings (1 percent each). Since quantities of other pollutants were so minute, they were not introduced into the mixture. It was assumed that the transport of these pollutants would be proportional to their presence in the field samples compared to iron and aluminum (up to 4 percent of transported iron). Next, the polluted sub-ballast was subjected to 25-year, 50-year, and 100-year return frequency rainfall events with duration of 1hour. Water runoff samples from the model were captured at the entrance to the catchment box 5 minutes, 10 minutes, 15 minutes, and 30 minutes after the start of runoff. At the end of experiments, after draining the water, sediments accumulated in the gutters and in the runoff catchment box were collected. Figures 28 and 29 show the water samples collected during the experiment and the total sediment captured from the experiment. These samples were analyzed by the CSU Soils Laboratory to determine how much of the pollutants were transported after a moderately high rainfall event. Tables 3 and 4 present the results of laboratory analysis for mineral content of runoff water and sediment.

Figure 28. Water samples collected after 5min, 10 min, 15 min, and 30 min from the start of runoff.

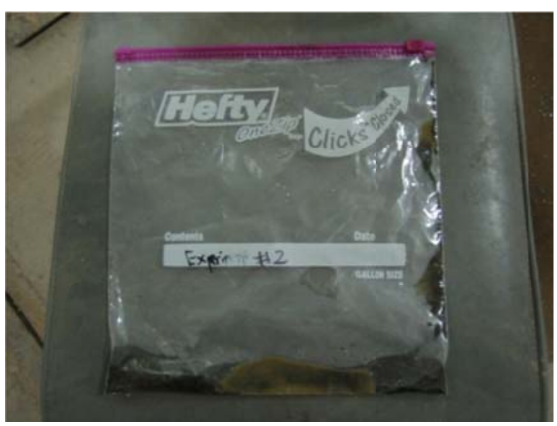


Figure 29. Sediment collected from the gutters and catchment box following a pollutant runoff experiment.

Table 3. Results of CSU Soils Laboratory analysis of water and sediment runoff samples for the 1-hour, 10-year rainfall event (Dissolved Minerals).

TOTAL ICP ANALYSIS

Experiment ID	Lab #	Sample ID #	Cl	Ag	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu
			Filtered (mg/L)											
25yr-10m	W385	1		<0.01	0.25	0.011	0.01	0.11	<0.01	10.7	0.006	<0.1	<0.1	<0.1
25yr-20m	W386	2		<0.01	0.11	<0.001	0.01	0.04	<0.01	8.33	<0.005	<0.1	<0.1	<0.1
25yr-30m	W387	3		<0.01	0.12	<0.001	0.01	0.04	<0.01	8.09	<0.005	<0.1	<0.1	<0.1
25yr-45m	W388	4		<0.01	0.09	<0.001	0.01	0.04	<0.01	7.72	<0.005	<0.1	<0.1	<0.1
50yr-5m	W389	5		<0.01	0.08	<0.001	0.01	0.06	<0.01	12.7	<0.005	<0.1	<0.1	<0.1
50yr-10m	W390	6		<0.01	0.06	<0.001	0.01	0.04	<0.01	7.64	<0.005	<0.1	<0.1	<0.1
50yr-15m	W391	7		<0.01	0.06	<0.001	0.01	0.03	<0.01	7.01	<0.005	<0.1	<0.1	<0.1
50yr-30m	W392	8		<0.01	0.08	<0.001	0.01	0.05	<0.01	6.73	<0.005	<0.1	<0.1	<0.1
100yr-5m	W393	9		<0.01	0.06	<0.001	0.01	0.04	<0.01	8.50	<0.005	<0.1	<0.1	<0.1
100yr-10m	W394	10		<0.01	0.05	<0.001	0.01	0.04	<0.01	7.11	<0.005	<0.1	<0.1	<0.1
100yr-15m	W395	11		<0.01	0.05	<0.001	0.01	0.05	<0.01	6.62	<0.005	<0.1	<0.1	<0.1
100yr-30m	W396	12		<0.01	0.05	<0.001	0.01	0.03	<0.01	6.34	<0.005	<0.1	<0.1	<0.1
25yr-5m	W397	17		<0.01	0.06	<0.001	0.01	0.07	<0.01	9.31	<0.005	<0.1	<0.1	<0.1
25yr-10m	W398	18		<0.01	0.05	<0.001	0.01	0.05	<0.01	8.86	<0.005	<0.1	<0.1	<0.1
25yr-15m	W399	19		<0.01	0.06	<0.001	0.01	0.04	<0.01	7.22	<0.005	<0.1	<0.1	<0.1
25yr-30m	W400	20		<0.01	0.06	<0.001	0.01	0.03	<0.01	6.55	<0.005	<0.1	<0.1	<0.1
25yr-Soil	R2054	13		<0.01	<0.01	0.018	0.09	0.06	<0.01	201	<0.005	<0.1	<0.1	0.1
50yr-Soil	R2055	14		<0.01	0.04	<0.001	0.04	0.09	<0.01	22.8	<0.005	<0.1	<0.1	<0.1
100yr-Soil	R2056	15		<0.01	<0.01	0.005	0.29	0.13	<0.01	139	<0.005	<0.1	<0.1	0.2
25yr-Soil	R2057	16		0.01	0.02	<0.001	0.02	0.14	<0.01	20.1	<0.005	<0.1	<0.1	<0.1

TOTAL ICP ANALYSIS

Experiment ID	Lab #	Sample ID #	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S	Sb	Se
			Filtered											
			mg/L											
25yr-10m	W385	1	3.79	<0.01	4.34	<0.01	0.01	5.82	<0.01	0.03	<0.005	7.92	0.22	0.067
25yr-20m	W386	2	3.16	<0.01	3.64	0.02	<0.01	5.15	<0.01	<0.01	<0.005	6.27	0.21	0.096
25yr-30m	W387	3	2.91	<0.01	3.65	0.01	<0.01	5.03	<0.01	0.01	<0.005	6.06	0.05	0.089
25yr-45m	W388	4	2.62	<0.01	3.49	0.01	0.01	4.73	<0.01	<0.01	<0.005	5.37	0.05	0.056
50yr-5m	W389	5	3.85	<0.01	4.99	<0.01	0.01	7.99	<0.01	0.08	<0.005	13.5	0.05	0.126
50yr-10m	W390	6	2.67	<0.01	3.54	<0.01	0.01	5.21	0.01	0.03	<0.005	5.72	0.01	0.096
50yr-15m	W391	7	2.51	<0.01	3.35	<0.01	<0.01	4.76	<0.01	<0.01	<0.005	4.67	0.19	0.111
50yr-30m	W392	8	2.27	<0.01	3.28	<0.01	0.01	4.58	0.01	0.01	<0.005	4.11	0.16	0.019
100yr-5m	W393	9	2.48	<0.01	3.99	<0.01	0.01	5.11	<0.01	0.03	<0.005	6.71	0.16	<0.001
100yr-10m	W394	10	2.12	<0.01	3.44	<0.01	<0.01	4.50	<0.01	0.04	<0.005	4.55	0.16	0.070
100yr-15m	W395	11	1.97	<0.01	3.20	<0.01	<0.01	4.29	<0.01	0.01	<0.005	3.62	0.16	0.174
100yr-30m	W396	12	1.76	<0.01	3.10	<0.01	<0.01	4.08	<0.01	<0.01	<0.005	3.26	0.13	0.145
25yr-5m	W397	17	3.13	<0.01	3.77	0.06	<0.01	7.18	<0.01	0.01	<0.005	10.6	0.19	0.116
25yr-10m	W398	18	3.00	<0.01	3.64	0.06	<0.01	6.36	<0.01	<0.01	<0.005	9.15	0.04	0.154
25yr-15m	W399	19	2.61	<0.01	3.21	0.04	<0.01	5.12	<0.01	0.04	<0.005	5.82	0.08	0.116
25yr-30m	W400	20	2.27	<0.01	3.13	0.01	<0.01	4.40	<0.01	0.03	<0.005	4.27	0.23	0.022
25yr-Soil	R2054	13	33.8	0.02	35.3	2.81	0.01	378	0.03	0.17	<0.005	585	0.16	0.166
50yr-Soil	R2055	14	7.63	<0.01	8.31	0.33	<0.01	45.3	<0.01	0.08	<0.005	37.1	0.18	0.027
100yr-Soil	R2056	15	43.4	0.04	20.0	2.31	0.09	306	0.06	<0.01	<0.005	324	0.31	0.193
25yr-Soil	R2057	16	6.04	0.01	5.97	0.13	0.01	20.8	0.01	0.04	<0.005	20.1	0.21	0.181

TOTAL ICP ANALYSIS

Experiment ID	Lab #	Sample ID #	Filtered					
			Si	Sn	Sr	Ti	V	Zn
			mg/L					
25yr-10m	W385	1	2.22	<0.01	0.08	0.01	<0.01	<0.01
25yr-20m	W386	2	1.83	<0.01	0.05	<0.01	<0.01	<0.01
25yr-30m	W387	3	2.28	0.02	0.05	<0.01	<0.01	<0.01
25yr-45m	W388	4	2.11	0.02	0.05	<0.01	<0.01	<0.01
50yr-5m	W389	5	2.14	<0.01	0.09	<0.01	<0.01	<0.01
50yr-10m	W390	6	2.16	0.01	0.08	<0.01	<0.01	<0.01
50yr-15m	W391	7	2.20	<0.01	0.05	<0.01	<0.01	<0.01
50yr-30m	W392	8	2.21	<0.01	0.11	<0.01	<0.01	<0.01
100yr-5m	W393	9	2.36	<0.01	0.06	<0.01	<0.01	<0.01
100yr-10m	W394	10	2.22	0.01	0.06	<0.01	<0.01	<0.01
100yr-15m	W395	11	2.16	<0.01	0.15	<0.01	<0.01	<0.01
100yr-30m	W396	12	2.10	<0.01	0.05	<0.01	<0.01	<0.01
25yr-5m	W397	17	1.97	0.03	0.08	<0.01	<0.01	<0.01
25yr-10m	W398	18	1.95	<0.01	0.07	<0.01	<0.01	<0.01
25yr-15m	W399	19	2.06	<0.01	0.07	<0.01	<0.01	<0.01
25yr-30m	W400	20	2.16	0.03	0.07	<0.01	<0.01	<0.01
25yr-Soil	R2054	13	7.39	<0.01	1.03	<0.01	0.10	<0.01
50yr-Soil	R2055	14	4.63	<0.01	0.15	<0.01	0.01	<0.01
100yr-Soil	R2056	15	8.66	0.01	1.02	<0.01	0.04	0.78
25yr-Soil	R2057	16	4.71	<0.01	0.14	<0.01	<0.01	0.04

Table 4. CSU Soils Laboratory analysis of water and sediment runoff samples for 1-hour, 25-, 50-, and 100-year rainfall events (Total Minerals).

TOTAL ICP ANALYSIS

			--------Total--------											
			K	**Li**	**Mg**	**Mn**	**Mo**	**Na**	**Ni**	**P**	**Pb**	**S**	**Sb**	**Se**
Experiment ID	**Lab #**	**Sample ID #**	--------mg/L--------											
25yr-10m	W385	1	39.2	0.04	50.1	3.44	<0.01	16.8	0.18	2.35	0.039	7.57	<0.01	<0.001
25yr-20m	W386	2	7.96	0.01	12.8	0.66	0.01	6.12	0.04	0.44	<0.005	5.46	<0.01	0.127
25yr-30m	W387	3	5.24	<0.01	8.34	0.34	0.01	5.65	0.02	0.23	<0.005	5.44	<0.01	0.002
25yr-45m	W388	4	4.66	<0.01	7.73	0.27	0.01	5.18	0.01	0.20	0.015	5.10	<0.01	0.071
50yr-5m	W389	5	6.50	<0.01	11.0	0.43	0.02	8.50	0.02	0.20	<0.005	13.0	<0.01	0.136
50yr-10m	W390	6	3.55	<0.01	5.88	0.16	0.02	5.45	0.01	0.10	<0.005	5.35	<0.01	0.011
50yr-15m	W391	7	2.95	<0.01	4.73	0.16	0.02	4.77	0.01	0.13	<0.005	4.50	<0.01	0.049
50yr-30m	W392	8	2.60	<0.01	4.44	0.07	0.02	4.34	0.00	0.00	<0.005	3.60	<0.01	<0.001
100yr-5m	W393	9	2.93	<0.01	5.69	0.10	0.02	4.78	0.01	0.15	<0.005	6.35	0.02	0.075
100yr-10m	W394	10	2.27	<0.01	4.24	0.06	0.01	4.00	0.01	<0.01	<0.005	3.93	<0.01	0.044
100yr-15m	W395	11	2.20	<0.01	4.25	0.06	0.03	3.96	0.01	0.08	<0.005	3.60	<0.01	0.173
100yr-30m	W396	12	1.80	<0.01	3.82	0.04	0.01	3.59	0.01	0.07	<0.005	2.83	<0.01	0.117
25yr-5m	W397	17	3.26	<0.01	5.46	0.21	0.02	6.09	0.01	0.11	<0.005	9.48	<0.01	0.058
25yr-10m	W398	18	3.08	<0.01	5.26	0.17	<0.01	5.42	0.01	0.07	<0.005	8.22	<0.01	<0.001
25yr-15m	W399	19	2.60	<0.01	4.45	0.14	<0.01	4.41	0.01	0.01	<0.005	5.27	<0.01	0.015
25yr-30m	W400	20	2.32	<0.01	3.84	0.06	<0.01	3.97	0.01	<0.01	<0.005	3.98	<0.01	0.156
25yr-Soil	R2054	13	8318	6.11	14390	552	<0.01	760	31.51	877	8.675	316	<0.01	<0.01
50yr-Soil	R2055	14	9913	7.28	16300	693	0.61	450	35.09	618	4.887	182	<0.01	<0.01
100yr-Soil	R2056	15	8264	5.02	15050	568	0.73	744	28.22	459	12.36	255	<0.01	<0.01
25yr-Soil	R2057	16	10720	8.93	18440	982	<0.01	652	42.46	569	19.83	215	<0.01	<0.01

TOTAL ICP ANALYSIS

Experiment ID	Lab #	Sample ID #	Si	Sn	Sr	Ti	V	Zn						
			Total											
			mg/L											
25yr-10m	W385	1	46.1	0.04	0.21	9.73	<0.01	<0.01						
25yr-20m	W386	2	23.0	0.05	0.08	1.44	<0.01	<0.01						
25yr-30m	W387	3	13.0	0.06	0.06	0.70	<0.01	<0.01						
25yr-45m	W388	4	11.6	0.07	0.06	0.61	<0.01	<0.01						
50yr-5m	W389	5	18.6	0.12	0.10	0.83	<0.01	0.03						
50yr-10m	W390	6	8.20	0.05	0.08	0.32	<0.01	0.02						
50yr-15m	W391	7	7.98	0.04	0.05	0.16	<0.01	<0.01						
50yr-30m	W392	8	2.88	0.10	0.10	0.15	<0.01	<0.01						
100yr-5m	W393	9	0.77	0.02	0.06	0.22	<0.01	<0.01						
100yr-10m	W394	10	2.68	0.07	0.05	0.10	<0.01	<0.01						
100yr-15m	W395	11	1.52	0.07	0.14	0.11	<0.01	<0.01						
100yr-30m	W396	12	2.30	0.11	0.05	0.08	<0.01	<0.01						
25yr-5m	W397	17	10.2	0.06	0.07	0.19	<0.01	0.03						
25yr-10m	W398	18	1.68	0.08	0.07	0.19	<0.01	0.03						
25yr-15m	W399	19	6.49	0.05	0.06	0.14	<0.01	<0.01						
25yr-30m	W400	20	2.44	0.06	0.06	0.06	<0.01	<0.01						
10yr-5m	W435	22	2.19	0.06	0.08	0.23	<0.01	0.04						
10yr-10m	W436	23	0.76	0.09	0.06	0.08	<0.01	0.01						
10yr-15m	W437	24	1.49	0.03	0.05	0.06	<0.01	<0.01						
10yr-30m	W438	25	3.30	<0.01	0.04	0.01	<0.01	<0.01						
25yr-Soil	R2054	13	133	2.15	19.7	1902	<0.01	22.1						
50yr-Soil	R2055	14	142	0.12	16.8	2253	<0.01	28.0						
100yr-Soil	R2056	15	245	0.57	18.9	1869	<0.01	1394						
25yr-Soil	R2057	16	162	3.17	28.0	2417	<0.01	466						
10yr-Soil	R2164	21	602	<0.01	17.5	2228	<0.01	75.2						

There are two sections to the laboratory analysis. One section is the data where samples of water and sediments were filtered and analyzed. This data is shown in Table 3 and represents the dissolved minerals. The other set includes the data where the samples of water and dried sediment were digested. This data set is shown in Table 7 and represents the total mineral content of the water and the dried sediment. The total dried sediment weight is also included.

Table 4 shows that the iron and aluminum content from the runoff sediments is 3.6 percent and 1.8 percent, respectively. However, since the total sediment weight is only 0.01lbs for a runoff volume of approximately 60 gallons (approximately 450lbs), the overall percent of metal within the water runoff is 22 mg/L (0.002 percent).

6 BALLASTED TRACKS AS A BMP

The ballasted tracks study showed that the RTD's light rail operations inevitably produce metals (from brakes, rotors, tracks, overhead lines, etc.). It also showed that these metals are contained within the confines of the ballasted tracks and are not released to the environment. Due to the design of ballasted tracks, the metal particles falling onto the coarse material in the ballast-region pass onto the underlying sub-ballast region. The finer silts and sands in the sub-ballast region retain these particles while the gravel outer shell protects against the transport of metal particles into the environment.

In that regard, the tracks may be regarded as a self-preserving BMP. However, the tracks cannot be used as a filter for the upstream runoff. Under such a case, the tracks would block oncoming flows and act as a dam. As a result, they will be saturated and the steel tracks resting on them will sink under the weight of light rail cars causing hazardous operational conditions. RTD's design criteria are to intercept and channelize the oncoming upper watershed runoff (perpendicular to tracks) along the toe of the tracks and to drain rainfall acting on the ballast through the use of sloping sub-ballast. As shown in Figure 1, the use of an 8-inch thick sub-ballast with a 2.5% slope resting on a compacted cohesive subgrade as well as the use of internal drain pipes aims to drain rainfall as quickly as possible to avoid saturated soil conditions.

In the following sections, pollutants encountered in RTD's light rail operation in the approach to Broadway Station are identified; their levels due to light rail operations are isolated.

In the ongoing analysis, the underlying hypothesis is "if under worst-case conditions, the tracks are shown to contain the heavy metals within their boundaries and pollutant levels do not exceed any regulatory limits, then in the rest of the light rail system the pollutant levels should be lower and the tracks can be considered a BMP for light rail operations."

6.1 Pollutants along Ballasted Tracks

The list of pollutants encountered along the 800-feet reach at the Broadway Light Rail Station is presented in Table 5 along with the corresponding EPA regulatory limits.

Among these pollutants, the maximum observed arsenic (As) and lead (Pb) concentrations appear to be relatively high. After inspecting the pollutant concentration data given in Table 2, it can be seen that the high lead (Pb) concentrations occur only at two of the sampling points, at Site No. 12(470 ppm) and at Site No. 25 (330 ppm), both at the approach to the ramp. At neighboring points 11 and 13 (50 ft to the east and 50 ft to the west of Site 12), the lead concentrations drop to 110ppm and 240ppm, respectively which are well below the limit of 420 ppm. The same trend is also observed for Arsenic (As). While arsenic levels are relatively high at Site 12 (45ppm versus the regulatory limit of 75ppm) and Site 23, at neighboring sites 11 and 13, the concentrations drop to 14.5 ppm and 8 ppm, respectively. The average lead and arsenic concentrations at the Broadway Station between Sites 11 and 25 are 157 ppm and 14.15 ppm, respectively. Away from the station, between sites 1 and 11 the average lead and arsenic concentrations are 24.7 ppm and 2.71 ppm, respectively.

The Broadway Station is located in a historically polluted site near Gates rubber factory. In the past, at the location where the light rail station is situated now, a metal foundry existed. As a result, residual of past operations might be appearing in the samples. From the limited data (one site, worst case scenario, and a short span of 800 ft in 39.4 miles of tracks), no further extrapolations can be made scientifically.

Table 5. Maximum measured heavy metal and the EPA's regulatory limits on heavy metals applied to soils (Adapted from U.S. EPA, 1993).

Heavy Metal	Maximum observed concentrations in soil samples from Broadway Station (parts per million, ppm)	Maximum Concentration in Sludge (EPA, 1993) (parts per million, ppm)	Annual Pollutant Loading rates		Cumulative Pollutant Loading Rates	
			(kg/ha/yr)	(lb/A/yr)	(kg/ha)	(lb/A)
Arsenic (As)	45	75	2.0	1.8	41	36.6
Cadmium (Cd)	6.4	85	1.9	1.7	39	34.8
Chromium (Cr)	13.3	3000	150	134	3000	2679
Copper (Cu)	66.5	4300	75	67	1500	1340
Lead (Pb)	472	420	21	14	420	375
Mercury (Hg)	N/A	840	15	13.4	300	268
Molybdenum (Mo)	3	57	0.9	0.8	17	15
Nickel (Ni)	10	75	0.9	0.8	18	16
Selenium (Se)	<0.01	100	5	4	100	89
Zinc (Zn)	550	7500	140	125	2800	2500

6.2 Pollutant Levels Due to Light Rail Operations

The results of pollutant transport experiments and field data collection and analysis has shown ballasted tracks not to be a pollutant source compared to predevelopment land. The pollutant concentrations contained within the ballasted tracks are within EPA limits and even under extreme rainfall conditions the runoff leaving the ballasted tracks were shown not to have transport capacity to carry the pollutants away from the ballasted tracks. As a result, ballasted tracks do not require BMPs.

6.3 Service Life of Ballasted Tracks

The long-term effectiveness of the ballasted tracks was measured in the oldest segment of the light rail which was almost 15 years old. Even though 15 years may not be considered long-term, extrapolating measured pollutant concentrations show that the long-term effectiveness of ballasted tracks to capture light rail pollutants is high. In that regard, the tracks may be regarded as a self-preserving BMP. However, they cannot be used as a filter for stormwater runoff. When ballasted tacks were saturated, experiments showed that the steel tracks resting on saturated soils could sink with the weight of light rail cars beyond the operational limits.

6.4 Function of Ballasted Tracks as BMP

Experiments have shown that under worst-case conditions, the ballasted tracks have retained pollutants generated during the light rail operations. This is because light rail operations produce small amounts of pollutants, and the design of subballast retains the pollutants generated during the operation of light rails.

The results of runoff coefficient experiments have shown that the initial 0.3 inch to 0.4 inch of rainfall was retained within the ballasted tracks (Molinas and Mommandi, July 2011). The initial 0.5 inch of rainfall is termed by Urban Drainage and Flood Control District as the water quality control volume and is believed to be the driving force for the initial sediment flush. Since the ballasted tracks retain the majority of the water quality control volume and release only a small portion of the initial 0.5 inch of rainfall, the pollutant production due to initial flush is negligible. Runoff coefficient experiments have also shown that ballasted tracks do not produce additional runoff compared to predevelopment land and therefore they do not require a BMP.

Field visits have shown that ballasted tracks form only a part of the light rail passageway and the above conclusions do not pertain to other parts of the light rail system. The embankments, bridges, entrances to construction sites, drainageways, and other parts of the system must be subject to inspections and the installation of BMPs as with any other highway construction and operation project. Field trips to Lakewood area of RTD's new light rail construction site have indicated an effort by RTD to provide a variety of BMPs for different components of the system. However, a compliance inspection is beyond the scope of this research and should be carried out by CDOT.

Figure 30. RTD’s light rail bridge construction in Lakewood over Highway 6.

Figure 31. BMPs for RTD’s light rail bridge construction in Lakewood over Highway 6.

Figure 32. BMPs for RTD's light rail bridge construction in Lakewood over Highway 6.

Figure 33. BMPs for RTD's light rail bridge construction in Lakewood over Highway 6.

Figure 34. BMPs for RTD's light rail construction in Lakewood near Federal Center.

Figure 35. BMPs for RTD's light rail construction in Lakewood along Highway 6.

Figure 36. BMPs for RTD's light rail construction in Lakewood along Highway 6.

Figure 37. BMPs for RTD's light rail construction in Lakewood along Highway 6.

Figure 38. BMPs for RTD's light rail construction in Lakewood along Highway 6.

Figure 39. Light rail tracks for the RTD's Lakewood line under construction.

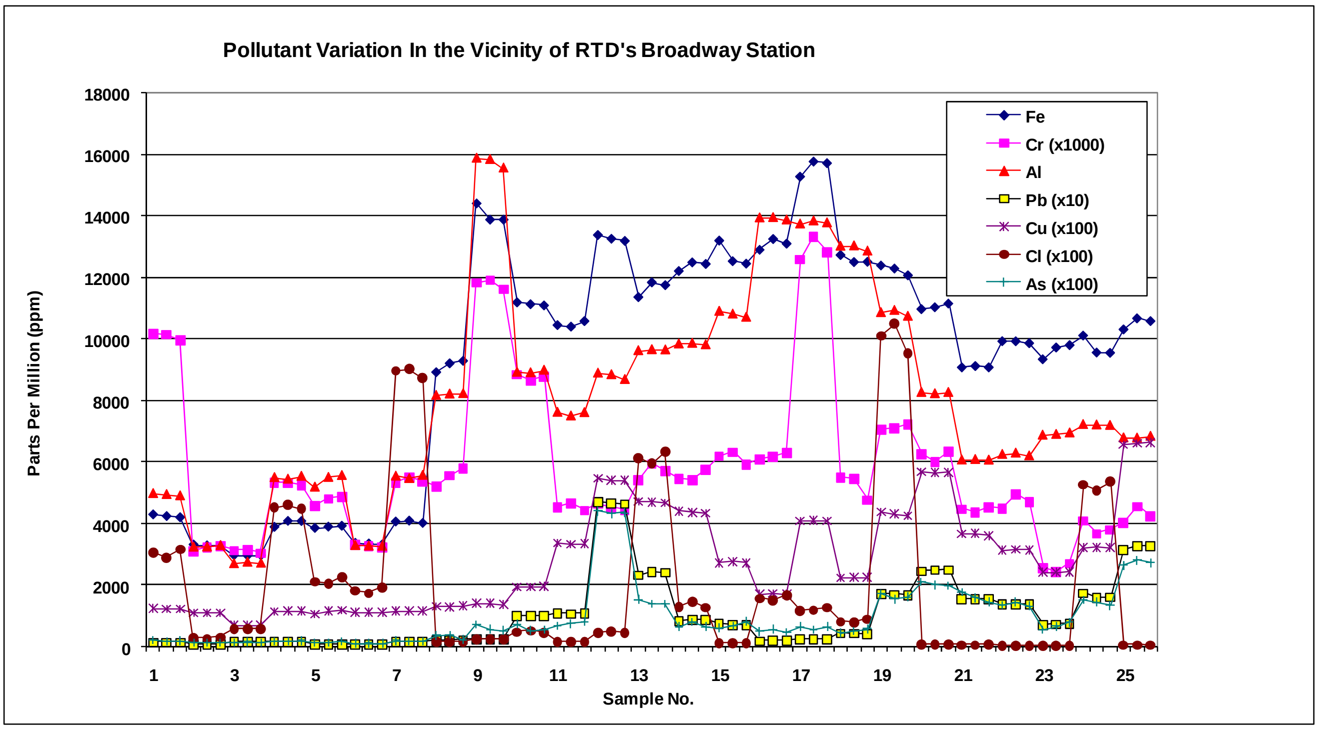
7 SUMMARY

The study entitled "Modeling Ballasted Tracks for Pollutant Transport" investigated ballasted tracks for pollutant production. In the following sections, study findings are summarized.

7.1 Pollutant Runoff

Pollutant runoff study was based on the field measurement of pollutant levels along ballasted tracks and introducing these measured levels of pollutants to the toe region of model tracks placed in a laboratory rainfall-runoff facility to determine runoff water quality.

For the field measurements, 25 samples at the approach to the RTD's Broadway Light Rail Station were taken. These samples were spaced 50ft apart and covered approximately 900ft section along the light rail tracks. The site was chosen because of its high volume of traffic, length of operation, and because it was a braking zone. Samples were taken between 700ft away from the station where no braking occurred and the platform area where most of braking (and metal abrasion) took place. The figure below summarizes the laboratory analysis of mineral contents.



Findings from the summary figure are:

1) Away from the station, in samples 1 through 3, levels of iron, aluminum, chromium, arsenic, lead, and chlorides (salts) are at low levels.

2) At sampling locations beneath the I-25 (samples 4, 7, 8, 9, 19), chloride and magnesium concentrations show a marked increase.

3) In the approach to the station (stations 9 through 13, 20 through 25) and along the platform (station 13 through 18) iron and aluminum concentrations are between 1 and 1.5 percent.

4) At breaking locations immediately before passenger embarking/leaving locations (sample 16 and 17) the metal concentrations is the highest.

5) Next, the 2 percent iron and aluminum concentration (total) observed from the soil samples were introduced into the laboratory model. The sub-ballast material in the toe region was replaced with a mixture containing a total of 2 percent aluminum and iron. The model was then subjected to a 10-year, 1 hr rainfall event. The runoff water and soil samples were collected 5 minutes, 10 minutes, 15 minutes, and 30 minutes after the start of runoff, and at the end of the experiment. Results of the sample analysis are presented in Tables 3 and 4. Comparing heavy metal levels with the EPA limits tabulated above shows that the RTD operations do not exceed any regulatory limits on heavy metals.

6) The measured soil runoff from the tracks during the 10-, 25-, 50- and 100-year events was very little. Total metals in transport were negligible.

8 CONCLUSIONS

As a philosophy, the study uses a conservative "worst-case" approach to support its findings. It was decided on the outset that if the system was found to not have any pollution problems under the worst-case conditions, then conclusions could be extended to the entire light-rail system using the same technology.

In particular, the following assumptions were made:

- Since the driving force in the pollutant runoff is the water flow, the infiltration losses into the subgrade were minimized in the experiments by introducing an epoxy-coated plywood surface for simulating the subgrade.
- In selecting the rainfall intensity for the Denver area, the past storms had shown that vast majority of the storms had their most intense period last for 1 hour. Therefore for the 25-year, 50-year, 100-year return frequency rainfall events, 1-hour duration was chosen.
- Similarly, rather than choosing a reach that represented average light rail traffic load and average age of the system, the soil sampling was conducted along the most heavily travelled reach of the ballasted track that has been in service the longest.
- Also, the soil sampling was concentrated at the toe region of the tracks (6 to 8 feet from tracks) where after 15 years of operation, it was believed to have the highest levels of pollutant concentrations.
- At the light rail station where 5 different lines converged, soil sampling was made in the direction of braking in order to observe the most metal abrasion.
- For comparison purposes the worst-case pollutant concentrations were used in comparisons with EPA regulations.

Conclusions from the study:

1. The state of runoff in regards to inflows was determined. The water leaving ballasted tracks carry minute amounts of heavy metals that are introduced into tracks from light rail operation.
2. The minor pollutants entering the system were determined and quantified from a field sampling program. The heavy metals concentrations at the most heavily travelled light rail station showed that pollutant concentrations were far below the regulatory limits. Table 5 presents a comparison between the maximum measured heavy metal concentrations and the EPA's regulatory limits for the soil samples collected from RTD's Broadway Light Rail Station. The measured heavy metal concentrations are given in the second column of Table 5. These values were derived from Table 2 by selecting the maximum concentrations from among all soil sampling sites. With the exception of lead concentration from one of the sampling locations, all heavy metal concentrations were found to be below the regulatory limits. The sampling location where EPA limit was exceeded was the location where once a metal foundry existed. Table 5 shows that the measured heavy metal concentrations from Broadway Station (the most travelled ballasted tracks which have been in operation for the longest period of time) are far below the regulatory limits. Therefore, pollutant runoff from these soils is also expected be below the regulatory limits.
3. The majority of runoff from the ballasted tracks is retained for the initial 0.5 inch of rainfall with the body of the tracks. The ballasted tracks do not produce more runoff than the predevelopment, and therefore do not require a BMP.
4. Ballasted tracks form only a portion of the light rail system. The embankments, light rail bridges, construction sites, drainageways, etc. forming the rest of the rail system is beyond the scope of this research and should be subject to CDOT inspections and recommended BMP treatments as any other highway project.

Table 5. Maximum measured heavy metal concentrations and the EPA's regulatory limits on heavy metals applied to soils (Adapted from U.S. EPA, 1993).

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Molybdenum (Mo)	3	57	0.9	0.8	17	15
Nickel (Ni)	10	75	0.9	0.8	18	16
Selenium (Se)	<0.01	100	5	4	100	89
Zinc (Zn)	550	7500	140	125	2800	2500

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