U.S. HIGHWAY 36 STORMWATER MONITORING AND MEDIA FILTER DRAIN EVALUATION

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EXECUTIVE SUMMARY

The Colorado Department of Transportation (CDOT) contracted with RESPEC to monitor stormwater runoff from the westbound lanes of U.S. Highway 36 (US36) in Boulder County and compare effluent pollutant concentrations from a media filter drain (MFD) and a roadside ditch. MFDs are used successfully in Washington State where rainfall events are typically long duration and low intensity. In comparison, rainfall events along Colorado's Front Range tend to be high intensity and short in duration. The goal of this study is to evaluate whether water quality treatment provided by the MFD, in Colorado's climate, is a significant improvement over a vegetated roadside ditch given that MFDs are more expensive to install and maintain.

RESPEC reviewed current research on MFD efficiency and lifespan. While there have been studies done on MFDs in the past, RESPEC evaluated the use of MFDs in Colorado's arid environment with short-duration and high-intensity rainfall events. This monitoring and evaluation will assist CDOT toward a clear decision on the use of MFDs as a stormwater control measure.

RESPEC collected and analyzed 32 paired storm samples at each site over the 3-year study period at two study sites. The MFD and the ditch are located on the north side of US36, on either side of the Boulder Overlook (US36, mile marker 42). The MFD monitoring segment extended approximately 1,800 feet in a westerly direction from the west side of the Boulder Overlook. The roadside ditch study segment extended approximately 1,200 feet in an easterly direction on the east side of the Boulder Overlook. The upgradient ends of the two control measures are approximately 1/3 of a mile apart and both receive runoff from the westbound lanes of US36.

Runoff samples were collected for laboratory analysis following runoff events that triggered monitoring equipment at the downgradient end of each study area. The study assumed that influent pollutant concentrations to each study area were similar because of the proximity of the sites and because each received the same traffic volume, precipitation, sweeping, and winter treatment. The assumption of similar influent pollutant concentrations allowed CDOT to use effluent data as a proxy for treatment efficiency. Examining the effluent data from the stormwater samples allowed quantifiable comparison of the roadside ditch and the MFD's abilities to treat stormwater runoff.

The effluent concentrations from the MFD exhibited better treatment efficiencies in 17 of the 35 pollutants tested, the ditch outperformed the MFD for 11 of the pollutants, and there was no discernable difference in treatment efficiency between the two sites for the remaining 7 measured pollutants. While the MFD was more effective at removing suspended sediment, phosphorus, iron, zinc, and some of the other heavy metals tested, the ditch had a higher treatment efficiency for copper as well as the ions and metals that are common components of roadway deicing chemicals.

While the MFD did outperform the roadside ditch for some of the parameters measured, the additional installation costs and maintenance requirements of the MFD likely outweigh these benefits. Alterations to the MFD design to further decrease the velocity of flows and to improve vegetation establishment in the Colorado Front Range could further improve MFD pollutant removal effectiveness. However, given the relatively high costs of the MFD and limited benefits, CDOT may want to consider alternative stormwater control measures.

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1.0 INTRODUCTION AND BACKGROUND

The Colorado Department of Transportation (CDOT) US36 Media Filter Drain Sample Monitoring and Structural Design Evaluation was performed under CDOT's HAA RFP 18-130 NM – DTD Environmental Programs Branch Support Services contract awarded to HDR Engineering, Inc. (HDR). RESPEC conducted water quality control measure research, environmental monitoring, environmental data collection and analysis, and maintenance of water quality sampling equipment under subcontract to HDR. HDR provided administrative oversight and project management assistance. PACE Analytical, LLC (PACE) furnished the water quality sampling kits and performed all laboratory analyses.

Evaluation of the design and performance of the U.S. Route 36 (US36) media filter drain (MFD), a permanent water quality control measure, was the primary goal of this effort. RESPEC conducted environmental monitoring, including environmental data collection and analysis, to evaluate whether the MFD installed during the recent US36 expansion removes more pollutants from highway runoff than an adjacent roadside ditch.

This report presents the results of this study in the context of whether MFDs are an effective emerging technology for treating highway runoff resulting from high intensity, short duration storms along Colorado's Front Range. Environmental monitoring generated recommendations for design, installation, and maintenance of the next generation of MFDs, a secondary goal of this effort. An analysis of Colorado's winter maintenance on roadways, considering freeze-thaw events and winter road treatments, are also considered in the maintenance and longevity of MFDs.

2.0 LITERATURE REVIEW— MEDIA FILTER DRAIN

2.1 BACKGROUND

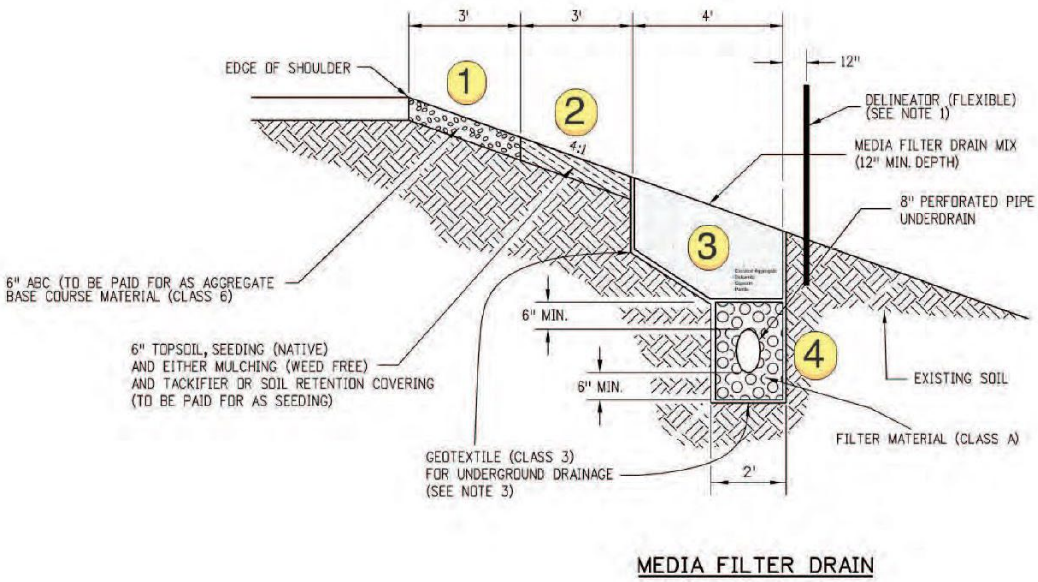
MFDs are permanent stormwater control measures (SCM) used to effectively remove suspended solids, phosphorous, dissolved zinc, and copper from roadway runoff, among other roadway pollutants of concern. MFDs are typically constructed in the pervious shoulder area along a highway, consisting of a no vegetation zone, a grass strip, a filter media mix, and a drain component that keeps the facility free draining. While there have been studies on how effective these have been in Washington State, where the MFD was first used, CDOT seeks to understand the effectiveness of MFDs in Colorado's arid to semi-arid environments. In addition, CDOT's Municipal Separate Storm Sewer System (MS4) Permit requires the Department to "…implement a wet weather monitoring program to assess wet weather impacts from highways and facilities and the performance of control measures used to control discharges." (COS000005, Part I.F.6.) Wet weather monitoring conducted during this study will contribute towards CDOT maintaining compliance with the MS4 Permit's wet weather monitoring requirements.

2.2 GENERAL MFD DESCRIPTION

Washington State Department of Transportation (WSDOT) developed the MFD, formerly known as the Ecology Embankment, as a SCM to treat roadway runoff (Hasselbach and Poor, 2014). From Washington State's Highway Runoff manual (2008), the MFD is a linear flow-through stormwater runoff treatment device that can be sited along highway side slopes (conventional design) and medians (dual MFDs), borrow ditches, or other linear depressions. Cut-slope applications may also be considered. The MFD can be effective where available right-of-way (ROW) is limited, runoff sheet flows from the highway surface, and lateral gradients are generally less than 25% (4H:1V).

However, the available literature provides little insight into applicable design storms, runoff intensity, and other hydrologic factors that may drive the success or failure of an MFD as a permanent water quality control measure.

MFDs have four basic components: (1) a gravel no-vegetation zone; (2) a grass strip; (3) the MFD mix bed; and (4) a conveyance system for flows leaving the MFD mix (Figure 1 and Figure 2). This conveyance system usually consists of a gravel-filled underdrain trench or a layer of crushed surfacing base course (CSBC). This layer of CSBC must be porous enough to allow treated flows to freely drain away from the MFD mix (WSDOT, 2019).



2.2.1 TREATMENT PROCESS

The MFD is designed to remove suspended solids, phosphorus, metals, and oil from highway runoff through physical straining, ion exchange, carbonate precipitation, and biofiltration. Treatment processes associated with each of the components of the MFD are described below from Washington State's Highway Runoff manual (2008). As discussed above, the four sequential processes are: no-vegetation zone; vegetated filter strip; MFD mix bed; and the gravel underdrain.

2.2.1.1 NO-VEGETATION ZONE

Stormwater runoff sheet flows from the paved road surface to the MFD over a vegetation-free gravel zone. The gravel zone promotes sheet dispersion and provides some pollutant removal. The primary function of this zone is to ensure sheet flow conveyance to the adjacent vegetated filter strip. Runoff must remain dispersed (sheet flow) across the MFD to enhance infiltration.

The no-vegetation zone also provides some treatment through sediment filtration and limited infiltration. Pollutants attached to, or adsorbed to, solids will be removed from the runoff with the solids. The range of particle sizes captured in the no-vegetation zone will depend on flow velocity, which in turn is correlated to the slope of the no-vegetation zone and the intensity of the precipitation event. Most sediment may be trapped during low intensity and/or very brief storms, and some of this flow may infiltrate to underlying soils, reducing pollutant loads to the downgradient portions of the MFD. Higher intensity storms will result in primarily coarse sediment trapping or, potentially, no sedimentation at all.

2.2.1.2 VEGETATED FILTER STRIP

After the no-vegetation zone, a vegetated filter strip is incorporated into the top of the fill-slope to reduce flow velocity to encourage sedimentation and limit the erosivity of flows reaching the MFD mix bed, thereby extending the life of the system.

While the vegetated filter strip provides some pollutant removal prior to filtration through the MFD mix bed, it is important to note that only the MFD mix bed is designed to fully treat highway runoff. The vegetated filter strip is considered additional treatment in the system and will extend the life of the MFD mix bed reducing long-term operations and maintenance needs.

Incorporation of compost amendment in vegetated filter strips is encouraged. Properly designed compost amended vegetated filter strips (CAVFS) are approved for basic and enhanced metals treatment (WSDOT 2006b; Ecology 2005). Because vegetated filter strips upslope of MFDs may not meet the width requirements of standalone filter strips, these lesser-width CAVFS will not have the same treatment effectiveness. However, they can still provide a degree of solids and dissolved metals treatment capability.

The vegetated filter strip physically filters sediments and pollutants associated with sediments from runoff. The soil matrix can remove phosphorus through sorption and precipitation with iron oxides, aluminum oxides, calcium, and ferric iron. Vegetative uptake may also be a pathway of phosphorous removal. Dissolved metals can be removed by sorption to iron, aluminum, and manganese oxides, precipitation with carbonates and sulfides, and sorption to exchange sites in clay and organic matter. Where filter strips are amended with compost, additional metals removal can be achieved through chelation and complexation with organic matter. An advantage of the compost-amended vegetated filter strip is improved removal of soluble cationic contaminants through sorption; further, metals are also removed through uptake by plants, biofilms, and soil organisms, and these populations are enhanced by compost amendment. To the extent that infiltration occurs into the soil underlying the vegetated filter strip, discharge pollutant loading is reduced.

2.2.1.3 MFD MIX BED

CDOT’s specified MFD mix contains aggregate, horticultural grade perlite, agricultural grade dolomite, and non-calcined agricultural grade gypsum. Dolomite and gypsum add alkalinity and ion exchange capacity to promote the precipitation and exchange of heavy metals for light metals, and precipitation of phosphorus. Perlite improves moisture retention, which is critical for the formation of a biomass of epilithic biofilm within the MFD mix bed. In addition, the perlite increases tortuosity of the matrix, enhancing retention for treatment chemical reactions. The combination of physical filtering, chemical precipitation, sorption by ion exchange, biological uptake, and infiltration provides the water treatment capacity of the mix. These processes are described in more detail below:

- Physical filtration. The granular filter media provides filtration of particulate materials and the pollutants associated with them.
- Chemical precipitation. Carbonate from dolomite increases the buffer capacity and alkalinity of runoff. This leads to precipitation through the formation of metal carbonates and hydroxides. Calcium from dolomite and gypsum, and magnesium from gypsum combine with phosphate to form relatively insoluble metal-phosphate precipitates.
- Sorption by cation exchange. A matrix containing gypsum and dolomite adsorbs metals from runoff by exchanging calcium and magnesium ions with heavier metals including copper and zinc.

» Biological uptake. Epilithic biofilm in the matrix can remove phosphorus, precipitate, and sequester metals, and metabolize petroleum hydrocarbons.

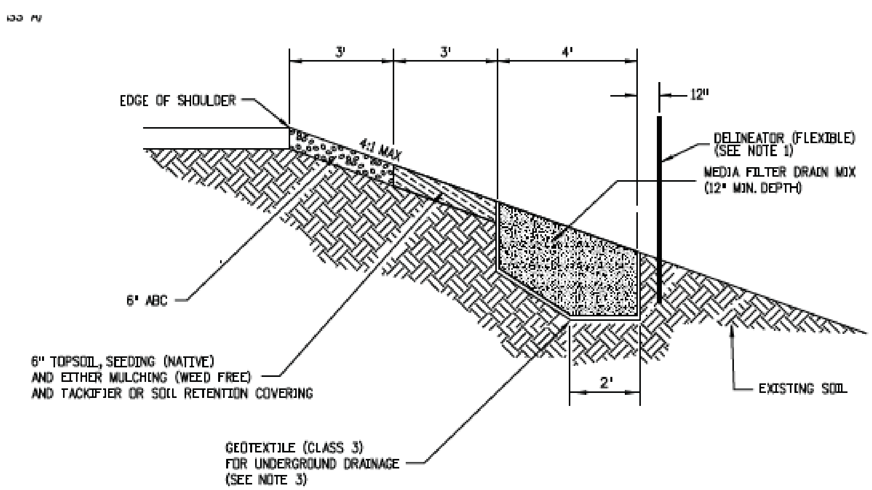
» Infiltration below the MFD mix bed. Runoff that infiltrates to underlying soils will reduce pollutant loading to the downstream surface discharge point.

2.2.1.4 GRAVEL UNDERDRAIN

The gravel underdrain trench provides hydraulic conveyance and should be evaluated for infiltration loss. Runoff that infiltrates to underlying soils will reduce pollutant loading to the downstream surface discharge point.

Together, the MFD's four components function as a treatment train to optimize pollutant removal. MFDs must be maintained to continue to function as designed. If properly installed and maintained, media filters can be highly effective for removing sediment, trash, metals, oil and grease, and organics; moderately effective for removing bacteria; and minimally effective for nutrient removal.

It is important to note that there are sections of the US36 MFD that incorporate a "Modified Media Filter Drain Design". This design does not include an underdrain like that of the rest of the MFD. A section view of this modified MFD design is found below.



MODIFIED MEDIA FILTER DRAIN

This modified form of the MFD is located at the locations listed in Table 1. The station numbers in the red boxes are the areas that are within the testing area for this study.

Table 1. Modified Media Filter Drain Locations

MODIFIED MEDIA FILTER DRAIN LOCATIONS		
BEGIN STATION	END STATION	OFFSET SIDE
1126+46.78	1126+92.90	LT
1131+86.90	1132+03.03	LT
1153+38.81	1153+48.83	LT
1157+59.55	1158+57.04	LT
1162+31.37	1162+46.43	LT
1182+73.73	1183+28.73	LT
1195+34.63	1196+19.73	LT
1121+12.93	1121+30.62	RT
1126+66.94	1127+31.71	RT
1131+85.17	1132+01.10	RT
1137+83.56	1137+88.56	RT
1153+31.07	1153+55.84	RT
1157+88.05	1158+14.60	RT
1162+32.88	1162+51.69	RT
1182+31.02	1182+66.56	RT
1195+22.73	1195+83.82	RT
1199+63.73	1199+90.51	RT
1212+82.55	1213+51.70	RT

MFDs have shown to be effective as runoff treatment for phosphorus, total suspended solids (TSS), and dissolved metals (Hasselbach and Poor, 2014). A study done by Hasselbach and Poor in Washington State compared aggregates to show removal efficiency and longevity in MFDs. The study defined the original aggregate designed to 2004 specifications, and new aggregate defined as aggregates using 2008 specifications. The new aggregate is finer than the original and cited as more economical and more readily available (Hasselbach and Poor, 2014).

In all test cases, Hasselbach and Poor allowed at least 43 hours between lab simulations of runoff through the filter media to simulate drying between storm events (2014). The study tested 2 methods. Method 1 tested performance, and Method 2 simulated accelerated aging. Each test followed the influent and effluent loads of copper and zinc. Their results are presented in Table 2 below.

Table 2. Mean Concentration Reduction Rates with Standard Deviations for all Performance Tests on New and Old Media Columns (Methods 1 and 2; Hasselbach and Poor, 2014).

Method	Media	Concentration	Loading Rate (in/hr)	Aging (yrs)	Cu Avg. % Conc. Reduction	Zn Avg. % Conc. Reduction
1	New	Typical	30	0	62 ± 17	78 ± 17
1	Old	Typical	30	0	66 ± 13	90 ± 10
1	New	Typical	50	0	64 ± 8	84 ± 4
1	Old	Typical	50	0	56 ± 8	95 ± 0
1	New	High	30	0	90 ± 5	93 ± 6
1	Old	High	30	0	89 ± 4	99 ± 4
1	New	High	50	0	90 ± 7	95 ± 7
1	Old	High	50	0	40 ± 12*	96 ± 2
2	New	High	30	~3.4	89 ± 3	93 ± 2
2	New	High	30	~6.8	91 ± 1	93 ± 2
2	New	High	30	~10.5	93 ± 2	94 ± 1

These findings show that both new and old aggregate mixes have a significant reduction in copper and zinc. This study found, however, that the new media may have extended lifespan of well beyond 15 years (Hasselbach and Poor, 2014). This study represented Washington State's annual precipitation of 40 in/year with runoff from 10 times the MFD area (Hasselbach and Poor, 2014). Given Colorado's annual rainfall is 14.3 in/year (U.S. climate data, 2010), the lifespan of MFDs using the new aggregate in Colorado could last longer than the estimated 15 years. The study also looked at dry periods between intense rainfall events, increasing the applicability of these findings to Colorado's semi-arid climate.

Comprehensive Environmental Inc. studied a variety of SCMs for the Vermont DOT to find effective practices for treating stormwater. In the study, they included an analysis of MFDs and Embankment Media Filters. Comprehensive Environmental Inc. cited the cost effectiveness of MFDs stating, "media filter drains have an effective life of 5-20 years, low to moderate operation and maintenance costs, and only require mowing maintenance as needed" (2012).

The low to moderate operation costs are cited as such because the construction of this SCM is, "essentially a roadside landscaping practice, readily observable and easily accessed for inspection and maintenance. Other than cleaning of the underdrain (as warranted by periodic inspection), this practice does not require special equipment or procedures to inspect and maintain" (Comprehensive Environmental Inc., 2012).

Regarding effectiveness, several different studies show how MFDs removal percentage differs per pollutant source. Table 3 below shows these findings.

Table 3. Target Pollutants and Treatment Effectiveness (Comprehensive Environmental Inc., 2012)

Pollutant	Pollutant Removal for the Media Filter Drain (by source study)			
	WSDOT, 2005	Wright Water Engineers et al., 2011	Geosyntec et al., 2010	Geosyntec et al., 2011
Total Copper	82%	57%		
Total Lead		67% - 85%		
Total Zinc	89%	59% - 83%		
Total Phosphorus	84%		47%	
Total Nitrogen			42%	
TSS	95%			
Turbidity				80%

2.4 POTENTIAL USE FOR SPACE CONSTRAINTS NEAR SENSITIVE WILDLIFE AND PLANT HABITAT

The large footprint required by many conventional runoff treatment options make them difficult to apply in areas with significant ROW constraints. The linear arrangement and smaller footprint make the MFD design suitable in many of these situations. In many cases, MFDs can be sited without the acquisition of additional ROW that other SCMs would require (WSDOT, 2019). Additionally, in situations where ROW is constrained by sensitive habitat that requires protection from roadway stormwater runoff, an MFD can often fit within the highway fill slopes. MFDs can provide a cost-effective and space-efficient SCM.

2.5 LITERATURE REVIEW SUMMARY

The literature on MFD pollutant removal efficiency indicates that, when properly installed, MFDs do an effective job at treating stormwater runoff. Specifically, MFDs have been cited to efficiently treat TSS, copper, zinc, lead, nitrogen, and phosphorous. Overall, in consideration of limited ROW, MFDs are an ideal stormwater control measure to implement in areas where there are sensitive habitats or wildlife.

3.0 LITERATURE REVIEW— ROADSIDE STORMWATER DITCH

3.1 BACKGROUND

Roadside stormwater ditches are widely used stormwater conveyances designed to transport stormwater runoff that flows off the roadway surface. These ditches are channelized structures that run alongside roadways, often in areas without curb and gutter. Although not typically built with the intention of improving stormwater quality or removing pollutants, when vegetated, ditches can remove pollutants through filtration, nutrient uptake, and other physiochemical processes (Colwell, 2000). Vegetated ditches have components of both grass swales and vegetated filter strips and exhibit similar pollutant removal processes and potential.

3.2 GRASS SWALE DESCRIPTION

Often utilized on highway projects, grass swales are simple approaches to convey runoff along and away from linear systems. Grass swales accept overland sheet flow runoff from adjacent impervious areas. They rely on their flat cross slope and dense vegetation to maintain sheet flows (WSDOT, 2019). Traditionally, highway swales have been designed to convey runoff from the largest storm events quickly away from the roadway. Consequently, highway swales are not designed for smaller storm events that produce the majority of annual runoff in most areas (Davis, Stagge, Jamil, & Kim, 2012). Other than conveying stormwater runoff from roadway areas, swales have the capability to create hydrologic conditions similar to pre-development conditions. The primary purpose of the swale is to convey stormwater while removing sediment and other pollutants coming directly off the pavement (WSDOT, 2019).

The major mechanisms for pollutant removal in swales are filtration by the vegetation, settling of particulates, and infiltration into the subsurface zone. As runoff travels through a swale, the vegetation reduces peak velocity while infiltration reduces flow volume. Attenuation of runoff flow promotes pollutant removal. In practice, check dams are sometimes placed in grassed swales to increase the detention time and to create a short-term storage effect. (Yu, Kuo, Fassman, & Pan, 2001). Effectiveness of swales are highly determined by the design characteristics of length, longitudinal slope, and presence of check dams. Each of these characteristics influences detention time and, therefore, efficiency of pollutant removal (Yu et al., 2001).

Vegetated filter strips between the swale and the impervious surface provide pretreatment to enhance infiltration and pollutant removal. The sediment and particulate pollutant load that could reach the swale is reduced by the pretreatment, which in turn reduces maintenance costs and enhances the pollutant-removal capabilities of the swale or ditch (WSDOT, 2019).

3.3 VEGETATED FILTER STRIP DESCRIPTION

Vegetated filter strips can be effective in reducing sediments and the pollutants associated with sediments such as phosphorus, pesticides, or insoluble metallic salts. Because they do not pond water on the surface for long periods, vegetated filter strips help maintain the temperature norms of the water and deter the creation of habitat for disease vectors such as mosquitoes. In less urbanized areas, vegetated filter strips can generally be located on existing roadside embankments, reducing the need for additional ROW acquisitions. Designs can be modified to reduce runoff volumes and peak flows when needed or desired to reduce ROW acquisitions (WSDOT, 2019).

3.3.1 LIMITATIONS OF VEGETATED FILTER STRIPS

If sheet flow cannot be maintained, vegetated filter strips will not be effective. Vegetated filter strips are generally not suitable for steep slopes or large impervious areas that can generate high-velocity runoff. Use of vegetated filter strips can be impracticable in watersheds where open land is scarce or expensive, such as project where less than 10 feet of roadside embankment is available for water quality treatment. Improper grading can also render this BMP ineffective. The flow attenuation properties of vegetated filter strips and amended vegetated filter strips are largely unknown. Qualitative evidence indicates that on outwash soils (National Resources Conservation Service [NRCS] Groups A and B), the compost-amended vegetated filter strip (CAVFS) can attenuate large quantities of runoff. Monitoring studies are being conducted to evaluate these properties and ultimately give designers the ability to model water losses in vegetated filter strips (WSDOT, 2019).

3.4 DESIGN SPECIFICATIONS

The design approach for grass swales involves site design techniques to maintain prescribed maximum sheet flow distances, as well as ensure temporary storage for the treatment of stormwater (WSDOT, 2019). Figure 4 shows the elements of a roadside vegetated filter strip.

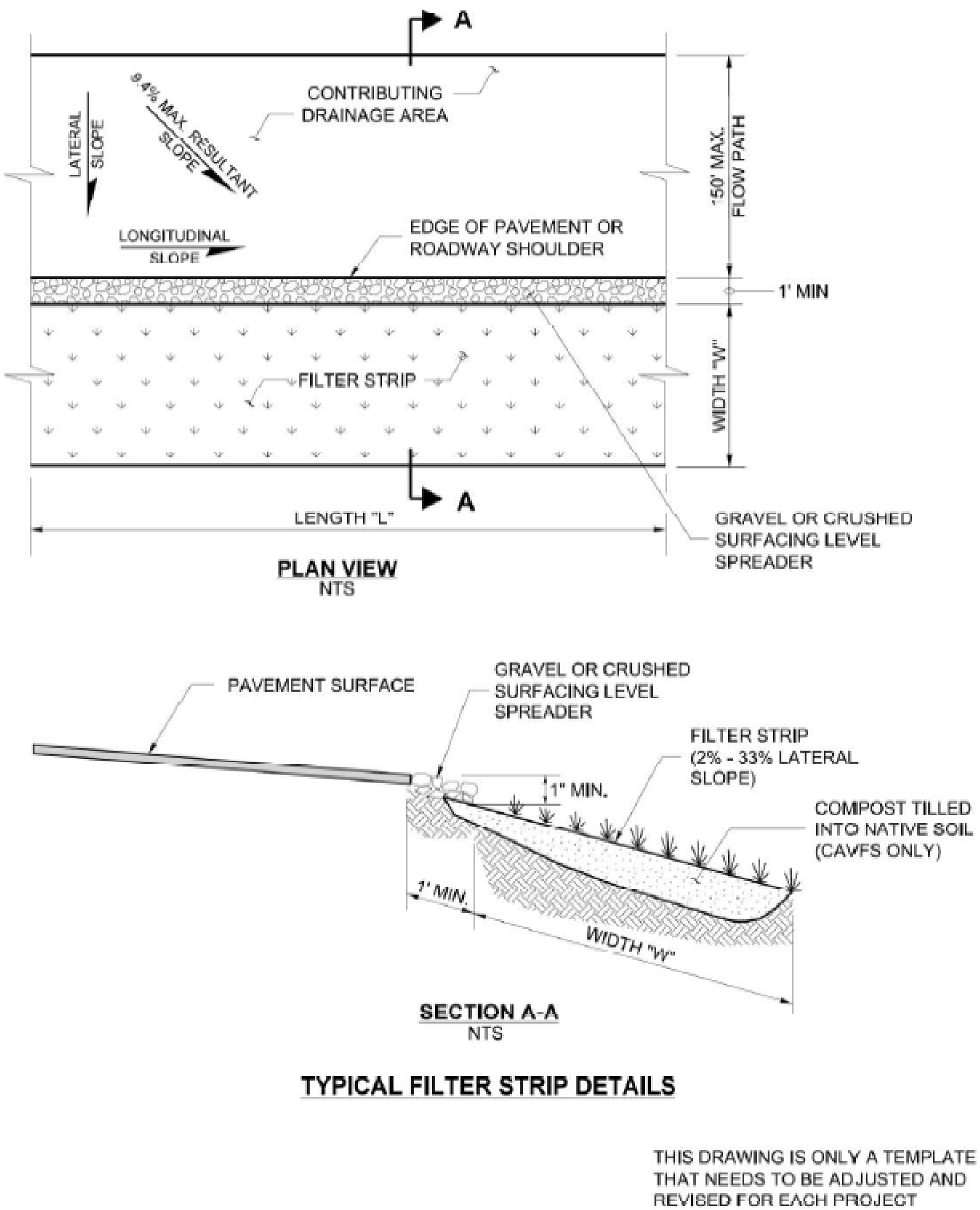


Figure 4. Plan and cross section views of a typical vegetated filter strip (WSDOT, 2019)

3.4.1 DESIGN CRITERIA AND SPECIFICATIONS

Grass swales and vegetated filter strips are designed to treat small drainage areas. Flow entering a vegetated filter strip must be sheet flow spread out over the entire length of the control measure. The greatest flow path from the contributing area delivering sheet flow to the vegetated filter strip should not exceed 150 feet. Additionally, it is important that the slope from the contributing area be less than or equal to 9.4% (WSDOT, 2019). Basic vegetated filter strips should be designed for lateral slopes (along the direction of flow) between 2% and 33%. Steeper slopes encourage the development of concentrated flow and flatter slopes encourage standing water. To ensure proper treatment of stormwater, it is important to have a minimum residence time of at least nine minutes (WSDOT, 2019).

Design guidelines for grass swales recommend the following parameters: a maximum longitudinal slope of 5%, 30 to 60 meters in length, 0.6-meter bottom depth, soil with high infiltration rate, deep-rooted and flood tolerant vegetation; and the inclusion of check dams (Yu et al., 2001). Although these design parameters may vary, Yu et al. provided that these design characteristics yield the most effective removal of pollutants.

3.5 SWALE TREATMENT EFFICIENCY

When implemented correctly, vegetated swales can be a useful control measure for treating stormwater runoff. Mainly able to treat TSS, the swale has demonstrated ability to reduce TSS concentration by 60% (Barrett, 2005). Similar studies noted that a 60% reduction in Zinc and a 62% reduction of Copper concentrations were also observed in swales (Barrett, 2005). Other studies have shown that there is a positive correlation between slope and TSS removal efficiency. Slopes between 1% and 3% have a removal efficiency ranging from 75% removal or better. However, when the slopes are greater than 3%, removal rates are near 30%, thus, slopes must be less steep to increase residence time and increase pollutant removal (Yu et. al., 2001).

4.0 LITERATURE REVIEW— EFFECTS OF WINTER ROADWAY MAINTENANCE AND FREEZE-THAW CYCLES

4.1 WINTER MAINTENANCE PRACTICES

In climates where freezing conditions are common, state departments of transportation use deicers to maintain road safety. CDOT uses both liquid and solid deicers for winter road maintenance (CDOT, n.d.). These deicers contain chlorides, which have been found to affect plant health. Effects of road salts and other deicers differ among species, but the general impacts are reduction in biomass and eventual death of the plants. Plants within a few meters of salted surfaces exhibit the most severe impacts from deicers (Cunningham, Snyder, Yonkin, Ross & Elsen, 2008).

Exposing plants to excess chloride results in:

- Increasing water stress. In the root zone, water molecules are held very tightly by salt ions, making it difficult for roots to absorb enough water. In sensitive species, this “physiological drought” may result in depressed growth and yield.
- Affecting soil quality. The sodium ion component in rock salt becomes attached to soil particles and displaces soil elements such as potassium and phosphorus. As a result, soil density and compaction both increase as drainage and aeration are reduced. In addition, chloride and calcium can mobilize heavy metals and nitrogen in affected soils. Plant growth and vigor are poor under these conditions.
- Affecting mineral nutrition. When the concentration of both the sodium and chloride components of salt in the root zone is excessive, plants preferentially absorb these ions instead of nutrients such as

potassium and phosphorus. When this occurs, plants may suffer from potassium and phosphorus deficiency.

- Accumulating to toxic levels within plants. The chloride component of salt is absorbed by roots and foliage and becomes concentrated in actively growing tissue. Plants repeatedly exposed to salt over long periods of time may accumulate chloride ions to toxic levels, resulting in leaf burn and twig die-back (Gould, 2013).

This aspect of road maintenance becomes a concern to roadside ditch and MFD pollutant removal efficiency because vegetation is crucial to the pollutant removal processes of both features. Ditches with sparse or absent vegetation can erode and become significant sources of sediment and other pollutants (Colwell, 2000). The loss of healthy vegetation will render the MFD's vegetated strip as less effective at removing pollutants and decreasing velocity of flows and could result in premature failure.

In addition to impacts to vegetation, increased soil compaction from salts could result in a lower infiltration rate and affect the ability of both the ditch and MFD to treat runoff pollutants. Further findings show that salt cations can displace and mobilize metal ions, including heavy metals in soils (Cunningham et al., 2008). Because of these numerous impacts, the winter application of road salts and other deicers may affect the soil matrix and decrease the overall performance of pollutant removal (Kakuturu and Clark, 2015).

4.2 FREEZE-THAW CONDITIONS

Colorado experiences freeze-thaw conditions during autumn, winter, and spring months. CDOT has expressed concern of how these conditions will affect MFD performance. Regarding freezing filter media, two stormwater infiltration SCMs monitored in southeastern Pennsylvania, showed seasonal variation, but did not display a decrease in performance of the infiltration SCMs (Emerson and Traver, 2008).

Concerning how MFDs will perform in cold climates, while MFDs may be more susceptible to freezing due to their shallow depth, studies have shown that, "infiltration and pollutant treatment are not greatly lessened in the winter season" (Comprehensive Environmental Inc., 2012).

A New Hampshire study on SCMs found that frost penetration cycles were observed for a total of 170 days over two years throughout the winter monitoring season. The frost penetration cycle is described as frost penetrating the media in below freezing temperatures, and following a rain and snowmelt event, the frost is thawed and once the event has ended, the frost penetrates again. The study states that "…frost penetration does not necessarily equate to filter media permeability: frozen media may still have significant porosity and permeability" (Roseen, Ballestero, Houle, Avellaneda, Briggs, Folwer, & Wildey, 2009). Their research also noted that frost reduces influent peak (Roseen et al., 2009).

Other studies on SCMs in Canada have shown that drainage rates have increased after freeze-thaw cycles (Ding, 2017). Roseen et al.'s study (2009) noted "seasonal contaminant removal performance varied little for the filtration, infiltration systems, and retention pond". Figure 5, shown below, demonstrates the impact of freeze-thaw cycles on SCM performance.

The MFD's process for treating stormwater and removing pollutants is similar to the functions of subsurface infiltration and sand filter treatment qualities. Presuming that this data is transferable to MFDs, it is reasonable to assume that the MFD's performance will not likely be affected by winter freeze-thaw conditions. It is, however, worth monitoring the effects of winter road maintenance on the MFD's vegetated strip to determine if over application of deicers or slicer materials affect the performance of the MFD.

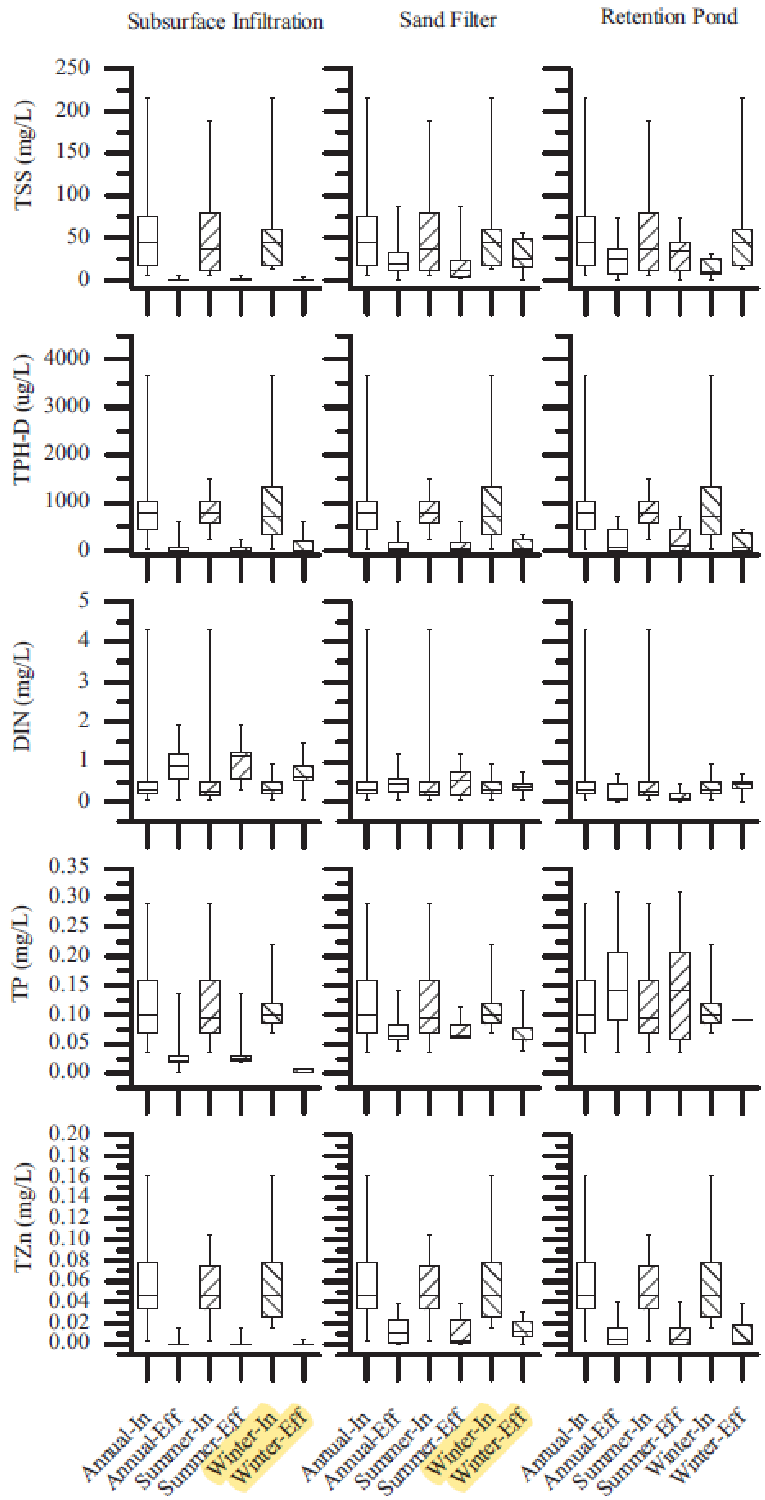


Figure 5. Annual and seasonal influent and effluent EMCs for a subsurface infiltration system, a surface sand filter, and a retention pond; box and whisker plots indicate maximum, minimum, 75th, and 25th percentiles, and median; (Annual-In = Annual Influent; Annual-Eff = Annual Effluent; Summer-In = Summer Influent; Summer-Eff = Summer Effluent; Winter-In = Winter Influent; and Winter-Eff = Winter Effluent (Roseen et al., 2009).

5.0 DESIGN EVALUATION

5.1 MEDIA FILTER DRAIN DESIGN SPECIFICATIONS

Implementing any control measure requires proper installation for maximum effect on treating stormwater. Specifically, installing MFDs requires the consideration of slope, runoff ratio, and soil types.

It is recommended that the lateral side slopes are less that 4H:1V and longitudinal slopes are no steeper than 5%. The sheet flow being directed toward the MFD should not be longer than 150 feet (WSDOT, 2019). Cited in the Comprehensive Environmental Inc. study, MFDs are not suitable for areas with steep slopes or large impervious areas generating high velocity runoff.

Additionally, MFDs require enough vertical separation from seasonal groundwater elevations to prevent groundwater intrusion into the filter bed and underdrain. Underdrains must be provided for areas with soils having a high clay content. It is recommended that sheet flows pass through the filter strip to prevent short-circuiting by concentrated flows. MFDs may be suitable as a stand-alone practice or designed in conjunction with other practices; for example, an underdrain may be used to direct stormwater to other control measures in a treatment train (Comprehensive Environmental Inc., 2012).

These findings suggest that the ideal locations for MFDs in Colorado are along roadsides that are bordered by areas with less than a 4:1 slope and without high groundwater. The vegetated filter strip is also key to attenuating and dispersing flow coming off road surfaces during high intensity precipitation events. CDOT will be challenged to maintain vegetated filter strips between the road surface and the MFD. MFDs, like other permanent structural SCMs, require adherence to an operation and maintenance plan to maintain treatment capacity as designed. The MFD, unlike a ditch or swale, is not a SCM that only requires periodic mowing.

5.1.1 NEW AGRREGATE

Hasselbach and Poor found that a more readily available fine aggregate had similar removal efficiencies as the original aggregate but had held up their integrity throughout an accelerate aging process that simulated 15 years of use (2014). This comes with an economical benefit of switching to the 2008 standard specification aggregate. Aggregate mixes made using the 2008 standard aggregate specification are more readily available and less expensive. Aggregate mixes made using the 2004 standard specification require a special order and are significantly more expensive (Hasselbach and Poor, 2014).

6.0 SITE CHARACTERIZATION

6.1 STUDY AREA

The study area is located on US36 between Superior and Boulder, Colorado (Figure 6). Using the 2019 annual data from CDOT's Online Transportation Information Systems (OTIS) database, the average daily traffic for this section of the road amounts to an average of 87,374 daily.

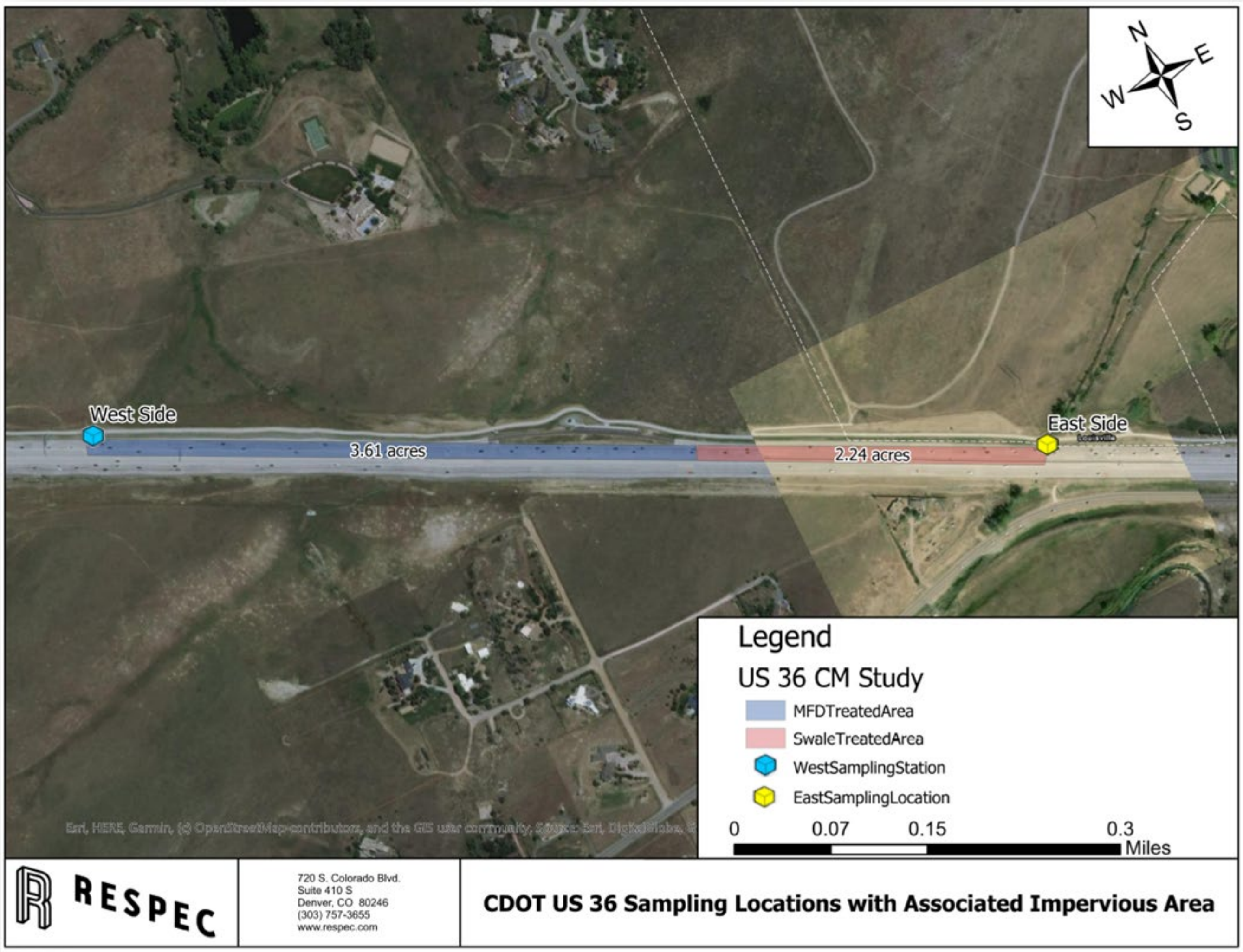


Figure 6. Map Location of the Study Area on US36 West-bound. The West Side sampling station is at 39°58'9.82"N, 105°11'39.94"W . The East Side sampling location is at 39°57'52.49"N, 105°10'56.41"W.

The study area includes approximately 4,700 linear feet of US36 westbound lanes and two roadside sampling points at a ditch and an MFD. The West sampling location pulls stormwater from a ditch underlain by an MFD (Figure 7). The MFD was installed during the US36 Express Lanes project that was completed in March 2016. The East sampling location pulls stormwater from a ditch that does not include an MFD (Figure 8). Each location receives runoff from the US36 westbound lanes.

Figure 7. General view looking east along the MFD from the drop inlet above the culvert that drains to the sample collection trough.

Figure 8. General view looking west up the ditch from the sample collection trough and equipment cabinet.

The area treated by each control measure was determined using longitudinal and horizontal elevations of the roadway. The impervious areas start where the longitudinal elevation of the roadway is highest and ends where the automatic samplers are set. The resulting impervious area treated for the MFD at the West sampling site equals 3.61 acres and 2.24 acres for the East sampling site in the roadside ditch. This site has a high point of 5,679 feet, separating the two control measures in the east and west directions with low points of 5,631 feet and 5612 feet, respectively. From the high point down to the west side sampling location, there is a -2.7% grade. From the high point down to the east side sampling location there is a -3.3% grade. The soil at this location drains typically well. According to the USGS data, the soil ranges from "excessively well drained to well drained." A map of these soil classes is found in Figure 9. The overall site K_{sat} values ($K_{best\text{-}fit}$) were determined to be 31.1 in/hr for the MFD site and 8.03 in/hr for the Ditch site. The method used to determine the overall site values are described in Weiss and Gulliver (2015).

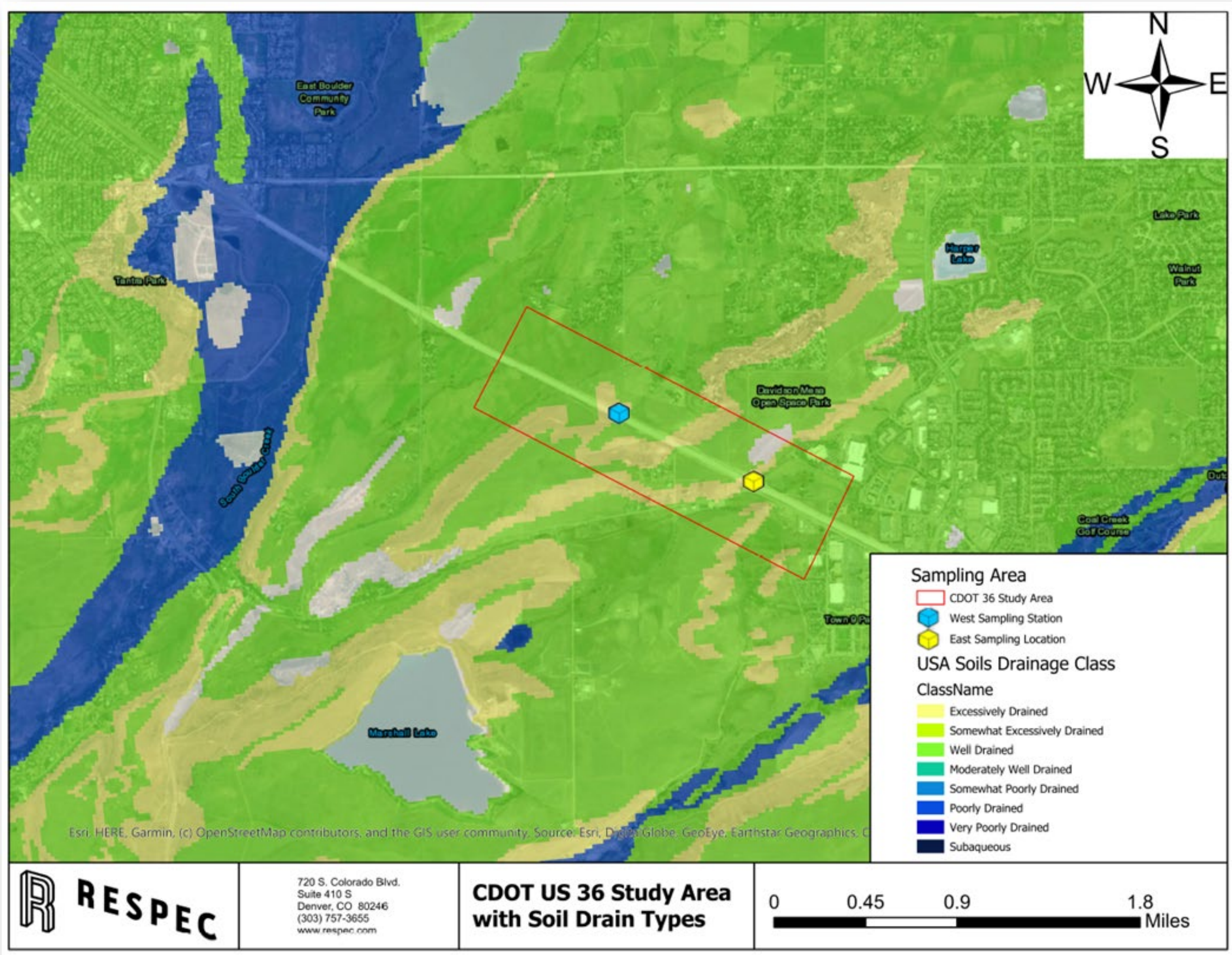


Figure 9. Soil Drainage Types in the Study Area

Runoff from the western portion of the study area flows through a gully to Boulder County Open Space. Runoff from the eastern portion of the study area is conveyed north, overland, through a mixture of commercial and agricultural properties. Potential receiving waters for study area runoff include Teller Lake, Burke Lake, Baseline Reservoir, Coal Creek, Rock Creek, Harper Lake, Cowdrey Reservoir. Of these receiving waters, both Coal Creek and Rock Creek are on the 303 (d) list of impaired waterways. Coal Creek is listed for E. Coli impairment, and Rock Creek is listed for Selenium (NHDPlus, 2020). The site-specific information will help establish relevance for other CDOT PWQ sites.

7.0 METHODS

7.1 FIELD METHODS

Figure 10. General view of the ISCO 3700 Portable Sampler located at the downgradient end of the ditch.

RESPEC monitored measurable storm events on US36 in between Superior and Louisville, Colorado from 2019 through July 2021. A storm event was considered measurable if it was a rain or snowmelt event that resulted in an actual discharge and that followed the preceding measurable storm event by at least 72 hours.

Stormwater sampling was completed based on CDOT's Wet Weather Monitoring (WWM) Standard Operating Procedures (SOP 2017 RSI-2772) & Sampling Analysis Project Plan (SAPP 2017 RSI-2774). The objective of this sampling was to examine the pollutant removal effectiveness of an MFD compared to a roadside ditch for pollutants included on CDOT's Pollutant of Concern (POC) list, and to assess the durability of these structures over time.

Sampling equipment was deployed at the two locations described in section 6.0 Site Characterization. Both sites used an ISCO 3700 Portable Sampler and an ISCO Signature Flow Meter powered by a marine battery and a solar panel (Figure 10). A TIENet 350 AV Sensor was then mounted in the flow stream and measured average flow and liquid level (Figure 11). The TIENet Model 306 Sampler Interface connected the Signature Flow Meter to the ISCO 3700 sampler. Through this connection, the Signature flow meter signaled the sampler to start or stop sampling and received signals from the sampler indicating when a sample was collected.

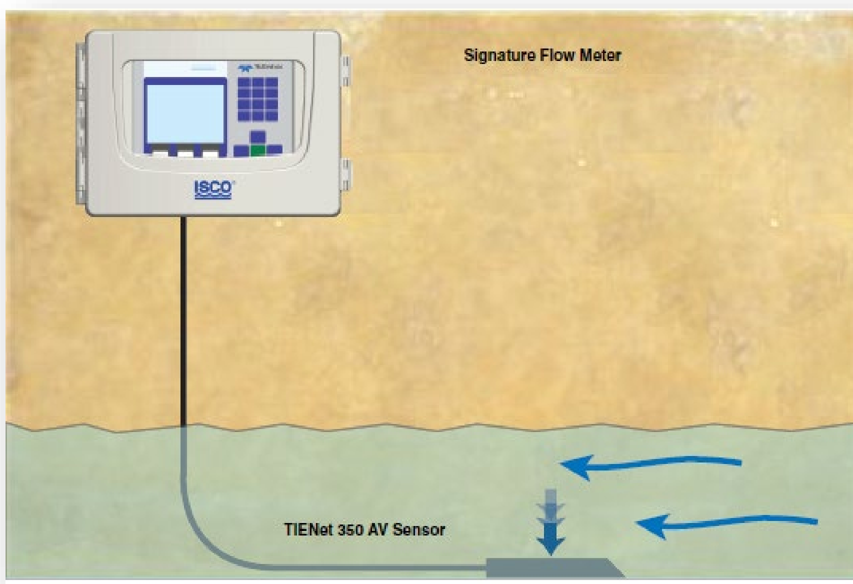


Figure 11. Diagram depicting the TIENet 350 AV sensor and the Signature Flow Meter.

A 3/8-inch suction line extended from the sampler's pump tubing intake, at the top of the liquid detector, to the liquid source at each site. A stainless-steel strainer was installed at the liquid source to filter out larger particulates from the samples.

The samplers were programmed to collect composite samples of the storm surge once the 350 AV sensor detected a ½-inch depth of water through the control measure. The 350 AV sensor at the west location was placed in the narrow end of a reinforced concrete flared end section where flows are concentrated during a rain event. The 350 AV sensor at the east location was placed in the lowest point of the ditch, attached to the base of the stainless-steel flume. For both samplers, once the sensor detected a depth of water of ½ inch for the duration of one second, the automatic sampler initiated the collection of 15 consecutive 400mL samples. The stormwater was then pumped into one 2.5-gallon polyethylene bottle. The west location pumped from a plastic trough designed to capture the stormwater from the flared end section outfall. RESPEC designed this capture system to avoid losing samples to the riprap placed at the end of the pipe. The east side pumped from a plastic trough where the stainless-steel strainer was suspended from two 8-inch eye bolts, which also served to stabilize the trough (Figure 12).

Figure 12. Plastic trough with stainless steel strainer installed in the eye bolts.

Grab samples were pulled in situations where there was an unsuccessful composite sample pull but there was significant flow at the time of collection. Grab samples are performed manually at each sampler location using the ISCO built in programs. The type of sample pulled, composite or grab, is noted on each chain of custody form.

```
Report 1 ISCO 1
Interval: 2021-02-20T00:00:00 to 2021-02-21T00:00:00
350 Level:
 Ave:   1.943 in
 Max:   2.689 in 2021-02-20T02:45:00
 Min:   0.410 in 2021-02-20T19:33:00
350 Velocity:
 Ave:  0.06 ft/s
 Max:  0.50 ft/s 2021-02-20T21:00:00
 Min:  0.00 ft/s 2021-02-20T00:00:00
Flow Rate:
 Ave: 3.42 gpm
 Max: 6.68 gpm 2021-02-20T21:45:00
 Min: 0.000 gpm 2021-02-20T18:30:00
Total Flow:
 Total:     390226 gal
 Interval:  4925 gal
300 Rainfall:
  0.00 in
Input Voltage:
 Ave:  12.56 volts
 Max:  13.90 volts 2021-02-20T13:45:00
 Min:  11.94 volts 2021-02-20T20:15:00
```

Figure 13. A 24-hour report downloaded from the Flow Meter.

The average flow rate over a 24-hour period (Figure 13) was downloaded from the Signature Flow Meter onto a flash drive after each rain event, as well as average water level readings at the 350 AV sensor, average velocity, total flow, inches of rainfall (only recorded at the MFD), and input voltage at the flow meter.

During each visit to the monitoring stations, the sampler systems were inspected. If they were triggered by a rain event, and a sample was collected, RESPEC filled out a field form (*see* Appendix A) to note what was completed on that trip. Each sample collected was prepared and transferred to the lab within 24 hours. After each rain event, once the sampling stations were dry, a calibration of the 350 AV Sensor was performed, and the samplers were set to trigger for the next rain event.

Figure 14. Ditch flume stuffed with vegetative debris after a storm event on July 1, 2021.

Regular maintenance to the ditch site included removing vegetative debris and sediment accumulated in the flume (Figure 14) to ensure an accurate flow reading, cleaning the solar panel to increase power output to the battery, and making sure that the union between the flume and the plastic trough was sealed to prevent water from draining out and not collecting in the trough. The sampler at the ditch tended to trigger during a light to moderate rain event, and not collect a sample. Frequent calibration and resetting of the trigger to capture the next rain event was often necessary.

Regular maintenance at the MFD site involved cleaning out the plastic sample collection trough and culvert of trash and vegetative debris, cleaning the solar panel, and breaking up and removing the ice sheets that would inhibit flow in the winter (Figure 15). The MFD would capture samples during light to moderate rain events, when the ditch would not, resetting the MFD sampling system for the next rain event was often necessary.

All collected samples were analyzed by PACE Laboratory Services in accordance with specified methods in Title 40 of the Code of Federal Regulations Part 136 (40 C.F.R Part 136), methods approved by the EPA pursuant to 40 C.F.R Part 136, or methods approved by the CDPHE Water Quality Control Division in the absence of a method specified in or approved pursuant to 40 C.F.R., Part 136. All lab samples were measured using the Practical Quantitation Limit (PQL). PQL is the minimum concentration of a pollutant of concern that can be measured with a high degree of confidence that the pollutant of concern is present at or above that concentration.

Figure 15. Broken up ice sheet inside the culvert at the MFD site during the winter months.

7.2 STORMWATER SAMPLE ANALYSIS

All stormwater samples taken from the two sampling sites were sent to PACE Laboratory and tested for CDOT's Pollutants of Concern (Table 4). The pH of each sample was tested in the field using a handheld pH sensor. All samples received from the laboratory (excluding specific conductance) were reported in micrograms per liter (µg/L), however, CDOT is accountable for most parameters using milligrams per liter (mg/L) for secondary drinking water standards. Therefore, parameters were converted to mg/L for analysis.

Although there were samples collected that were sent to the laboratory where only one sampling location had a sample pulled, the only samples that are included in the analysis are the dates in which there was a sample pulled from both the east and west sampling stations. This allows comparison of pollutant concentrations and calculated loads between roadside ditch and MFD sites for the exact same rain events. All other analyzed samples were discarded in the analysis of pollutant removal efficiency. A total of 32 paired sampling events were analyzed during the course of this work—12 in 2019, 3 events in 2020, and 17 in 2021. Additionally, there were 5 samples in the summer of 2021 where the values for Nitrate-Nitrite and TKN were omitted: the MFD sample on 5/30/2021, both the MFD and ditch samples on 6/25/2021, and both the MFD and ditch samples on 7/1/2021. A laboratory error in the preservatives provided for these samples resulted in erroneous values for these parameters.

To estimate the performance of the SCMs, RESPEC reviewed the concentrations of each roadway pollutant of concern in the effluent samples from the MFD and the swale and calculated pollutant loads.

Table 4. MS4 and CDOT WWMP roadway pollutants of concern

Parameter	Required by MS4 Permit	Required by CDOT WWMP
Ammonia Nitrogen		X
Arsenic/Arsenic Dissolved		X
Cadmium/Cadmium Dissolved	X	X
Calcium Dissolved		X
Chloride	X	X
Chromium/Chromium Dissolved	X	X
Conductivity/Specific Conductance	X	X
Copper/Copper Dissolved	X	X
Hardness as $CaCO_3$	X	X
Iron/Iron Dissolved	X	X
Lead Dissolved	X	X
Magnesium/Magnesium Dissolved	X	X
Manganese/Manganese Dissolved	X	X
Nickel/Nickel Dissolved	X	X
Nitrate-Nitrite		X
Oil and Grease (hexane)	X	X
pH		X
Phosphorus	X	X
Selenium/Selenium Dissolved	X	X
Sodium	X	X
Total Inorganic Nitrogen	X	X[a]
Total Kjeldahl Nitrogen (TKN)		X
Total Suspended Solids (TSS)	X	X
Zinc/Zinc Dissolved	X	X

[a] Note that inorganic nitrogen is composed of nitrate (NO_3), nitrite (NO_2), and ammonia (NH_3). By analyzing for ammonia, nitrogen, and nitrate-nitrite, as recommended in the WWM PDD, CDOT is meeting the MS4 permit requirements to measure inorganic nitrogen.

In the absence of influent concentrations, CDOT assumes influent entering the two SCMs is similar, if not identical, because of the close proximity of the two sites, the identical traffic loads, weather, and maintenance operations. It is assumed that any differences in effluent pollutant concentration represents differences in treatment efficiencies between the two sites. The lab results then allow for the two control measures to be compared to each other by calculating percent difference between the MFD and vegetated swale effluent for each CDOT pollutant of concern. Same-day only analyses allow for the comparison of effluent pollutant concentrations without the influence of confounding variables such as rainfall intensity and accumulation, traffic load, temperature, and wind.

The equation used to determine percent difference is as follows:

[(MFD lab result for POC) – (Vegetated Swale lab result for the same POC)] ÷ (MFD lab result for POC)] × 100

By calculating the median percent difference for each POC across all storm events, we can understand trends in treatment efficiency between the MFD and the vegetated swale.

7.3 POLLUTANT LOAD CALCULATIONS

A variation of the Simple Method (Schueler, 1987) was used to calculate pollutant loads in pounds for each parameter measured from each paired sample. The following equation was used:

$$L = 0.226 * R * A * C$$

The storm volume was calculated using the measured precipitation (*R*; in inches) from a local weather station and then multiplied by the calculated drainage area (*A*; in acres) at each site. All rainfall data, excluding two storm events where the preferred weather station equipment was down[1], was taken from the KCOBOULD117 weather station. Precipitation data from this station was accessed via Weather Underground. Because of the proximity of the two sites to one another, the same precipitation measurement (*R*) was used for both sites. The calculated storm volume was then multiplied by the concentration (*C*; in mg/L) of each parameter during each event. Lastly, a unit conversion factor of 0.226 was applied to covert the calculated load (*L*) into pounds.

[1] The KCOBOULD117 weather station had no reported weather data between 05/10/2021 and 05/18/2021. Instead of eliminating the two paired events captured on 05/10/2021 and 05/16/2021 from analysis, an alternative weather station, BOULDER 6.8 SE (accessed via the AgACIS Database), was used for the precipitation values for these two events. This weather station is 1.74 miles from the Ditch monitoring station and 2.28 miles from the MFD monitoring station.

8.0 RESULTS

8.1 RANGE OF CONCENTRATIONS

The pollutant concentrations at both sites throughout the study period varied widely (Table 5). All measured concentrations of POCs—excluding oil and grease at the MFD, total and dissolved cadmium at both sites, and dissolved nickel at the MFD—ranged by at least one order of magnitude. The concentration of dissolved magnesium in the ditch had a range of five orders of magnitude and the ranges in chloride concentrations was greater than 3000 mg/L for both the roadside ditch and MFD sites.

Table 5. The range of concentrations of each parameter at each site across all paired samples (n=32). All concentrations are in mg/L unless otherwise specified.

Parameter	Ditch	MFD	Parameter	Ditch	MFD	Parameter	Ditch	MFD	Parameter	Ditch	MFD
Suspended Solids	5.63 - 1540	8.3 - 760	Arsenic	0 - 0.0105	0.000127 - 0.00558	Copper, Dissolved	0.00449 - 0.0267	0.00654 - 0.0384	Nickel	0.00179 - 0.0346	0.00226 - 0.0218
Specific Conductance (umhos/cm)	102 - 12700	293 - 10400	Arsenic, Dissolved	0.00047 - 0.00293	0.000494 - 0.00233	Iron	0.161 - 34.1	0.247 - 28.1	Nickel, Dissolved	0.00123 - 0.0287	0.00139 - 0.00542
Hardness, Total (mg/L as CaCO3)	17.6 - 937	20.6 - 719	Cadmium	0.000165 - 0.000745	0.000226 - 0.0005	Iron, Dissolved	0.0446 - 0.736	0.0196 - 0.271	Selenium	0.000448 - 0.00277	0.000453 - 0.00206
Oil & Grease (Hexane Extr)	1.4 - 29.1	1.46 - 6.25	Cadmium, Dissolved	0.000199 - 0.0005	0.000226 - 0.0005	Lead	0.00102 - 0.0595	0.000549 - 0.0244	Selenium, Dissolved	0.000444 - 0.00205	0.000437 - 0.00175
Chloride	9.62 - 3740	55.1 - 3160	Calcium	4.04 - 152	12.4 - 154	Lead, Dissolved	0.000385 - 0.00349	0.000281 - 0.00536	Sodium, total recoverable	11.5 - 2160	43 - 1880
Ammonia Nitrogen	0.0317 - 0.612	0.05 - 0.164	Calcium, Dissolved	3.69 - 154	3.1 - 158	Magnesium, total recoverable	1.76 - 128	3.26 - 81.2	Sodium, Dissolved	11.6 - 2350	44.2 - 1880
Kjeldahl Nitrogen, TKN	0.654 - 3.69	0.271 - 2.03	Chromium	0.0039 - 0.0509	0.00486 - 0.0324	Magnesium, Dissolved	0.00335 - 139	1.48 - 82.4	Zinc	0.0162 - 0.495	0.0117 - 0.308
Nitrate-Nitrite	0.05 - 2.05	0.056 - 1.54	Chromium, Dissolved	0.00114 - 0.0346	0.00153 - 0.02	Manganese	0.00647 - 0.904	0.0136 - 0.833	Zinc, Dissolved	0.00394 - 0.0708	0.00638 - 0.0654
Phosphorus, Total	0.143 - 1.19	0.05 - 0.419	Copper	0.00752 - 0.14	0.00154 - 0.131	Manganese, Dissolved	0.00206 - 0.0266	0.00175 - 0.116			

8.2 MEDIAN PERCENT DIFFERENCE IN CONCENTRATION

The median percent difference for the concentration of each pollutant of concern across all paired samples is provided in Table 6. The median was used instead of the mean in order to prevent large concentrations from any single event from skewing the results. Negative values highlighted in blue indicate parameters where the MFD had lower pollutant concentrations than the ditch, while positive values highlighted in yellow indicate the parameters where the ditch had lower pollutant concentrations than in the MFD. Numbers further from zero indicate larger differences in concentrations, while the numbers closer to zero indicate the median difference between the effluent concentrations at each site was minor. Pollutants where there was no median difference (0.00%) are highlighted in light gray.

Table 6. Median difference in pollutant concentration between the MFD and ditch sites for all paired storms (n=32).

Parameter	Median Difference	Parameter	Median Difference	Parameter	Median Difference	Parameter	Median Difference
Suspended Solids	-74.34%	Arsenic	-109.77%	Copper, Dissolved	14.73%	Nickel	-34.16%
Specific Conductance	53.59%	Arsenic, Dissolved	-39.21%	Iron	-76.13%	Nickel, Dissolved	-31.11%
Hardness, Total (mg/L as CaCO3)	38.59%	Cadmium	0.00%	Iron, Dissolved	-257.00%	Selenium	-2.32%
Oil & Grease (Hexane Extr)	0.00%	Cadmium, Dissolved	0.00%	Lead	-99.84%	Selenium, Dissolved	0.00%
Chloride	70.40%	Calcium	42.20%	Lead, Dissolved	0.00%	Sodium, total recoverable	53.08%
Ammonia Nitrogen	0.00%	Calcium, Dissolved	47.45%	Magnesium, total recoverable	44.42%	Sodium, Dissolved	53.07%
Kjeldahl Nitrogen, TKN	-68.50%	Chromium	-21.10%	Magnesium, Dissolved	61.70%	Zinc	-84.88%
Nitrate-Nitrite	-12.30%	Chromium, Dissolved	0.00%	Manganese	-17.42%	Zinc, Dissolved	-17.68%
Phosphorus, Total	-152.44%	Copper	3.31%	Manganese, Dissolved	-25.14%		

There were 17 POCs where the median percent difference indicated better performance of the MFD than the ditch. These included: total suspended solids, Kjeldahl nitrogen, nitrate-nitrite, phosphorus, arsenic, dissolved arsenic, chromium, iron, dissolved iron, lead, manganese, dissolved manganese, nickel, dissolved nickel, selenium, total zinc, and dissolved zinc.

There were 11 POCs where the median percent difference indicated better pollutant removal performance of the ditch. These included: specific conductance, total hardness, chloride, calcium, dissolved calcium, copper, dissolved copper, magnesium, dissolved magnesium, sodium, and dissolved sodium.

The median percent difference for seven of the pollutants of concern were zero, indicating no difference in pollutant removal performance was observed between the two sites. These parameters included: oil and grease, ammonia, total cadmium, dissolved cadmium, dissolved chromium, dissolved lead, and dissolved selenium.

8.3 PAIRED SAMPLE POLLUTANT LOADS OVER TIME

For each paired sample, the calculated pollutant loads were graphed for each sample location (Figure 16 - Figure 21). Graphs for each POC were included to show the differences in pollutant loads between the Ditch and MFD sites and to show any patterns in the pollutant loads over time. The load of each pollutant over time in the Ditch is a solid yellow line while the MFD is shown as a blue dashed line.

While some parameters, such as Calcium (Figure 18), clearly showed one site with lower pollutant concentrations throughout the study period, most POCs did not exhibit obvious and consistent patterns over time. As seen with Total Suspended Solids (Figure 16), oftentimes the relative loads at the two sites varied by event with the MFD outperforming the ditch in some events and the ditch outperforming the MFD in others. While the median percent difference in concentration gives a good overall picture of trends, the graphs of load by event illustrate the variation throughout the study period.

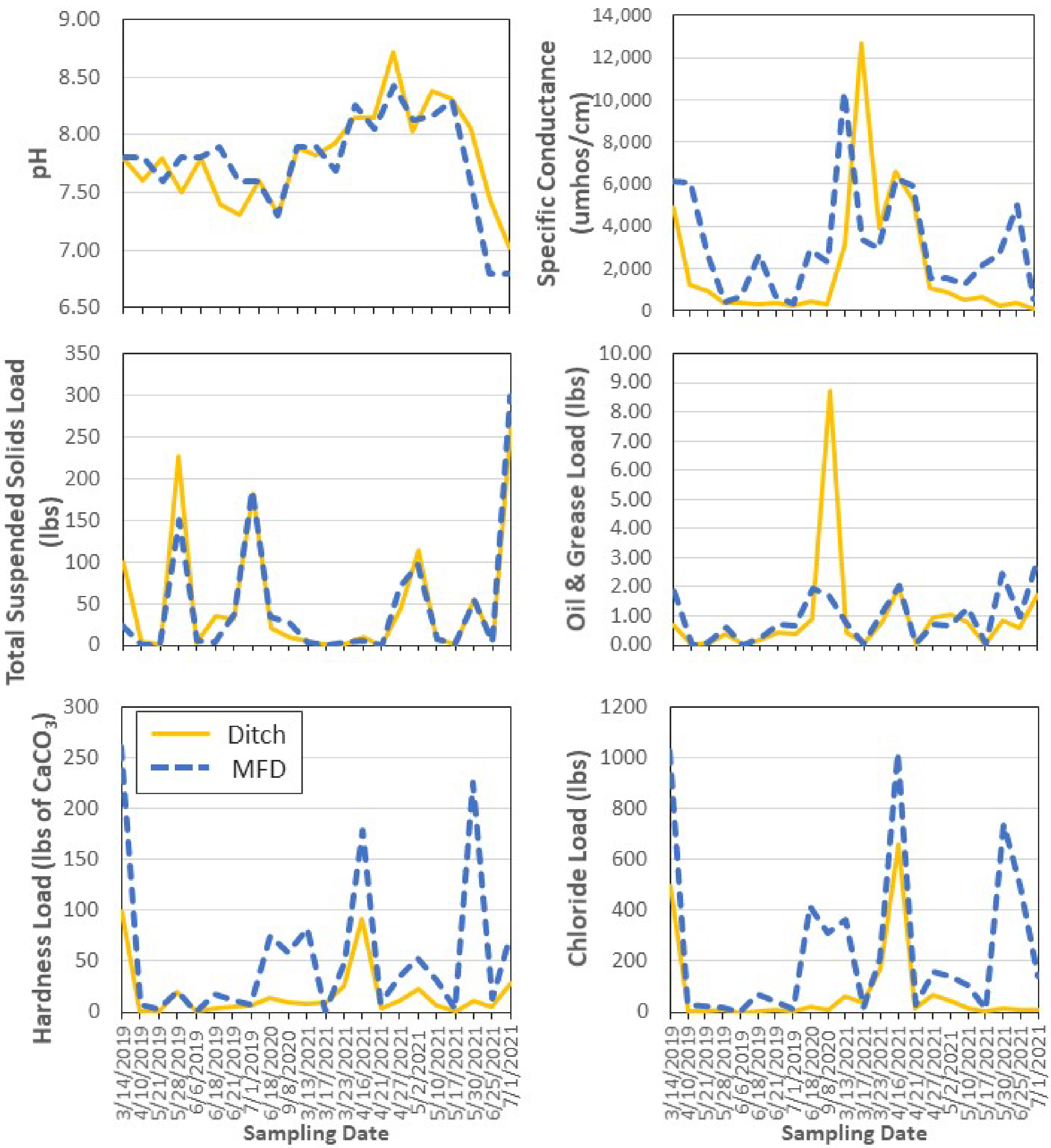


Figure 16. Graphs showing the measured pH and Specific Conductance and the calculated pollutant loads (in pounds) of Oil and Grease, Total Suspended Solids, Hardness, and Chloride in paired samples from the two sites. The ditch is shown in the yellow solid lines while the MFD is shown as the blue, dashed lines.

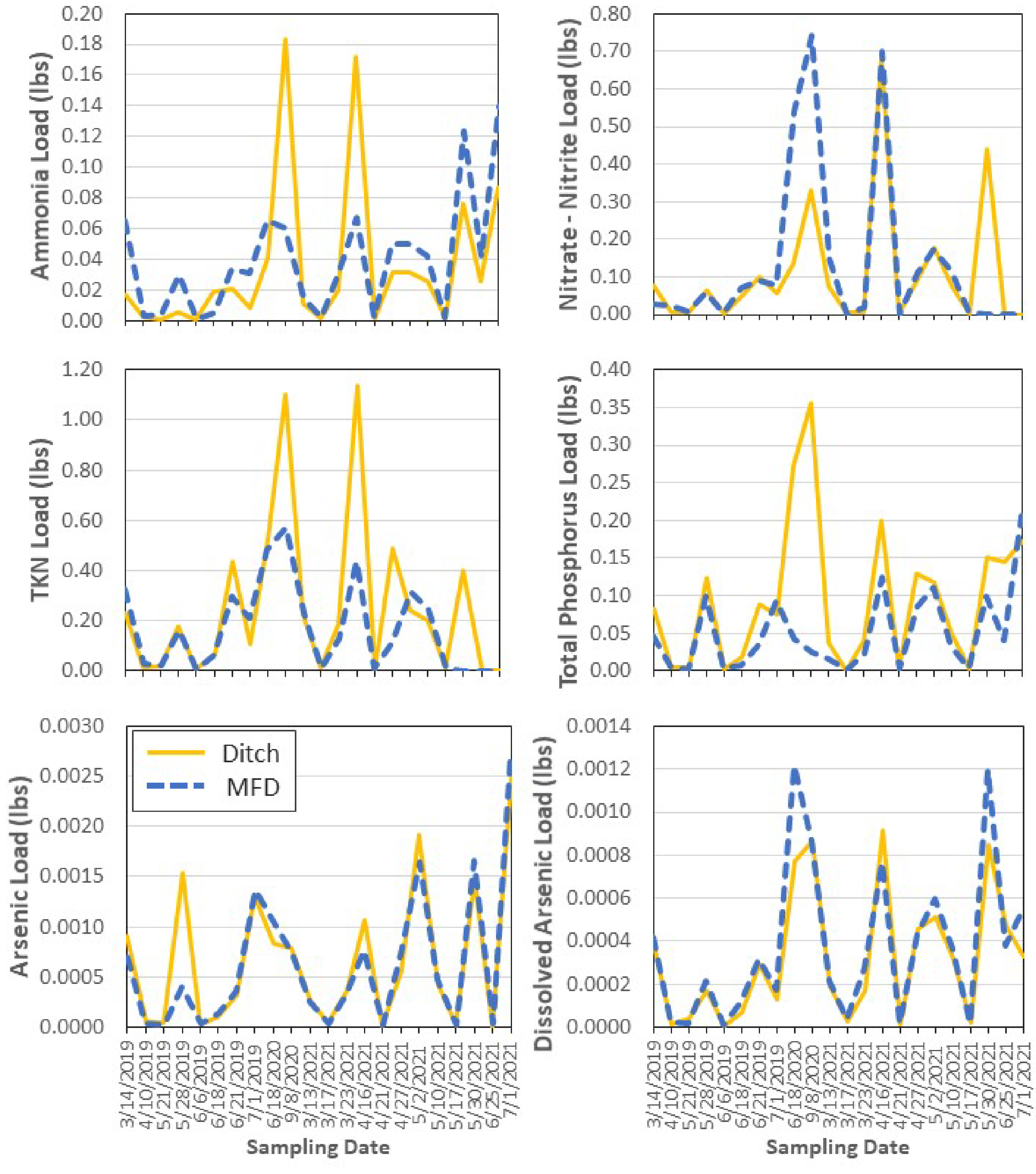


Figure 17. Graphs showing the calculated pollutant loads (in pounds) of Ammonia, Total Kjeldahl Nitrogen, Nitrate – Nitrite, Total Phosphorus, and total and dissolved Arsenic in paired samples from the two sites. The ditch is shown in the yellow solid lines while the MFD is shown as the blue, dashed lines. Results were omitted for TKN and Nitrate-Nitrite for the samples from the MFD on 5/30/2021, and the MFD and Ditch on 6/25/2021 and 7/1/2021 due to laboratory error in the preservation of these samples.

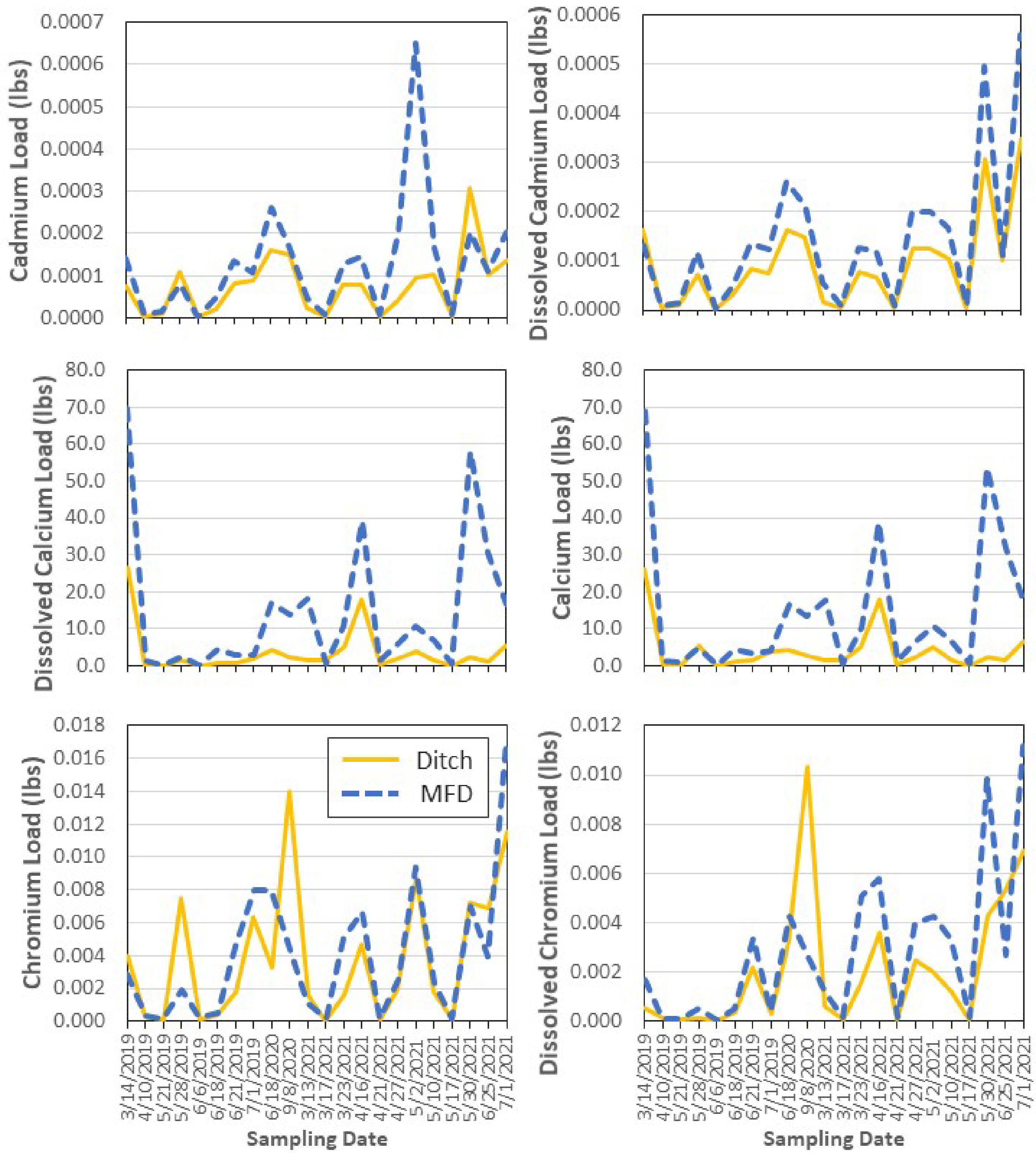


Figure 18. Graphs showing the calculated pollutant loads (in pounds) of total and dissolved Cadmium, Calcium, and Chromium in paired samples from the two sites. The ditch is shown in the yellow solid lines while the MFD is shown as the blue, dashed lines.

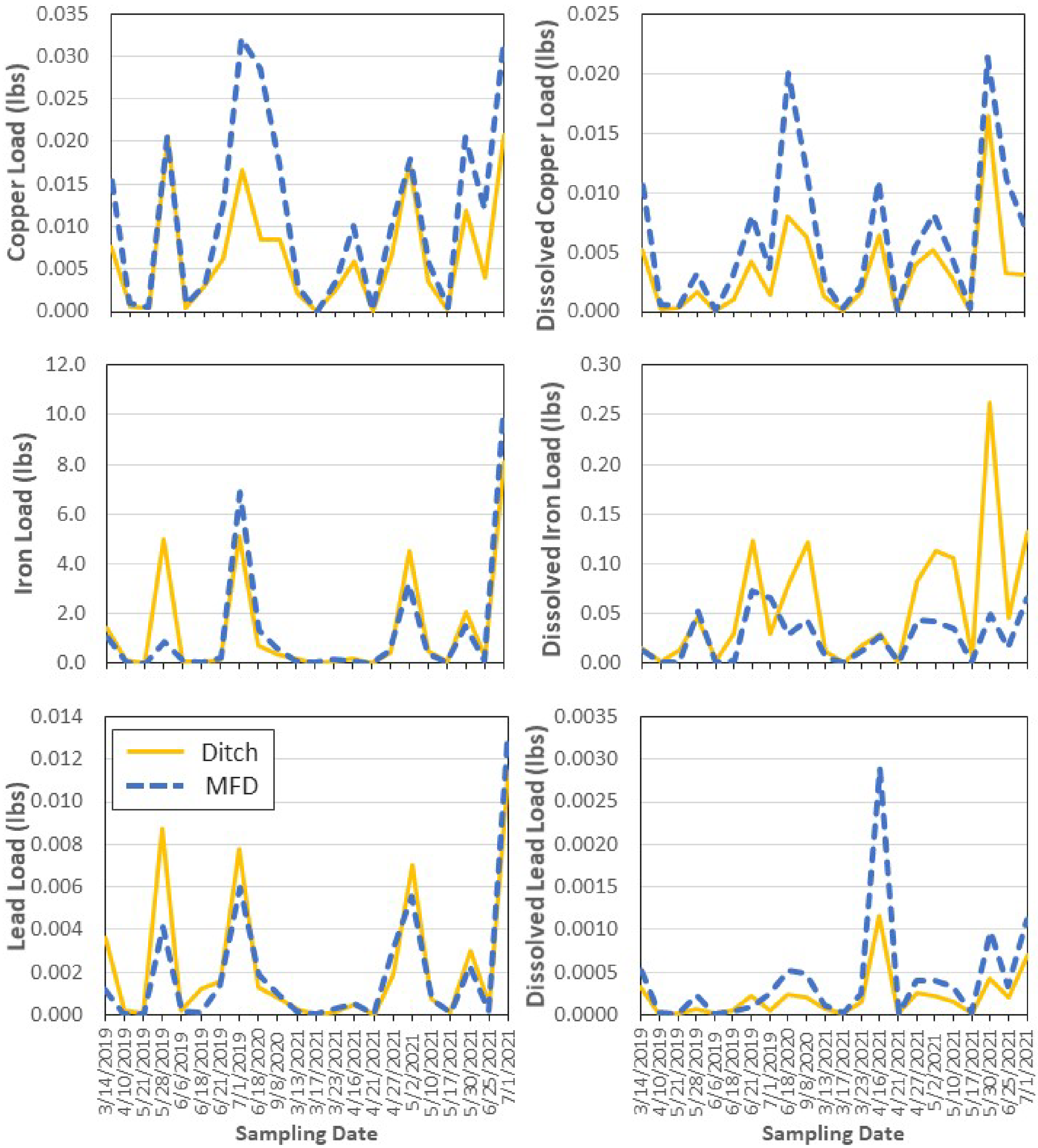


Figure 19. Graphs showing the calculated pollutant loads (in pounds) of total and dissolved Copper, Iron, and Lead in paired samples from the two sites. The ditch is shown in the yellow solid lines while the MFD is shown as the blue, dashed lines.

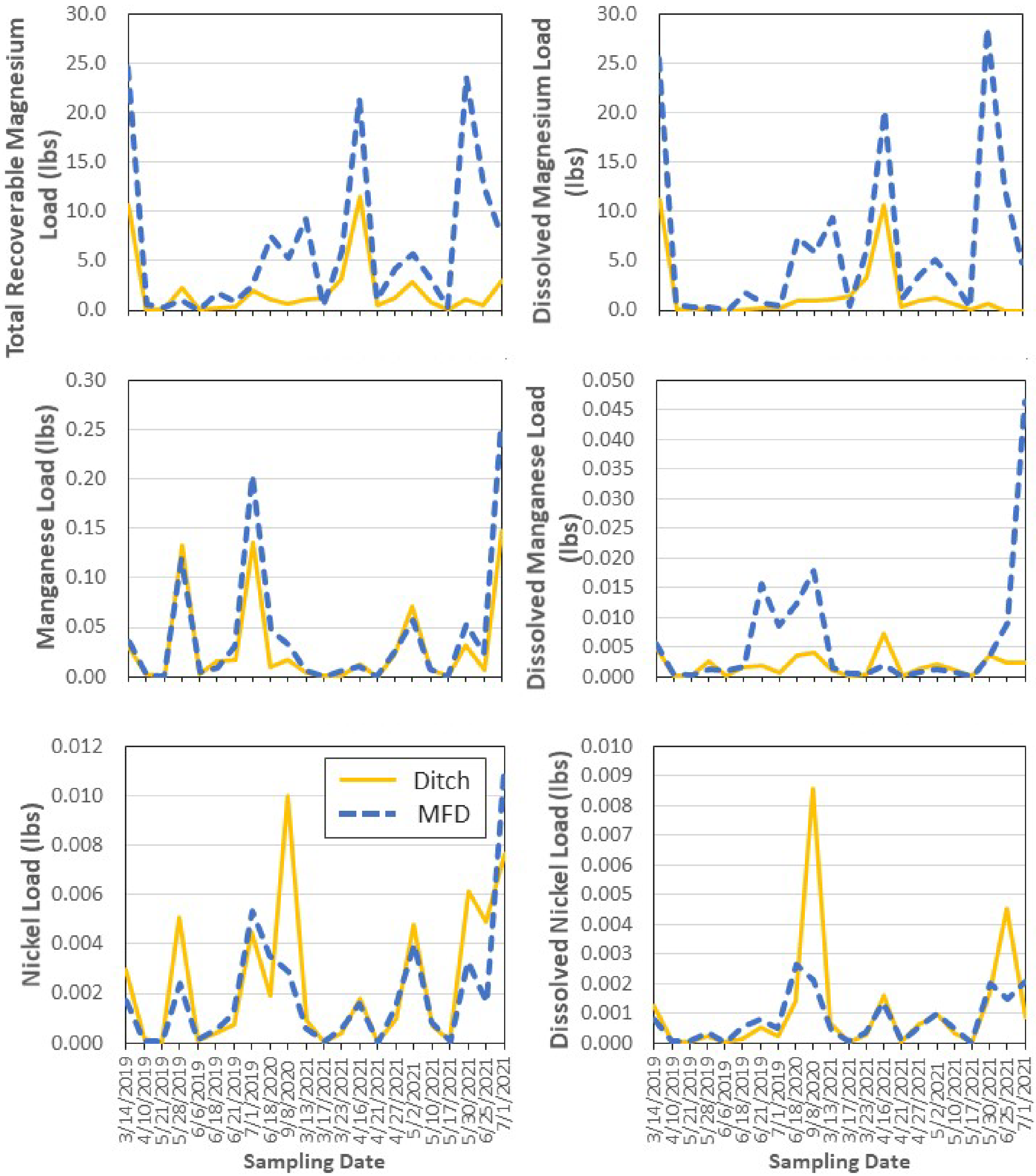


Figure 20. Graphs showing the calculated pollutant loads (in pounds) of total and dissolved Magnesium, Manganese, and Nickel in paired samples from the two sites. The ditch is shown in the yellow solid lines while the MFD is shown as the blue, dashed lines.

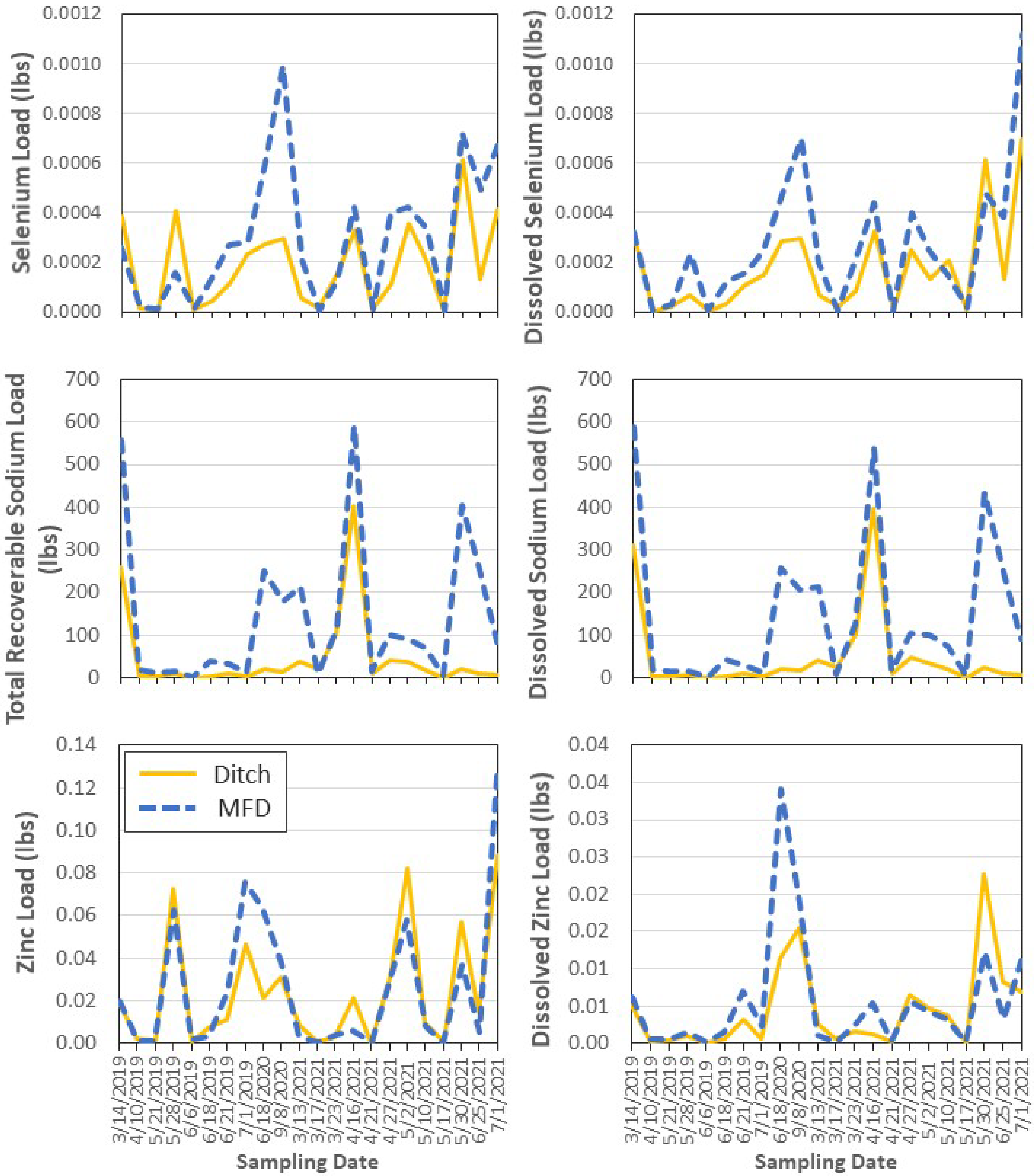


Figure 21. Graphs showing the calculated pollutant loads (in pounds) of total and dissolved Selenium, Sodium, and Zinc in paired samples from the two sites. The ditch is shown in the yellow solid lines while the MFD is shown as the blue, dashed lines.

8.4 SAMPLES BELOW DETECTION LIMIT

There were several POCs that remained below the detection limit (BDL) of the lab analysis methods used for most of the sampled events. In order to be able to utilize any sample that was reported by the lab as BDL in analysis, a value of one half the reported detection limit was used. This method of calculating half the detection limit is widely used to avoid the confounding effects of working with null values or artificially assigning these parameters a value of zero. The POCs that remained below detection limit for the majority of paired samples included: dissolved lead (56.8% of values BDL), oil & grease (70.5% of values BDL), ammonia (77.3% of values BDL), and dissolved cadmium (84.1% of values BDL). While we can still make some inferences about the differences in the pollutant treatment efficiencies between the two sites, the ability to conclusively determine patterns is more limited than with other parameters.

8.5 SEASONAL PATTERNS IN POLLUTANT LOADS

There was not a clear seasonal pattern in the loads of most POCs over the study period. However, chloride (Figure 16), total and dissolved calcium (Figure 18), total and dissolved magnesium (Figure 20), and total and dissolved sodium (Figure 21) exhibited increased loads in samples taken from the ditch in the winter and early spring compared to samples taken in the summer and fall. While the MFD loads for these pollutants had peaks in the winter and early spring, the MFD also exhibited high loads of these pollutants outside of this seasonal pattern. In general, the MFD also consistently had higher loads of each of these pollutants than the roadside ditch samples.

9.0 DISCUSSION AND ANALYSIS

9.1 POLLUTANT REMOVAL CAPACITY OF THE MFD AND DITCH

In comparing the median percent differences in pollutant concentrations between the MFD and roadside ditch, the MFD outperformed the roadside ditch for 17 of the 35 total parameters measured while the ditch outperformed the MFD for only 11 parameters.

There were four parameters where the MFD consistently and substantially outperformed the ditch (percent difference of around 100% or greater) including phosphorous, total arsenic, dissolved iron, and total lead (Table 6). Another four parameters had median percent differences greater than 50%, including TSS, TKN, total iron, and total zinc (Table 6). Because both phosphorus and iron bind to and are transported by sediment in the water column, the lower median TSS concentrations in the MFD effluent is likely at least partially responsible for the reduced concentrations of phosphorous and iron in MFD effluent. Chemical and biological interactions within the MFD mix bed may also be responsible for the observed reductions in heavy metals and phosphorous.

Contrary to the research and design specifications outlined in sections 2 and 5 of this report, the observed results show that the MFD was slightly less efficient at removing copper than the roadside ditch. Although the results were more variable, with the effluent samples from the MFD sometimes exhibiting similar copper loads to the ditch (Figure 19), overall, the median percent difference indicated that the concentrations from the ditch were slightly lower than that of the MFD (Table 6). The small median percent difference between the two indicates that this difference is small, however it is still notable since copper is one of the pollutants of concern that MFDs are designed to remove whereas roadside ditches are not designed for the intentional removal of copper.

Since this area drains to Rock Creek, which is listed as impaired for selenium, it is important to also note that there was little observed difference in the selenium treatment efficiencies of the MFD and ditch. The median effluent concentrations for total selenium at the MFD were only very slightly lower than the ditch (2.32%, Table 6) and there was no observed difference in the concentrations of dissolved selenium at the two sites. This research indicates that, in the climate of the Colorado front range, MFDs would not be an effective SCM to install to meet any future regulations requiring selenium reductions.

9.2 SALTS FROM WINTER ROADWAY OPERATIONS

Excluding total and dissolved copper, the nine remaining pollutants of concern where the ditch outperformed the MFD were all pollutants associated with salts used in winter maintenance operations. The timing of the peaks in concentrations generally correlated to when deicing chemicals were being applied to US36, in the winter and early spring, whereas lower concentrations were observed in samples from the summer and fall at both sites. These patterns indicate that deicing chemicals from winter operations are the likely source of these pollutants. While some of the other POCs on state roads and highways may be from environmental deposition (nitrogen and phosphorous) or a consequence of use by the driving public (oil and grease, heavy metals from brake dust, etc.), deicing chemicals are controlled and intentionally applied to the roadway surface by CDOT. While that may make it easier to control the source of these pollutants by reducing or controlling application of deicing chemicals, deicing practices on state highways are critical to the safety of the driving public in the state of Colorado. Therefore, it may not be feasible or desirable to reduce the application of these chemicals to the roadway and instead selecting SCMs that can treat for these salts and other deicing chemicals may be crucial to reducing the impacts of highway stormwater runoff.

With few exceptions, the calculated loads of salt ions in the effluent from the ditch were lower than those in the MFD. The higher calculated loads in the MFD effluent could be the result of two factors. The roadside ditch could have a higher capacity to treat water containing high concentrations of salts or the MFD could be leaching salts, resulting in salt ion effluent concentrations that were higher than influent concentrations. This leaching could occur through a cycle of salts concentrating in the MFD media during drying and evaporation and then being remobilized and flushing out in subsequent storms.

As discussed in section 4.1, the application of road salts can have significant impacts on the effectiveness of stormwater control measures. Some of these impacts are evident at the MFD site—namely, the negative impacts on vegetation growth. The vegetated filter strip at the MFD site maintained only sparse vegetation throughout the length of the study. This reduced vegetation not only reduced pollutant removal capacity from the vegetation itself, but increased velocity of flows coming into the MFD mix, thereby reducing the MFD's capacity to infiltrate stormwater. Due to the proximity of the MFD's vegetated filter strip to the roadway, the vegetation in this area was likely being more severely impacted by the application of road salts than some of the vegetation present in the roadside ditch (Cunningham, Snyder, Yonkin, Ross & Elsen, 2008).

In a state where winter precipitation generates a significant portion of the annual runoff, the SCMs installed need to be able to not only withstand the potential impacts of high salt loading on vegetation but, where possible, they need to help remove those pollutants as well.

9.3 COST OF INSTALLATION AND MAINTENANCE

The costs of installation and maintenance of the MFD are significantly higher than the costs associated with roadside ditches. MFD design, specialized materials, proper installation, and verification of proper installation require additional funds and time by CDOT and contracted staff. Additional costs would also be associated with maintaining a proper vegetated strip, including replanting with salt tolerant species, and including additional soil amendments. Although typical maintenance involves only vegetation management, there would be more significant costs associated with any underdrains that required maintenance and cleaning to ensure that the MFD continued to drain properly and continued to effectively remove pollutants. Without this proper maintenance, the MFD could become a source of pollutants. If sediments and other pollutants accumulated on the MFD surface they could then be washed out into downstream waters by high flows that were no longer able to infiltrate into the ground through the MFD mix bed.

Comparatively, roadside ditches are a standard roadside drainage practice. Because they are widely used, costs of design and installation are significantly lower, and the risks of improper installation and required re-work and reinspection are lower. Roadside ditches do not require special materials or equipment for construction and maintenance of ditches is limited to vegetation management.

9.4 STUDY LIMITATIONS

9.4.1 LIMITATIONS OF CALCULATED POLLUTANT LOADS

The pollutant load in stormwater runoff is calculated by multiplying the pollutant concentration by the rate of stormwater flow. At both sites, vegetative debris and trash would often accumulate around the 350 AV Level. When the sensor was obstructed by such debris, it would capture erroneous velocity readings. These difficulties in obtaining reliable flow measurements from the equipment at both sites required use of the Simple Method to calculate the volume of stormwater flow at each sampling site. As described more thoroughly in section 7.3 Pollutant Load Calculations, the Simple Method uses the drainage area and the measured precipitation to calculate storm volume.

This method has some problems that limit the accuracy of pollutant load calculations. A major limitation to this method is that it discounts any stormwater infiltration that occurred during a storm event—it assumes that 100% of the precipitation that fell in the drainage area contributes to the calculated pollutant load leaving the site. While the infiltration rates taken during dry weather could be used to partially resolve this, they would be an overestimate of infiltration that was occurring for both high intensity short storms and longer duration, low intensity storms. In the high intensity storms, increased runoff rates reduce infiltration. In long duration storms, soils may reach saturation before the end of a storm so that infiltration rates vary throughout the length of the storm, decreasing as saturation is achieved. These limitations significantly impact flow and, in turn, impact the loads calculated as part of this study.

Additionally, for parameters where the measured concentrations were consistently BDL, the Simple Method may generate artificial trends. Because all concentrations BDL were assigned a concentration of half the detection limit, the drainage area size becomes the sole determining factor in the load. This can be clearly seen in the Dissolved Cadmium Load (Figure 18). If only examining the figure, it appears as though the MFD was consistently worse than the ditch at removing dissolved cadmium from stormwater. However, 84.1% of all dissolved cadmium values were BDL, and oftentimes they were BDL at both sites during a sampling event. The higher calculated dissolved cadmium load for many events at the MFD is due solely to the larger drainage area of the MFD. For this reason, particular care should be used when comparing loads calculated using the Simple Method for parameters that were frequently BDL (see section 8.4 Samples Below Detection Limit, for list of parameters with concentrations frequently BDL).

9.4.2 SAMPLING CHALLENGES

There were several challenges throughout the course of this study that impeded storm sampling.

9.4.2.1 ELECTRICAL SYSTEM FAILURES

RESPEC did an electrical evaluation of the MFD system on 9/3/2020 and observed that the marine battery was losing power. Several factors could have been the cause.

Solar panel observations:

- Cracked in the corners indicating possible vandalism.
- Signs of water damage and possible delamination (Figure 22).
- The panel was lying flat on the box, instead of facing the sun, possibly diminishing solar panel output.
- The rain gauge was casting a shadow on at least 1/3 of the panel at the time of the visit.
- Several days of cloudy and hazy skies (from area wildfires) may have contributed to slower charge times.

Figure 22. Deteriorated solar panel at the MFD site.

Battery observations:

- No regulator between the solar panel and the battery which would control the charge to the battery.
- Battery may have lost capacity due to high temperatures in the monitoring box. Denver recorded at least 73 days in 2020 with a high temperature greater than or equal to 90 degrees.
- The Teledyne ISCO Signature Flow Meter was set to require a minimum of 12 volts of direct current (VDC) to function.

RESPEC replaced the battery in September 2020. The next month, RESPEC replaced the solar panel and installed a regulator to control the charge to the battery, stop overcharging, and prevent the solar panel from pulling power from the battery at night.

9.4.2.2 PEST CONTROL

Both the MFD and ditch sites had issues with mice living in the housing of the sampling equipment at various points throughout the study (Figure 23). RESPEC installed a mouse repellent device, and the mice did not return.

Figure 23. Mouse droppings on the sampler unit console.

9.4.2.3 FLOW METER CONNECTION ISSUES

In June 2020, the Signature flow meter at the MFD appeared to not be working. RESPEC performed an inspection of all connections, found that the connection to the sampler at the flow meter was loose, and tightened this connection. The fuse had also blown and needed replaced.

In addition to troubles with the connections, as mentioned in 9.4.1, measurements from the flow meters at both sites were often skewed due to the presence of vegetation or other debris getting caught on or covering the flow meter's sensor. When this occurred, the flow meter would produce erroneous velocity readings.

Figure 24. Vegetation at the ditch, burned after a small brush fire.

9.4.2.4 BRUSH FIRE

In July 2020, a small grass fire, approximately 100 feet in length, occurred at the ditch site. The cause of the fire was undetermined by a City of Louisville arson investigator. The sampling equipment was not damaged by the fire. The grass and ground cover upstream of the ditch flume burned (Figure 24).

9.4.2.5 VANDALISM AND THEFT

Vandalism was a problem at the MFD site. In May 2020, a camera and a solar panel were stolen from the monitoring station. The camera had been installed in the culvert to take a picture every 15 minutes and correlate the flows shown in the photo with the flow recorded on the Teledyne ISCO Flowlink Global application. The sampler wirelessly transmitted data though a CDOT Verizon account to Flowlink Global. This remote monitoring system was replaced with a RESPEC contractor that lived locally and would visit the site either during a storm event or immediately after, to collect samples and manually download data from the ISCO flow meter.

9.5 MAINTENANCE RECOMMENDATIONS

There are a few recommendations for maintenance of roadside MFDs based on the results of this study. First, CDOT should require regular infiltration testing of the MFD to demonstrate that the infiltration rate is within design parameters. Because the MFD relies on infiltration to function properly, monitoring infiltration rates is crucial to the success of this SCM. CDOT should also consider spacing check dams along the length of the MFD to reduce flow velocity and further promote infiltration during the frequent high-intensity storm events along the Colorado Front Range. When infiltration rates slow below specifications, CDOT should consider cleaning the underdrain structure to restore infiltration rates and improve MFD function.

CDOT should also monitor the MFD for reduced vegetation density along the vegetated filter strip. The filter strip may need to be restored to effectively limit flow velocity and encourage infiltration. Poor soil conditions along Colorado's Front Range may necessitate the addition of soil amendments and a salt tolerant seed mix. If these methods are effective at improving vegetation condition in existing MFDs, CDOT should consider adding soil amendment and the use of salt-tolerant seed mixes to the MFD design specification to facilitate vegetation establishment on any newly constructed MFDs. These adaptations could contribute towards the long-term viability of the filter strip given the proximity to the roadway and the impacts of winter deicing chemicals on this vegetation.

10.0 CONCLUSIONS

Pollutant concentrations measured and the associated calculated loads at the roadside ditch and MFD sites in this study varied widely across storm events, indicating that storm dynamics may strongly influence pollutant concentrations and pollutant removal capacity. Despite this variation, results did indicate that the MFD is more effective than the roadside ditch at removing some pollutants from stormwater, including certain heavy metals, total suspended solids, and phosphorus. However, the MFD proved to be relatively ineffective at removing pollutants associated with winter deicing chemicals, with the ditch outperforming the MFD for these parameters. Winter deicing chemicals may also be limiting the MFDs effectiveness by killing the vegetation in the designed vegetated strip, increasing the velocity of flows in the MFD and reduced infiltration capacity. Alterations to the MFD design to further decrease the velocity of flows and to improve vegetation establishment in the Colorado Front Range could potentially improve MFD pollutant removal effectiveness. However, given the relatively high costs of MFD installation and maintenance, and the limited water quality benefits, the MFD may not be best suited for use in the semi-arid climate of Colorado.

11.0 REFERENCES

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APPENDICES

APPENDIX A: SAMPLING LOCATION FIELD LOGBOOK DATA

SAMPLING LOCATION FIELD LOGBOOK DATA

SAMPLE/STATION ID: ISCO 03/US 36

DRAIN TYPE/SIZE: DITCH ALONG CDOT ROW

FLOW DESCRIPTION: DRAINS TO CDOT ROW THEN BOULDER OPEN SPACE

LATITUDE: 39.964598 **LONGITUDE:** -105.182391

MAINTENANCE FACILITY: N/A

DATE	TIME	BOTTLE NO.	RAINFALL AMOUNT	FLOW (CFS)	COMP/ GRAB	SNOW RAIN MIX
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
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					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M
					C / G	S / R / M

APPENDIX B: AUTOMATIC SAMPLER/ATTACHMENTS CALIBRATION

AUTOMATIC SAMPLER/ATTACHMENTS CALIBRATION

CDOT Site ID/Name	**ISCO 03/US 36 HWY DITCH**			
DATE:	**TIME:**	**Personnel:**		
Latitude: 39.964598		**Longitude: -105.182391**		
Sampler Reading before Calibration **From the status menu**				
Battery:	A/V Level: N/A	Flow:	Precipitation amount:	
Previous Program Start Date: N/A			Time: N/A	
Sampler Calibration including Area Velocity Meter, Pump Operations, Distributor Arm, and Solar Panel				
Review all Set-up information:	Good		Reset	
Check Distributor Arm:	Good	Bad	Fixed	
Check Pump Operations:	Good	Bad	Fixed	
Check Solar Panel & Clean:	Good	Bad	Fixed	
Check Tipping Bucket:	Good	Bad	N/A	
A/V Level:	Flow:	Battery:		
Calibration Successful:	YES	NO		
DATE:	**TIME:**	**Program Running:**	**YES** **NO** **N/A**	
Collected By:		Signature:		

Comments:____