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Evaluating Roadway Subsurface Drainage Practices

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16. Abstract (Limit: 200 words)

This project involved the evaluation of some configurations of pavement subsurface drainage systems, including the conventional edgedrain system, and two centerline configurations, at 2-foot and 4-foot depths. Testing of these configurations took place on a newly constructed eight-mile section of Nobles County CSAH 35 near Worthington. Drained roadway sections were 500 feet long for each drainage treatment. Each of the treatments was replicated six times, with the outflow for each replication outlet through a tipping-bucket flow monitoring system. The experimental design tested both the drain configuration and the effect of relative elevation of the roadway. Measurement of relative wetness of the pavement base and subgrade materials for each of the drainage treatments was conducted with a Geonics electromagnetic induction instrument (EM38). Data were collected from March 2006 until November 2008, with breaks during the winter periods. Statistical analyses were conducted to look for treatment effects, using both drained volumes as well as the EM38 measurements as measures of drain efficacy. Additional project work included a finite element analysis of the drainage configurations, EM38 evaluation of drainage effectiveness of an open-graded base construction for streets in the city of Worthington, and evaluation of the potential drain plugging effect of crushed concrete fill.

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Evaluating Roadway Subsurface Drainage Practices

Final Report

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We wish to thank Dwayne Haffield, City Engineering for the city of Worthington, in providing suggestions for city streets to conduct the EM38 measurements to detect differences in drainage system quality. Dwayne spent several hours showing us new drainage design under construction, and outlining the attributes of the new drainage configuration.

Several students assisted with project activities and should be acknowledged for their help. These include graduate students Sam Johnson, Eric Otto, and Mikhail Titov, and undergraduates Nick Moore, Mike Talbot, Troy Roth, Russell Depuydt, Geoff Kramer, and Angela Gorham. Sam and Eric were involved in the early part of the project and designed the experimental layout. They also designed and constructed the tipping buckets for tile outflow measurements. Mikhail Titov was responsible for all of the finite element flow modeling work under the direction of John Nieber. The work of Nick Moore was especially important in supporting project activities in the field. He organized the periodic field campaigns, maintained/calibrated the equipment, and organized the collected drainage data and EM38 data. Without his seemingly tireless assistance, the project would not have progressed as it did.

Finally, John Nieber wishes to thank Dr. Gary Sands, Department of Bioproducts and Biosystems Engineering, for managing the project while he was on sabbatical leave in 2005-06.

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Executive Summary

This project involved the evaluation of the efficacy of drainage systems, the purpose being to test the effect of drainage configuration. The study centered upon the drainage of the roadway base materials in the County State Aid Highway No. 35 (CSAH 35), Nobles County, MN. The study site consists of a 43,850 ft. stretch of road between the towns Worthington and Rushmore, close to the southwest corner of the State of Minnesota, at 43°37'12" N and 95°35'47" W. In addition, some work was done on selected streets within the city of Worthington.

To perform this evaluation, two sets of experiments were devised. In the first set, three drainage treatments were examined; one in which the drains were located on the roadway edge, and two in which the drains were installed along the roadway centerline, one at a depth of 2 ft. and the other at 4 ft. In the second set, it was examined whether the elevation of the roadway relative to the surrounding landscape or the orientation of the drains at either side of the road had a significant impact on the efficacy of the drain.

The edgedrains yielded by far the greatest volume of drainage water during the two-year period of monitoring, 2006-2007. Drains located on the north side of the road had higher average volumes drained for March and April monitoring periods. Drains located at lower elevation had also a higher drainage volume during the same period.

Measurements of electrical conductivity were performed using an electromagnetic instrument, Geonics EM38, for the different drain configurations. The EM38 measures the bulk electrical conductivity of subsurface materials, and is sensitive to the moisture content of those materials. Higher electrical conductivity will generally mean moisture contents are higher. For all cases, readings with the vertical orientation of the EM38 were higher than those with the horizontal orientation. Values for edgedrains were higher than those for the centerline drains for measurements taken in selected days of July and August of 2006, as well as April of 2007. For May 2007, however, values were a little higher for the 2ft. centerline drainage treatment, while values for both the edgedrains and the 4ft. centerline drains were very similar.

Statistical analyses were performed to compare the collected drained water from the different drainage treatments. For all the periods considered, there were significant differences between the edgedrains and the centerline drain. There was no significant difference between the two centerline drain treatments. According to these results, and because the edgedrains collected much more water than the other two treatments, it seems reasonable to conclude that edgedrains are the recommended drainage treatment. However, one must consider that if the source of excess water is upward flowing ground water, perhaps the centerline drains will have some advantage in removing the excess water.

Regarding drain orientation, results indicated that there were no significant differences between edgedrains located at either side of the road. These results indicate that edgedrains located at either side of the road collect approximately the same amount of water; therefore, both locations must have drains installed. Similarly, when comparing drainage volumes from drains on both high and low areas of the road, results indicated that there were no significant differences

between drains located at either high or low areas of the road. According to these results, drains placed in both high and low areas of the road collected similar amount of water; therefore, both elevations must have drains installed.

When comparing the effect of both the drainage treatment and the EM38 orientation on the values of the electrical conductivity measurements, the results show that: 1) for all cases, there was a difference between the means of the electrical conductivity measurements and the EM38 orientation; 2) for all cases, there was no interaction between the drainage treatment and the EM38 orientation; and 3) for all but one case, there was difference between the means of the electrical conductivity measurements and the drainage treatment. These results suggest that, as it was concluded above, a specific drainage treatment should be used; likewise, the results indicate that additional study is needed for the EM38, so as to select the orientation of the device that best fit measurements of water content of base course and subgrade materials underlying pavements.

A finite-element numerical analysis for the situation involving variably-saturated flow toward subsurface drains placed beneath roadway pavements was conducted using COMSOL-MP software. The three experimental drain configurations considered were also examined in this analysis. The results displayed by the limited number of cases examined showed that the 4ft. depth centerline drain will remove more of the infiltrated water when the soil beneath the pavement subgrade is essentially impermeable. In the area where CR 35 is located this impermeable condition is probably more the rule than the exception, at least we can say that based on the limited number of borehole logs we had available for our analysis.

For the purpose of assessing the potential impact of the quantity of crushed concrete used in base course materials on drain tile condition, samples of edgedrain tiles were collected from two county roads in Nobles County, CR 32 and CR 35. CR 32 was used as a control in this assessment because it did not have any crushed concrete placed in the base course or in the permeable unpaved shoulder. The drains for CR 32 were about 12 years old. The drains on CR 35 were about 4 years old, and crushed concrete was present throughout the permeable shoulder material. The tile samples, along with the geofabric surrounding the tiles were analyzed for presence of precipitated carbonates. The CR 32 sample showed strong presence of carbonate deposits, while the samples from CR 35 did not show such presence. The results, although interesting, were somewhat contrary to what might have been expected, because the CR 32 samples should not have shown any reaction to the application of the HCL solution, as they did. It is not clear what the source of the calcium carbonate is for the samples derived from CR 32. It might be that the trench sand used for the CR 32 tile installation is carbonate sand, in which case, the reaction to the acid would be expected.

Finally, subsurface drainage conditions in four streets in the city of Worthington were compared using electrical conductivity readings taken with the EM38 electromagnetic instrument. Both vertical and horizontal orientations of the EM38 were used. The roads evaluated were Pleasant Street and Eckerson Drive in the southwest part of Worthington, and Cecillee Street and Spring Avenue in the northwest part of the city. Both Eckerson Drive and Cecillee Street have open graded base material for enhanced drainage, while both Pleasant Street and Spring Avenue have poorer construction for drainage. Results from the EM38 measurements indicated that the treatments (roads) were different, and Spring Avenue seems to be the road with a least effective drainage system, followed by Cecillee Street. Both Pleasant Street and Eckerson Drive perform in a pretty similar way. All of these pavements, except Eckerson Drive showed signs of stress in the form of cracking. Spring Avenue was the worst of these, followed by Pleasant Street. Both of these had significant alligator cracking, which is a sign of poor subsurface drainage conditions. Cecillee showed some signs of cracking, but the cracks were mainly of the transverse type, with some longitudinal cracks. The EM38 measurements are somewhat in line with these observations of pavement stress, but the correspondence is not perfectly convincing. The EM38 reading might have been somewhat confounded by differences in utilities lying beneath the pavements.

The use of the EM38 device promises to be an good approach to discriminate the water content conditions beneath roadway pavement. Additional work with the instrument is needed to test it on pavements where actual moisture content measurements beneath pavement are available.

Chapter 1

Introduction

1.1 Overview

The problem of draining excess water from beneath highway pavements has received much attention from pavement designers and researchers for at least 50 years. One of the first sets of design recommendations regarding subsurface drainage for roadways was published by the Federal Highway Administration in the early 1950's. Since that time there have been numerous attempts by state and local highway departments to install subsurface drainage systems that meet local/regional conditions. And since that time new drainage products and materials have become available to the designer/contractor for implementation of subsurface drainage into roadway systems. Studies that have evaluated the overall benefits of subsurface drainage include Forsyth et al. (1987), Anon (1989), DeBarardino (1995), Hall and Correa (2003) and Meininger (2004). While there is a significant initial capital cost associated with installing drainage systems either with road construction or retrofitting existing roadways, the positive payback in terms of reduced roadway maintenance due to water associated damage is quite clear.

A number of evaluations of alternative drainage designs, and also how well installed drainage systems perform have been published in the literature. Studies that have evaluated alternative drainage system designs include Cochran and Hagen (1995), Kearns (1992), TRB (1994), van Sambeek (1989), McEnroe et al. (1993), Barry and McCuffey (1997) and Birgisson (2002). Studies that have evaluated the condition and performance of subsurface drainage systems under field conditions include those by van Sambeek (1989), O'Reilly and Brennan (1989), TRB (1993), Wilson-Fahmy et al. (1996), Raymond et al. (1996), Flechenstein and Allen (1996, 2000), Koerner et al. (1996), and Harrigan (2002). Many of these latter studies have involved the use of cameras placed into tile drains to visually examine drain condition, or exhuming of drains to examine the condition first-hand.

This project involves the evaluation of the efficacy of drainage systems for drainage of roadway base materials in the County State Aid Highway No. 35 (CSAH 35), Nobles County, MN. The study site consists of a 43,850 ft stretch of road between the towns Worthington and Rushmore, close to the southwest corner of the State of Minnesota, at $43^0$37'12" N and $95^0$35'47" W. It lies between CSAH 13 and CSAH 10, and had a new overlay after the installation of three different subsurface drainage configurations. There is a 97.5 ft variance in elevation across the length of road. This particular site was selected because it was undergoing construction during the projects inception. Such timing offered the ability to tailor the roads construction to meet the studies objectives.

1.2 Objectives

The objectives of the present project are:

1. Look at the efficiency of edgedrains compared to centerline drains. Specifically comparing edgedrains to centerline drains at depth of two and four feet.
2. Determining any advantage in draining only low points in a road profile.
3. Evaluate the effect of additional crushed recycled concrete in the base and shoulder on drain performance with respect to possible plugging by concrete constituents.
4. Explore the ability of electromagnetic inductance to measure soil moisture content in road base and sub grade material.
5. Constructing drain design standards by employing statistical analysis and flow models.

1.3 Outline for this Report

Chapter 2 describes the experimental design selected for this project, including study sections, sample populations, drainage treatments, outlet locations, as well as monitoring approaches and devices.

Chapter 3 shows the monitored drainage volumes for the three treatments devised; additionally, volumes from edgedrains located at both sides of the road and volumes coming from selected drains located in both high and low areas are also presented.

Chapter 4 presents the monitored EM38 measurements, for selected dates during the two-year period of data collection, for the three drainage treatments devised as well as the five locations for each drain site.

Chapter 5 shows the statistical analysis performed to compare the drainage treatments: drainage volume by drainage treatment; drained volume by edgedrain orientation; drained volume by drain elevation; and, electrical conductivity by both drainage treatment and EM38 orientation.

Chapter 6 describes the numerical simulation of variably-saturated flows in the vicinity of and beneath highway pavements as affected by the presence of subsurface drainage tile.

Chapter 7 presents an assessment of the potential impact of the quantity of crushed concrete used in base course materials on drain tile condition.

Chapter 8 shows the statistical analysis performed to compare the moisture conditions beneath four selected sections of residential streets in Worthington.

Chapter 9 presents the main conclusions and recommendations derived from the results obtained in this research project.

The appendices include additional and detailed information about the project, presented as both tables and figures.

Chapter 2

Experimental Design

2.1 Introduction

The location selected to conduct the drainage efficacy experiment was County Highway 35 in Nobles County, close to the southwest corner of the State of Minnesota, approximately at $43^0$37’12” N and $95^0$35’47” W. At the time of the project an eight-mile section of the highway was under reconstruction with plans calling for the removal of pavement, reconstruction of the subgrade and base course material. This section of road extended west from the west end of Worthington to the city of Rushmore. Since tile edgedrain was already planned for the roadway, the experiment to evaluate the efficacy of diverse drainage configurations fit very well into the project. The plan was to choose replicated experimental treatments that would test some of the hypotheses set forth in the project proposal. In effect, the experimental treatments were intended to examine the differences between edgedrain versus centerline drain configurations, and to determine the relative effect of draining only low areas versus draining road sections with higher elevations.

2.2 Study Sections

The CSAH 35 was separated into 500 ft sections starting from the western end of the highway construction near Rushmore, MN. There are 87 total sections along the 43,850 ft stretch of highway. Using the construction plans that were availed from Nobles County, the 87 sections were separated into three sample populations. Sample population 1 consists of relatively flat highway sections, and sample population 2 consists of sloping sections (about 1%-3% slope). There are 37 highway sections in sample population 1 and 23 sections in sample population 2. The third population consists of 27 highway sections where culverts and/or road intersections are present and were not used in site selection.

From population 1, 30 sections were randomly chosen and assigned one of three drainage treatments: edge-drains, 2-ft centerline drains, or 4-ft centerline drains. Each drainage treatment was assigned 10 highway study sections. From population 2, 10 sections were chosen, and. each of them will be drained using edge-drains. These study sections will be used to test the effect of landscape elevation (high versus low) on drainage. Many of these sites will be in the eastern end of the roadway, but there are a few sections in the middle portion of the roadway that will be suitable as well.

The locations of each of the study sites and their corresponding outlet locations are shown in Tables 2.1-2.4. Additional details of the experiment design can be found in Appendix A.

Table 2.1 Placement of drain outlets

STATION	STATION	STATION	STATION	STATION
5 + 00	60 + 00	165 + 00	250 + 00	405 + 00
10 + 00	65 + 00	170 + 00	255 + 00	410 + 00
15 + 00	70 + 00	195 + 00	260 + 00	415 + 00
20 + 00	75 + 00	200 + 00	300 + 00	420 + 00
25 + 00	80 + 00	220 + 00	305 + 00	425 + 00
30 + 00	95 + 00	225 + 00	310 + 00	430 + 00
35 + 00	100 + 00	230 + 00	385 + 00	
45 + 00	105 + 00	235 + 00	390 + 00	
50 + 00	125 + 00	240 + 00	395 + 00	
55 + 00	130 + 00	245 + 00	400 + 00	

2.3 Monitoring

Flow from each of the study sections will be monitored using a tipping bucket device (Figures 2.1 and 2.2), which will be enclosed inside a sheet metal box with a lock. The box will be buried at or near ground level for safety precaution. A battery-powered recorder will record the number of times that the bucket tips (flow volume), emptying the water through a pipe to the concrete headwall.

The tipping buckets will be placed at as many of the drain outlets as cost permits. Study sections assigned 2 or 4 ft centerline drainage treatments will have a drain outlet on one side of the road. Conventionally, the edgedrains would have two outlets, one on each side of the road. However, due to the cost of tipping bucket devices, there will be just one outlet for the edgedrains as well.

The outlets should be placed on the side of the highway with the deepest ditch, as a difference in elevation is necessary in the placement of the tipping buckets (Figure 2.1). At each of the outlets, the tipping buckets will continuously record the flow volume, and data stored on data loggers will be downloaded on a bi-monthly to monthly basis.

Also, an electromagnetic induction device called the EM38 will be used to determine relative moisture contents of the sub-grade material. EM38 measurements can be taken through the pavement, and will show differences in the conductivity of the sub-grade. Considering other factors, such as soil texture and temperature, differences in conductivity will be used to determine relative moisture contents.

Table 2.2 Drainage system locations

FROM STATION	TO STATION	DRAINAGE SYSTEM
5 + 00	10 + 00	2 ft Centerline
10 + 00	15 + 00	Edge
15 + 00	20 + 00	2 ft Centerline
25 + 00	30 + 00	4 ft Centerline
30 + 00	35 + 00	4 ft Centerline
45 + 00	50 + 00	4 ft Centerline
55 + 00	60 + 00	4 ft Centerline
65 + 00	70 + 00	2 ft Centerline
70 + 00	75 + 00	4 ft Centerline
75 + 00	80 + 00	Edge
95 + 00	100 + 00	Edge
100 + 00	105 + 00	2 ft Centerline
125 + 00	130 + 00	Edge
165 + 00	170 + 00	Edge
195 + 00	200 + 00	Edge
220 + 00	225 + 00	4 ft Centerline
225 + 00	230 + 00	2 ft Centerline
235 + 00	240 + 00	4 ft Centerline
240 + 00	245 + 00	Edge
245 + 00	250 + 00	2 ft Centerline
250 + 00	255 + 00	4 ft Centerline
255 + 00	260 + 00	2 ft Centerline
300 + 00	305 + 00	2 ft Centerline
305 + 00	310 + 00	Edge
385 + 00	390 + 00	2 ft Centerline
395 + 00	400 + 00	Edge
405 + 00	410 + 00	4 ft Centerline
410 + 00	415 + 00	4 ft Centerline
415 + 00	420 + 00	2 ft Centerline
425 + 00	430 + 00	Edge

Table 2.3 Placement of edgedrain outlets for sloping landscapes

STATION	STATION
85 + 00	280 + 00
90 + 00	285 + 00
110 + 00	290 + 00
115 + 00	330 + 00
130 + 00	335 + 00
135 + 00	355 + 00
140 + 00	360 + 00
145 + 00	365 + 00
180 + 00	370 + 00
185 + 00	

Table 2.4 Edgedrain study sites for sloping landscapes

STATION	TO STATION	DRAINAGE SYSTEM
85 + 00	90 + 00	Edge
110 + 00	115 + 00	Edge
130 + 00	135 + 00	Edge
140 + 00	145 + 00	Edge
180 + 00	185 + 00	Edge
280 + 00	285 + 00	Edge
285 + 00	290 + 00	Edge
330 + 00	335 + 00	Edge
355 + 00	360 + 00	Edge
365 + 00	370 + 00	Edge

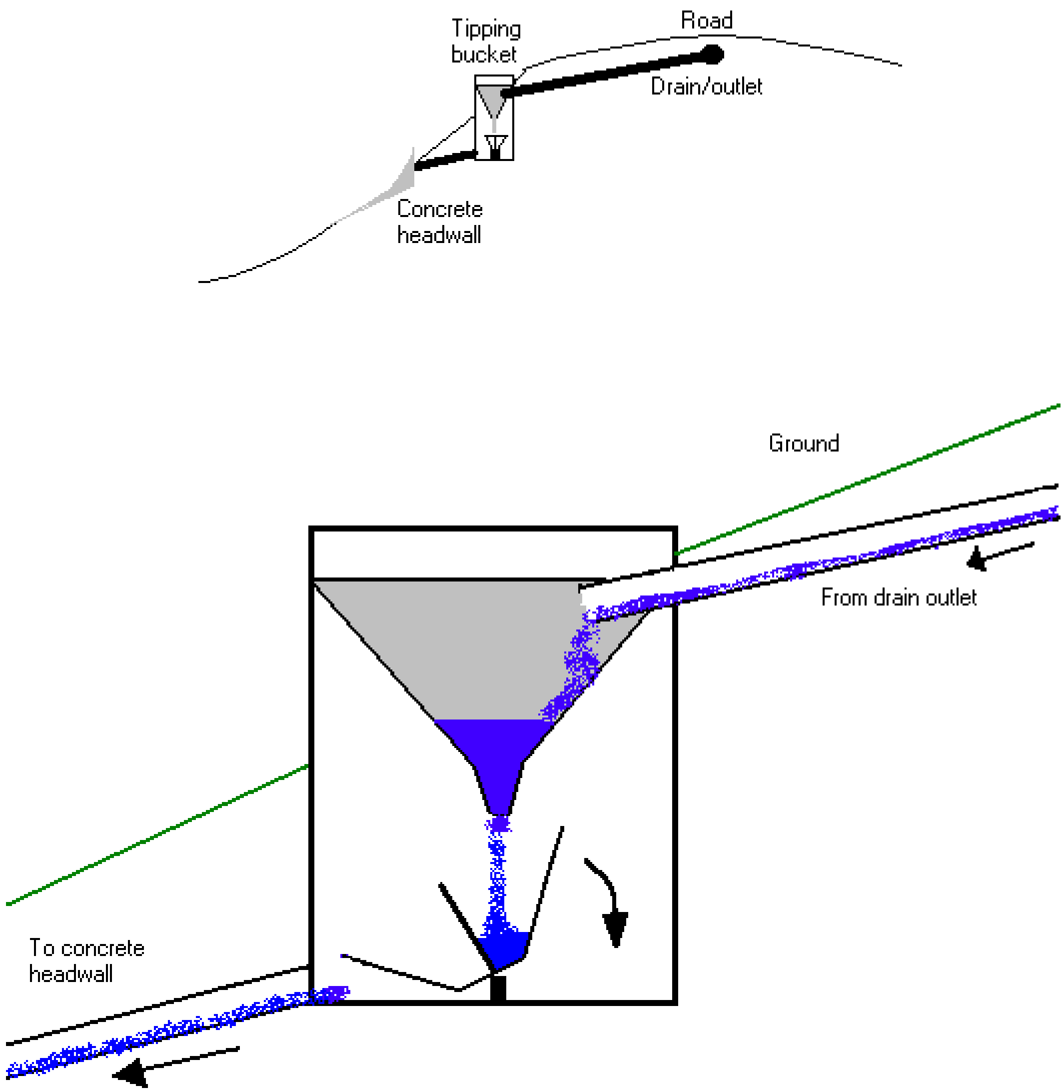

Figure 2.1 Tipping bucket system

Figure 2.2 A constructed tipping bucket, with a data logger on top of the meter

Chapter 3

Monitored Drainage Outflow

3.1 Introduction

The monitored drainage volumes presented in this report will be used for later statistical analysis to: 1) compare the effectiveness of drainage of base and sub-grade materials where the drain configuration is either the conventional edge-drain or centerline drain, and 2) compare the effectiveness of drainage of base and sub-grade materials where drain configuration is either the location of drains along the entire roadway or only in the low points.

As proposed and described in Nieber *et al*. (2006), outflow was recorded automatically by event counters set up with the tipping bucket units. These tipping buckets were all calibrated under laboratory conditions, prior to installation, and after removal from the monitoring locations. Sites were visited at least once a month to record counts and maintain tipping bucket units. Outflow volume for each site was calculated from the logged counts, and recorded in an Excel spreadsheet for later statistical testing. Monitoring was conducted from March to November in 2006 and 2007.

The monitored drainage volumes, during the two-year period of data collection, for the three treatments devised, are presented. Drainage volumes from edgedrains located at both sides of the road are also presented, as well as volumes coming from selected drains located in both high and low areas. Additional details about the drainage volume data collected for this study are provided in Appendix B.

3.2 Drainage Volume from Edge/Centerline Drains

2006

Figure 3.1 show the monthly average volume of water drained from the three treatments during the 2006 monitoring period. Edgedrains collected much more water than the other two centerline drain treatments combined during the whole year. Volumes collected during both March and April were considerably higher than those of the other months. With the exception of both March and April the 4ft centerline drains collected more water than the 2ft centerline drains.

2007

Figure 3.2 shows the monthly average volume of water drained from the three treatments during the 2007 monitoring period. In a behavior similar to that of the 2006 year, edgedrains collected much more water than the other two treatments combined during the entire year. Likewise, volumes collected during both March and April were considerably higher than those of the other months. With the exception of only March, the 4ft centerline drains collected more water than the 2ft centerline drains.

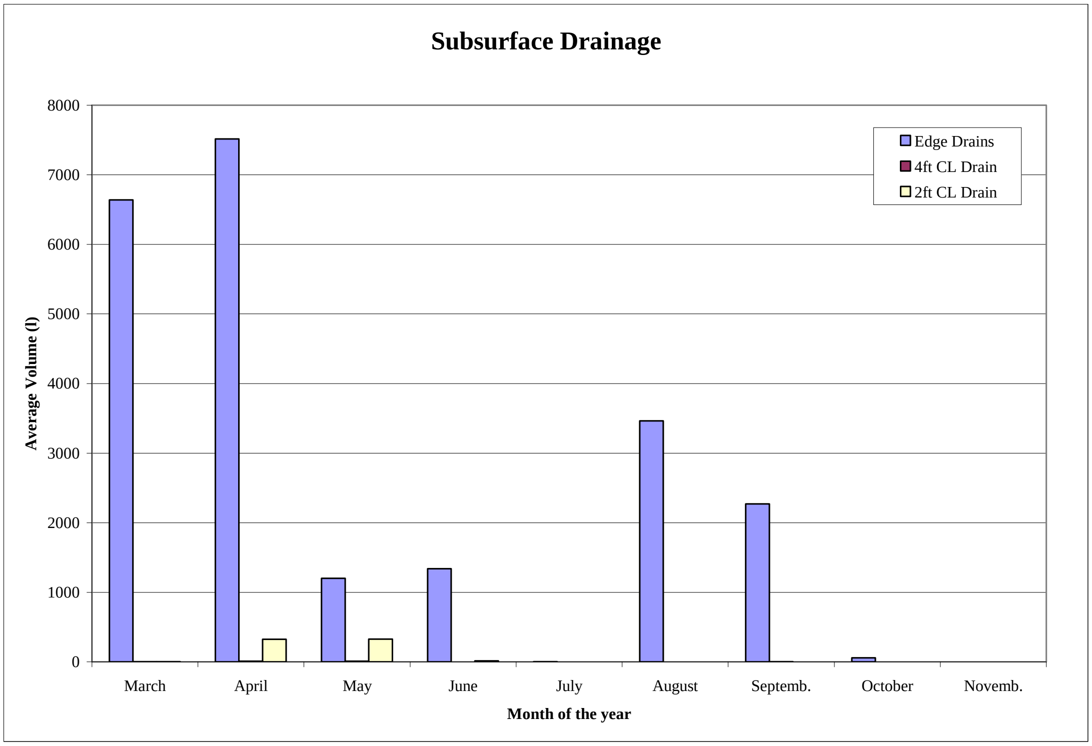

Figure 3.1 Average drained volumes for edge/centerline drains (l) – 2006

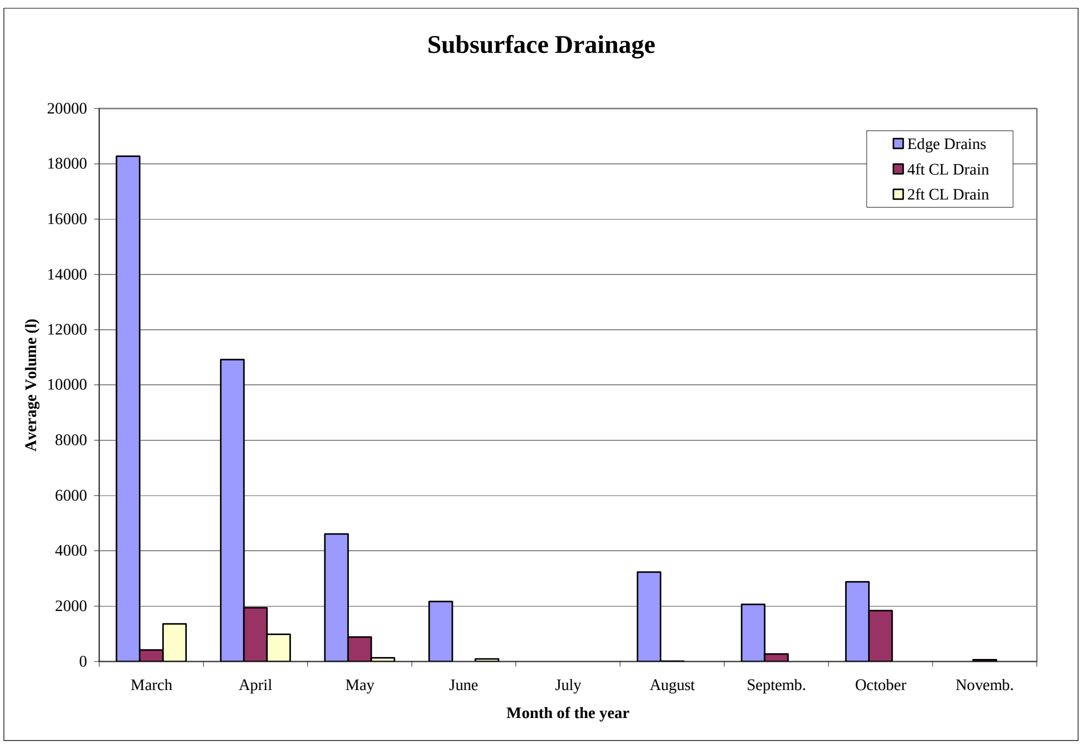

Figure 3.2 Average drained volumes from edge/centerline drains (l) – 2007

2006-2007

Figure 3.3 shows the monthly average volume of water drained from the three treatments during the 2006-2007 years. As expected, water collected from both the 2ft centerline drains and the 4ft centerline drains were exceeded by the volume collected from edgedrains. With the exception of only March, the 4ft centerline drains collected more water than the 2ft centerline drains.

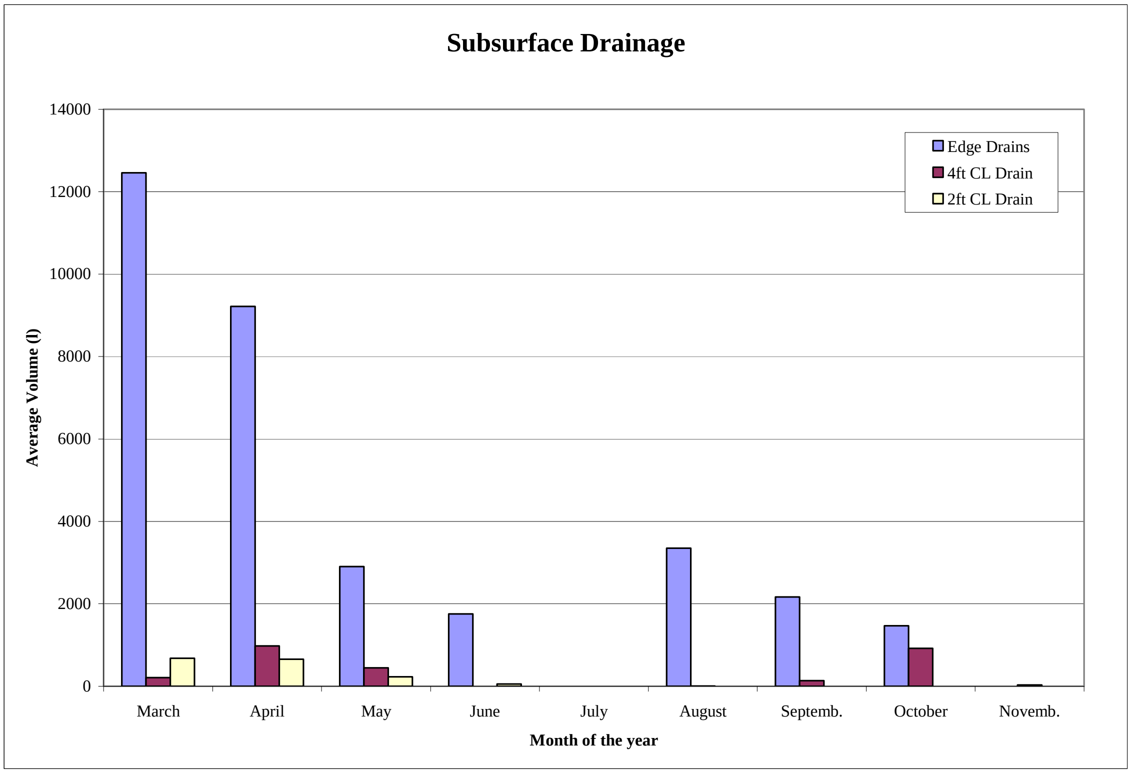

Figure 3.3 Average drained volumes from edge/centerline drains (l) – 2006/2007

3.3 Drainage Volume from North/South Edgedrains

2006

Figure 3.4 presents the monthly average volume of water drained during 2006 from edgedrains located on either side of the road under study. According to these values, there is not a clear difference in behavior due to the locations of drains: during March and April, volumes coming from the north drains clearly exceed those coming from the south drains; however, during June and September, the results show an opposite behavior. During the rest of the year, volumes coming from either drain location are similar.

2007

Figure 3.5 presents the monthly average volume of water drained during 2007 from edgedrains located on either side of the road. In contrast to the results obtained for the 2006 monitoring

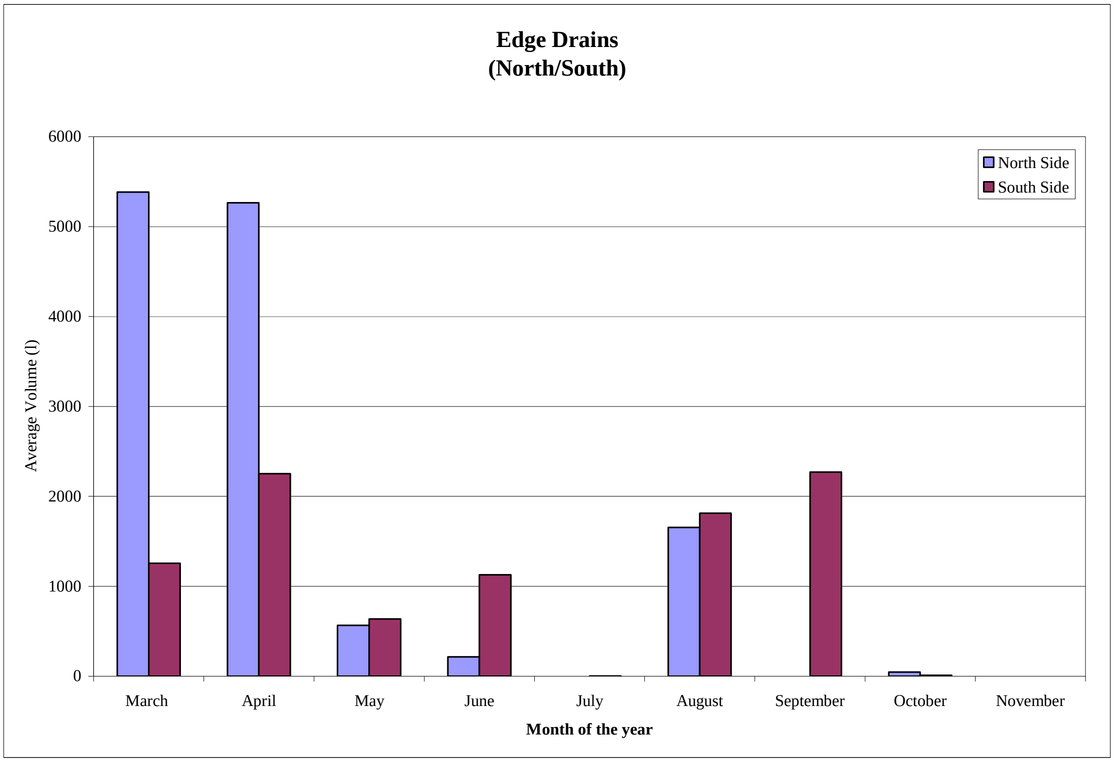

Figure 3.4 Average drained volumes from north/south edgedrains (l) - 2006

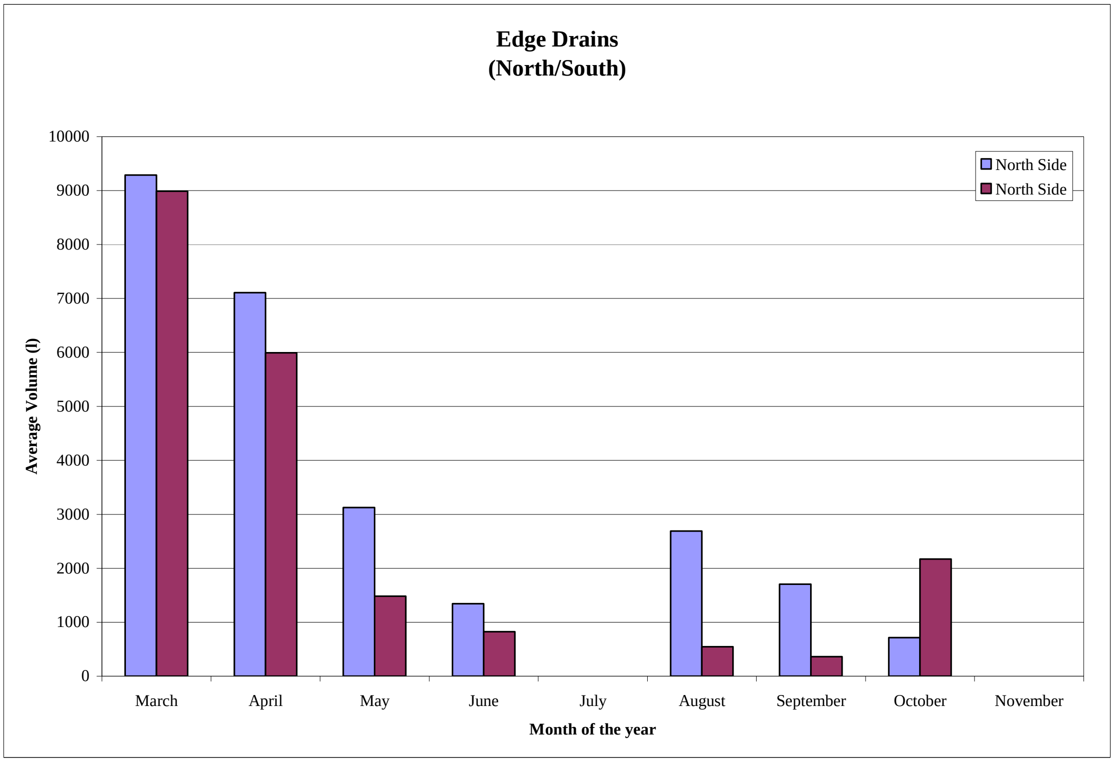

Figure 3.5 Average drained volumes from north/south edgedrains (l) - 2007

period, for the 2007 monitoring period the drains on both sides of the road had similar behavior for March, April, July and November, but in May, August and September the north side drains had higher drainage volumes than the south side drains. Both drains showed significant volumes drained for October in contrast to that observed for the 2006 monitoring period.

2006-2007

Figure 3.6 presents the monthly average volume of water drained during 2006-2007 from edgedrains located at either side of the road. Again, there is not a clear difference in behavior due to the locations of drains: during March, April, May, and August, volumes coming from the north drains exceed the ones coming from the south drains; however, during June, September, and October, the results, although close, show an opposite behavior.

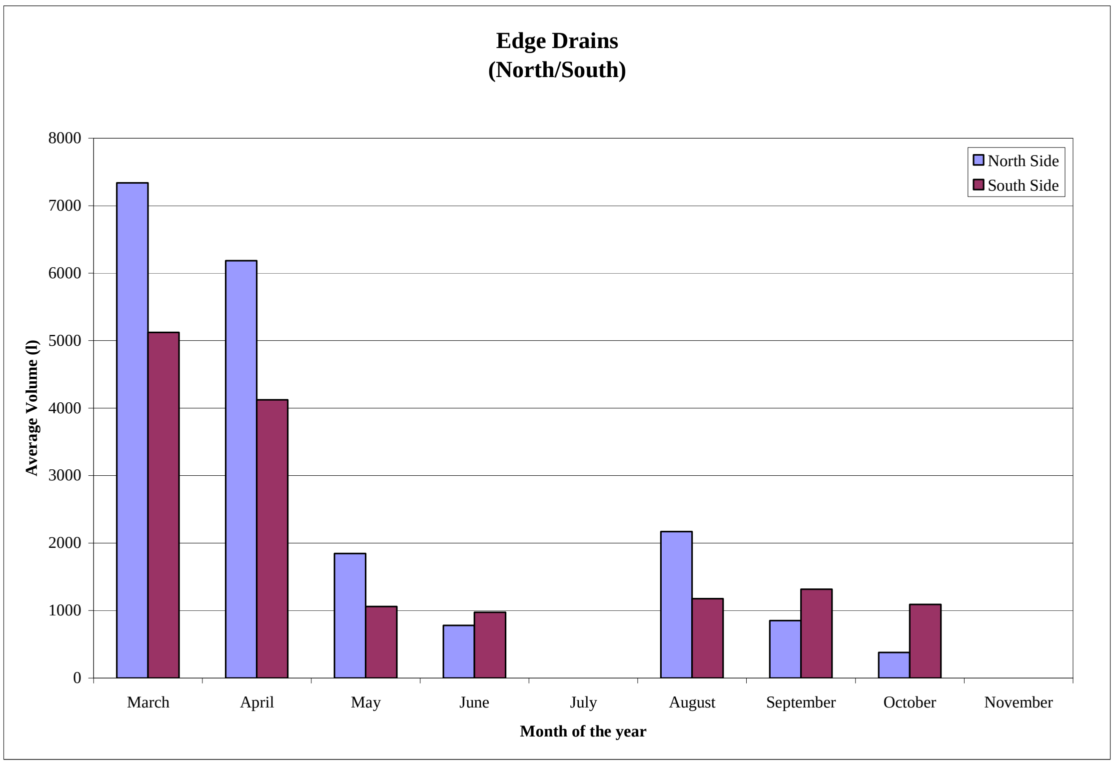

Figure 3.6 Average drained volumes from north/south edgedrains (l) – 2006-2007

3.4 Drainage Volume from High/Low Areas

Drains located at different elevations along the road were selected. All three treatments were included: seven (7) edgedrains, six (6) 2ft centerline drains, and five (5) 4ft centerline drains. Figure 3.7 shows the location of buckets according to high and low areas within the road length. Low areas are those that present concavities in the longitudinal road profile; high areas, on the contrary, are areas where convexities are present.

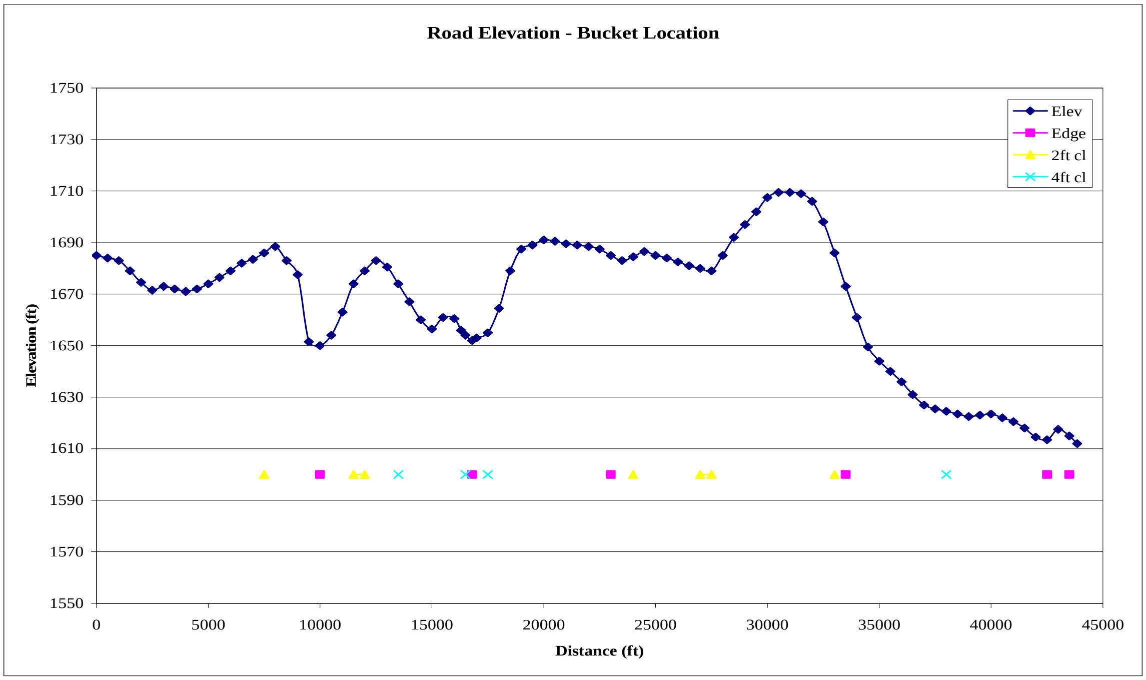

Figure 3.7 Location of buckets according to high and low areas

2006

Figure 3.8 presents the average drained volume from high/low areas during the 2006 year. As it can be observed, with the exception of August, when the drainage water coming from low areas is about three times that coming from high areas, the values are fairly close to each other in either elevation.

2007

Figure 3.9 presents the average drained volume from high/low areas during the 2007 year. The results obtained for this year show a higher value, in several months, for water coming from drains located in low areas. However, the months with the highest drainage volume (March and April) show high values for both locations.

2006-2007

Figure 3.10 presents the average drained volume from high/low areas during the 2006-2007 period of time. Again drainage water coming from drains located in low areas exceeds, in several months, the drainage coming from drains located in high areas. However, for the other months, the values are fairly close to each other in either elevation, especially during both March and April, when the highest outflow of the year occurs.

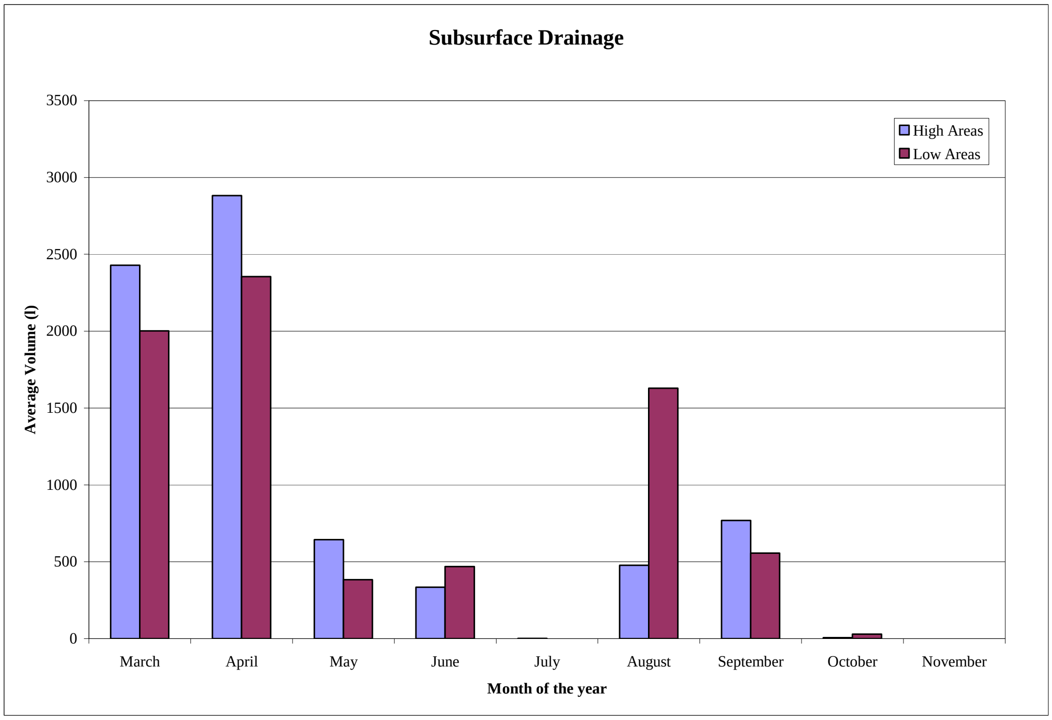

Figure 3.8 Average drained volumes from high/low areas (l) – 2006

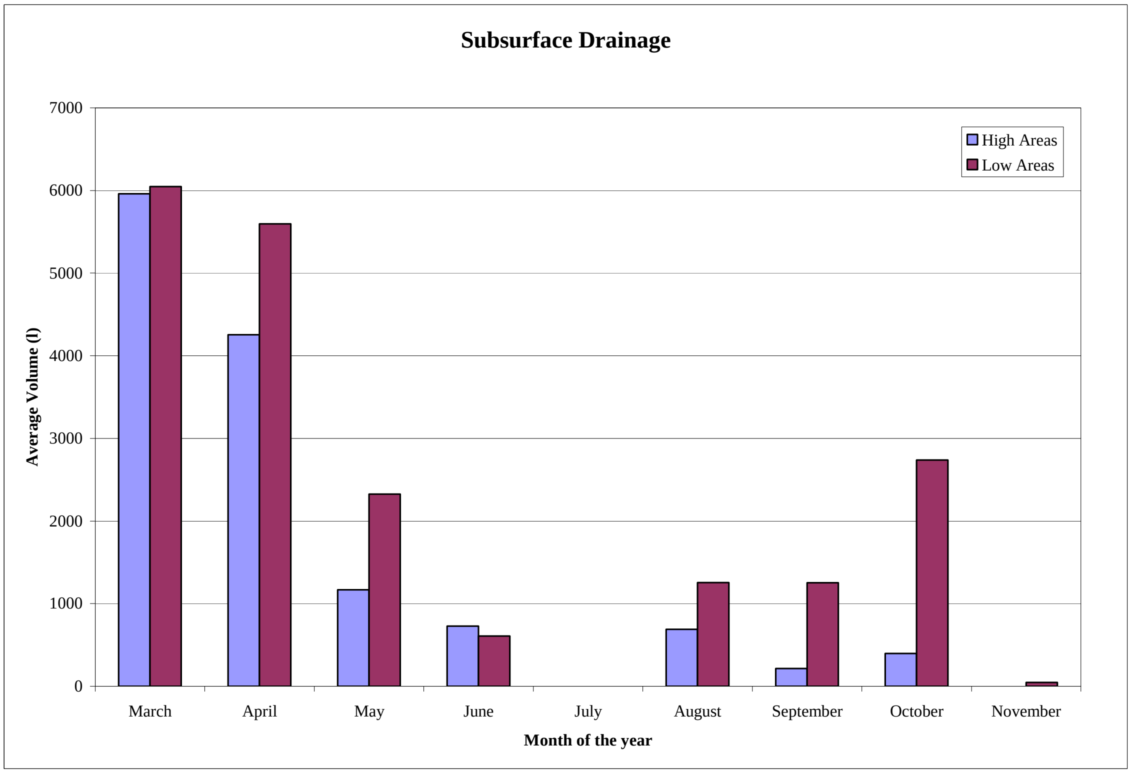

Figure 3.9 Average drained volumes from high/low areas (l) – 2007

3.5 Summary

The drainage volume from different configurations of subsurface drain tiles installed on a newly constructed CSAH 35 located near Worthington, Minnesota is summarized. Conventional edgedrains, and two centerline drain configurations were tested at the site. The edgedrains yielded by far the greatest volume of drainage water during the two-year period of monitoring, 2006-2007. The monitored drainage volume from the centerline drain configurations showed that the 2ft configuration yielded greater yields in 2006, while in 2007 neither of the drain configurations had a consistently higher drainage volume.

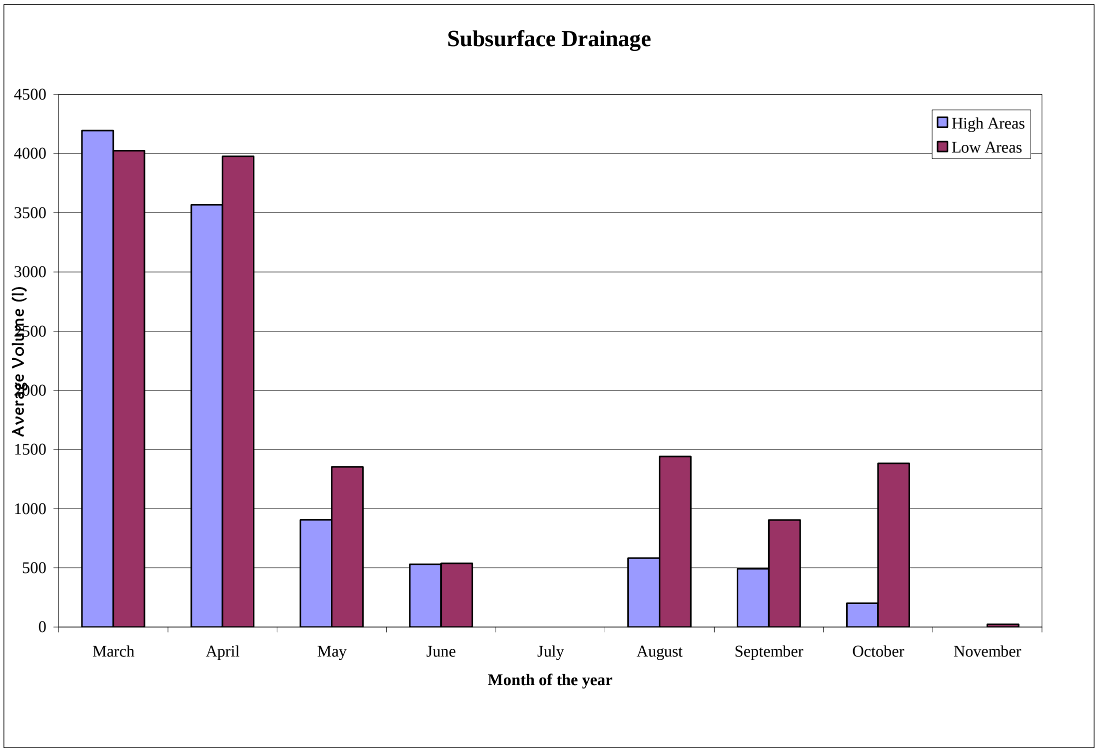

Figure 3.10 Average drained volume from high/low areas (l) – 2006/2007

The edgedrains have two drains for each treatment location while the centerline drain configurations have only one drain at each location. So there is some question about whether there is a difference between edgedrains on one side of the road or the other. CSAH runs in a east-west direction, so the edgedrains were compared as north versus south drains. Results show that the drains on the north side had higher average volumes drained for March and April monitoring periods, but that during the rest of the period the drained volumes were not appear to be considerably different. These measured differences in drainage volumes will be investigated using detailed topographic, soil and geologic data collected from GIS databases for the site, and rainfall data from local weather stations.

Comparisons were made between the drains to determine the effect of elevation of drain installation. The general conclusion from this comparison indicates that in general the drains at lower elevation have a higher drain volume during March and April monitoring periods, but that during the rest of the year the drainage volumes do not have a tendency to depend on elevation.

Chapter 4

Electrical Conductivity Measurements Using the EM38

4.1 Introduction

The EM38, an electromagnetic induction instrument, was employed to estimate relative moisture contents of the sub-grade material. EM38 measurements can be taken non-invasively through the pavement, and indicates differences in the electrical conductivity (E.C.) of the sub-grade. Considering other factors, such as soil texture and temperature, differences in E.C. will be used to estimate relative moisture content. Background information on the EM38, as well as detailed information on measurements taken, can be found in Appendix C.

The monitored EM38 measurements, for selected dates during the two-year period (2006, 2007) of data collection, are presented. It was considered both the three drainage treatments devised (edgedrains, 2ft centerline drains, and 4 ft centerline drains) and five locations for each drain site (north of road, north shoulder, center, south shoulder, and south of road). For all of the locations the output from the EM38 instrument was acquired for both vertical and horizontal orientations.

Figure 4.1 shows the measurement scheme, where the location of the drain outlet is clearly marked on the road at each drainage outlet. Measurements were made with the EM38 at the locations indicated by the solid circles. As indicated, measurements were taken at several locations along transects running along the road. A photograph showing the EM38 in use at one of the CSAH 35 site locations is presented in Figure 4.2.

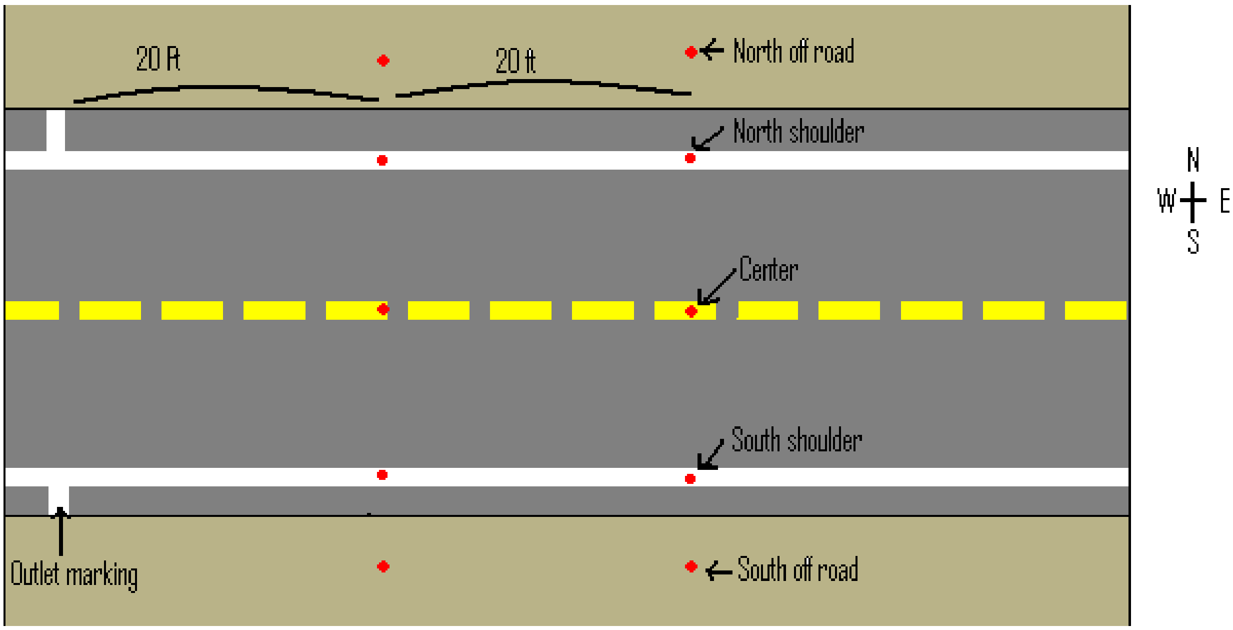

Figure 4.1 Measurement scheme for the EM38 induction instrument

Figure 4.2 Using the EM38 instrument at the CSAH 35 field site

4.2 EM38 Measurements by Drainage Treatment and Measurement Location

July 10, 2006

Figure 4.3 shows the EM38 measurements from the three drainage treatments and the five measurement locations devised, while Figure 4.4 shows the EM38 measurements from the drainage treatments only, regardless of measurement locations. Results are presented for both the horizontal and vertical orientation of the EM38 instrument.

Results show that, for all cases, measurements with the vertical orientation are higher than measurements with the horizontal orientation. Edgedrain and 4ft centerline drain measurements are higher in the southern locations, while 2ft centerline drain measurements are higher for the center and northern locations. When locations are combined, edgedrain measurements are higher than both 4ft and 2ft centerline drain measurements, which are similar.

July 11, 2006

Figure 4.5 shows the EM38 measurements from the three drainage treatments and the five measurement locations devised, while Figure 4.6 show the EM38 measurements from the drainage treatments only, regardless of measurement locations. Results are presented for both the horizontal and vertical orientation of the EM38 instrument.

Similar to the measurements from the previous day, results show that, for all cases, vertical measurements are higher than horizontal ones; this day, however, measurements are, in general, a little higher. Edgedrain and 4ft centerline measurements are higher in the southern locations, while 2ft centerline drain measurements are higher for the center and northern locations.

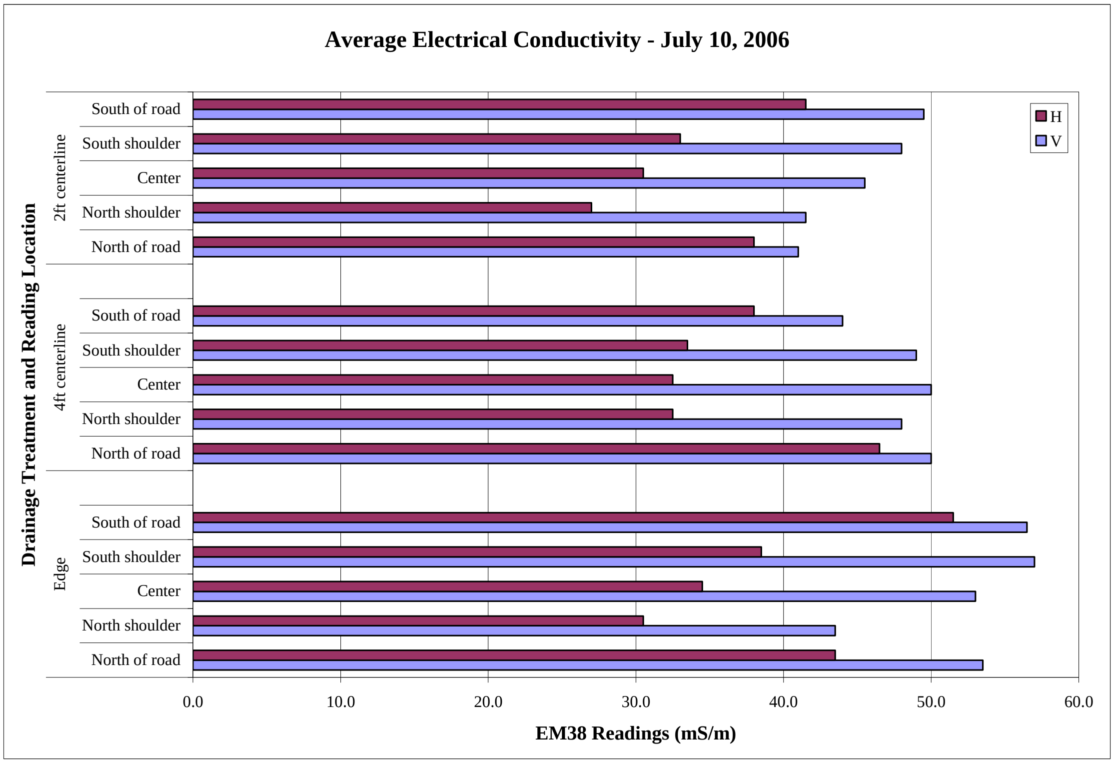

Figure 4.3 Average E.C. (mS/m) by treatment and location – July 10, 2006

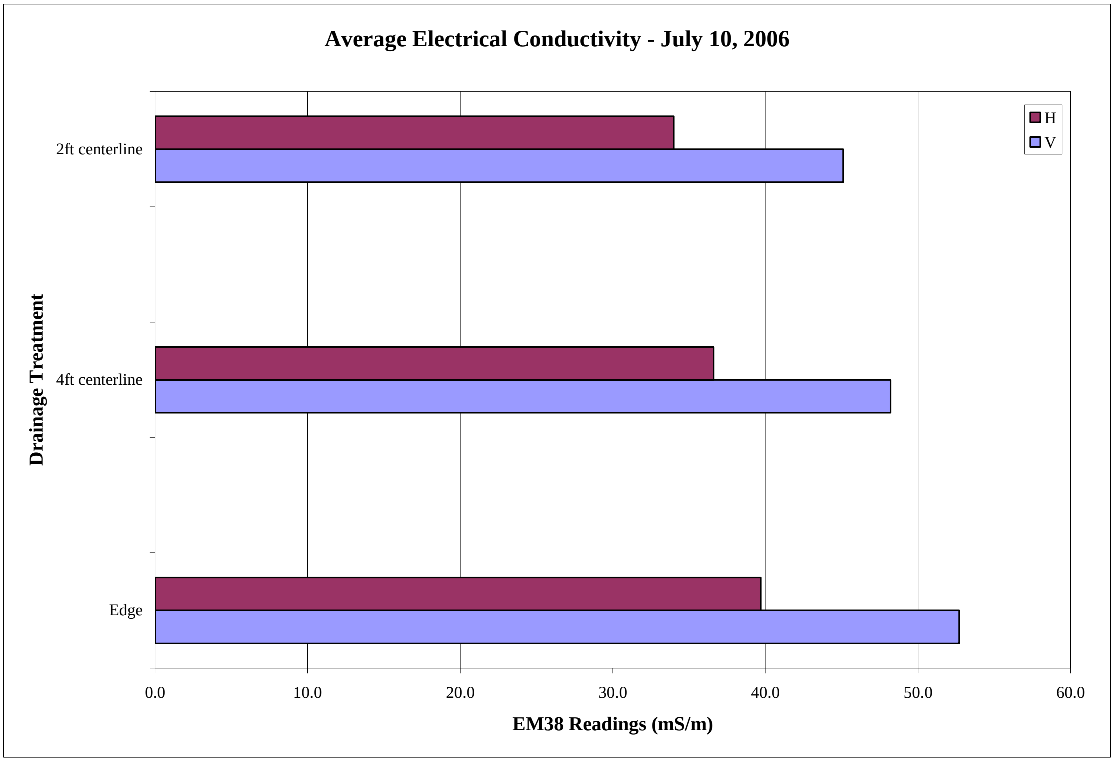

Figure 4.4 Average E.C. (mS/m) by treatment only – July 10, 2006

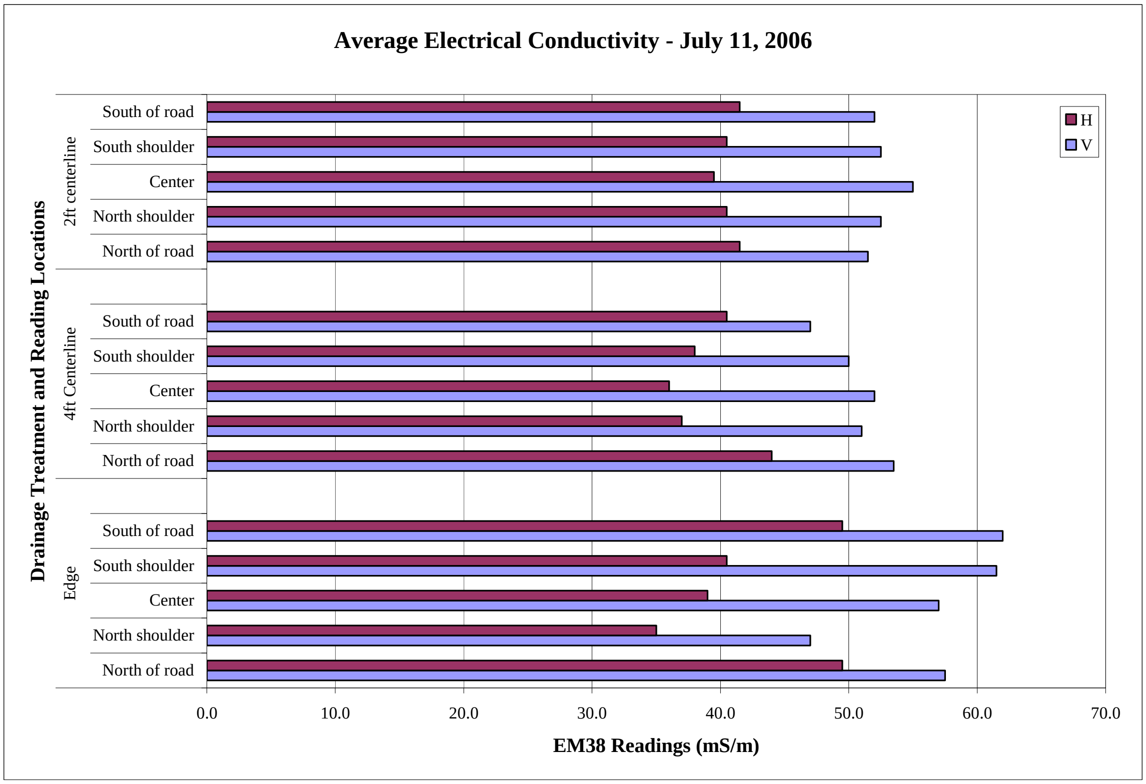

Figure 4.5 Average E.C. (mS/m) by treatment and location – July 11, 2006

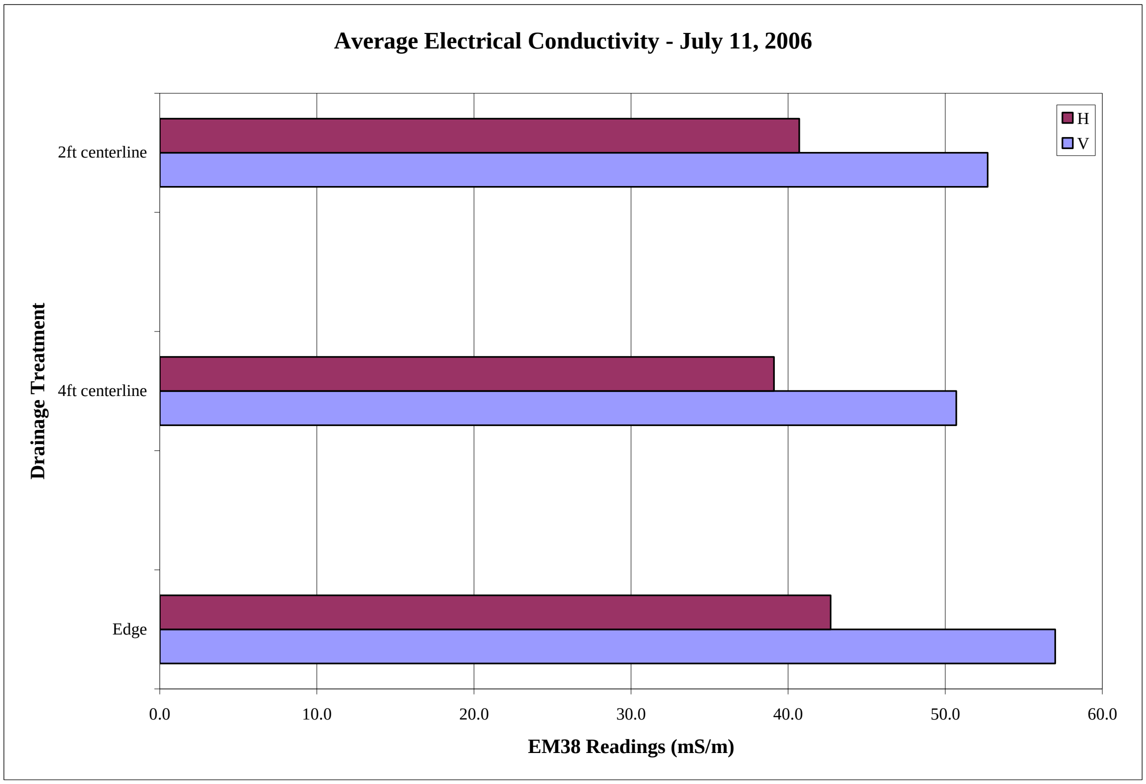

Figure 4.6 Average E.C. (mS/m) by treatment only – July 11, 2006

When locations are combined, edgedrain measurements are higher than both 4ft and 2ft centerline drain measurements; 2ft centerline drain measurements are higher than those from 4ft centerline drain.

July 10-11, 2006

Figure 4.7 shows the differences in EM38 measurements from the three drainage treatments and the five measurement locations devised in two consecutive days. Figure 4.8 shows the difference in EM38 measurements from the drainage treatments only, regardless of measurement locations, for the same period of time. Results are presented for both the horizontal and vertical orientation of the EM38 instrument.

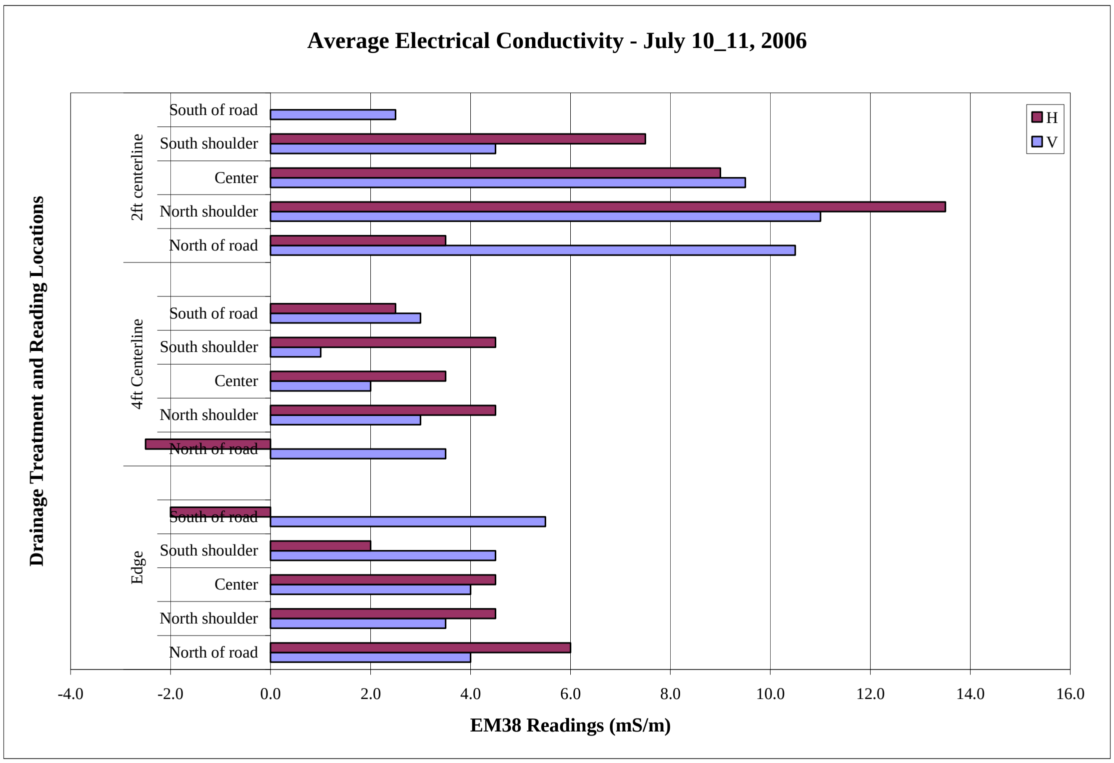

Figure 4.7 Differences in average E.C. (mS/m) by treatment and location – July 10-11, 2006

Results show that, for most drainage treatments and measurement locations, measurements from the second day are higher than those from the first day. For most cases too, and contrarily to what happen during the first day, horizontal measurements from the second day are higher than the horizontal ones.

When locations are combined, there are no differences in measurements from the 4ft centerline drains. Measurement from the 2ft centerline drains are higher than those from the edgedrains and, for both drainage treatments, the vertical measurements are higher than horizontal ones. Measurement from the 2ft centerline drains are higher than those from the edgedrains and, for both drainage treatments, the vertical measurements are higher than horizontal ones.

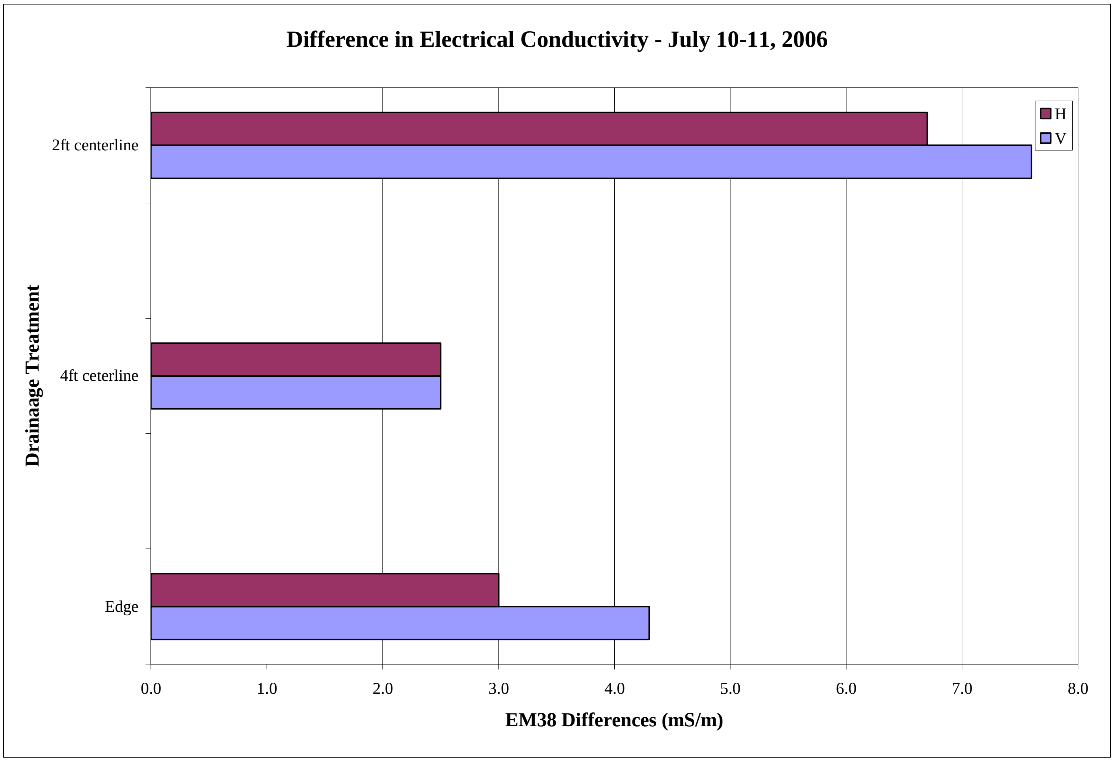

Figure 4.8 Differences in average E.C. (mS/m) by treatment only – July 10-11, 2006

August 8, 2006

Figure 4.9 shows the EM38 measurements from the three drainage treatments and the five measurement locations devised, while Figure 4.10 shows the EM38 measurements from the drainage treatments only, regardless of measurement locations. Results are presented for both the horizontal and vertical orientation of the EM38 instrument.

Results show that, for all cases, the vertical measurements are higher than the horizontal ones. This day, however, the behavior of the measurement locations are very similar for the three drainage treatments, showing higher values in locations away from the center of the road. When locations are combined, measurements from both edgedrain and 2ft centerline drains are very similar, and just slightly higher than those from 4ft centerline drains.

April 21, 2007

Figure 4.11 shows the EM38 measurements from the three drainage treatments and the five measurement locations devised, while Figure 4.12 shows the EM38 measurements from the drainage treatments only, regardless of measurement locations. Results are presented for both the horizontal and vertical orientation of the EM38 instrument.

Results show that, for all cases, the vertical measurements are higher than the horizontal ones. The measurement locations are similar for the three drainage treatments, showing higher values in locations away from the center of the road. When locations are combined, measurements from

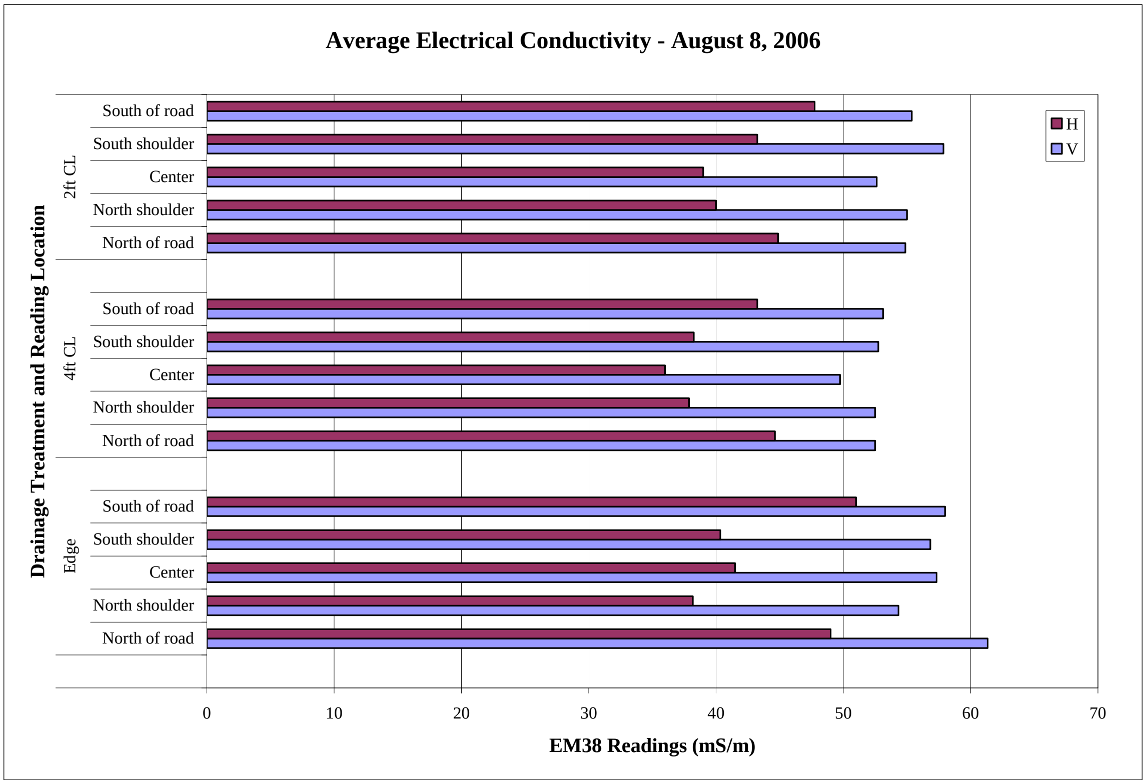

Figure 4.9 Average E.C. (mS/m) by treatment and location – August 8, 2006

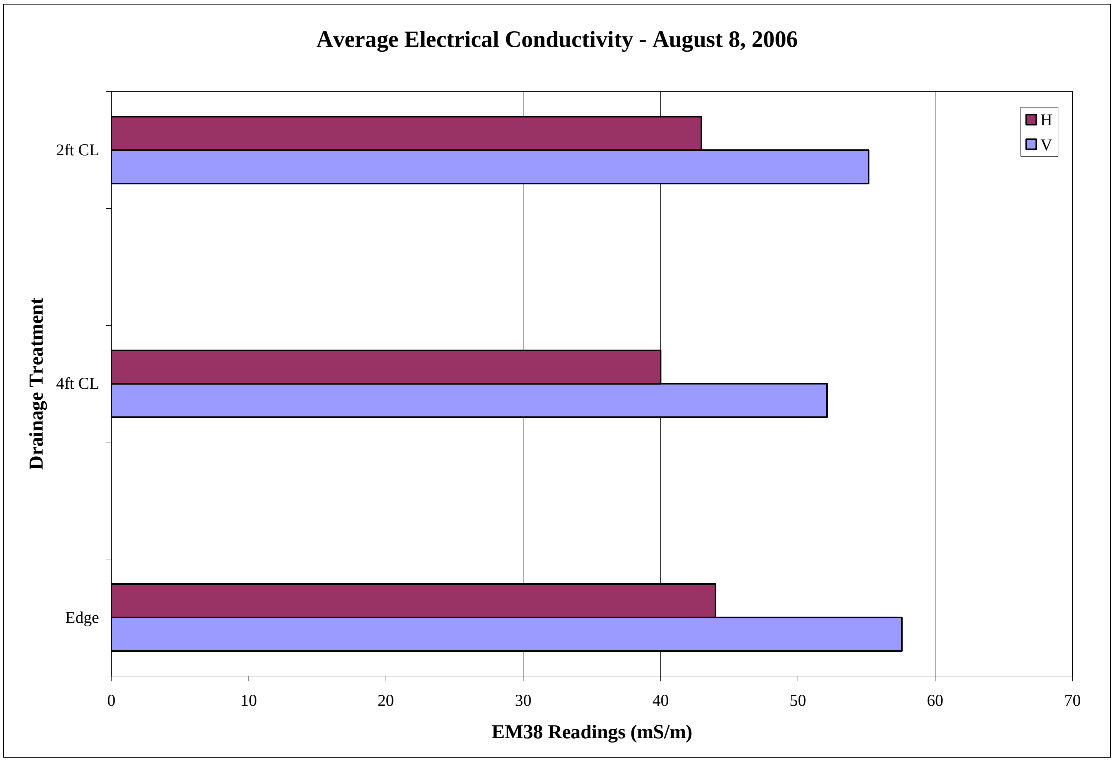

Figure 4.10 Average E.C. (mS/m) by location only – August 8, 2006

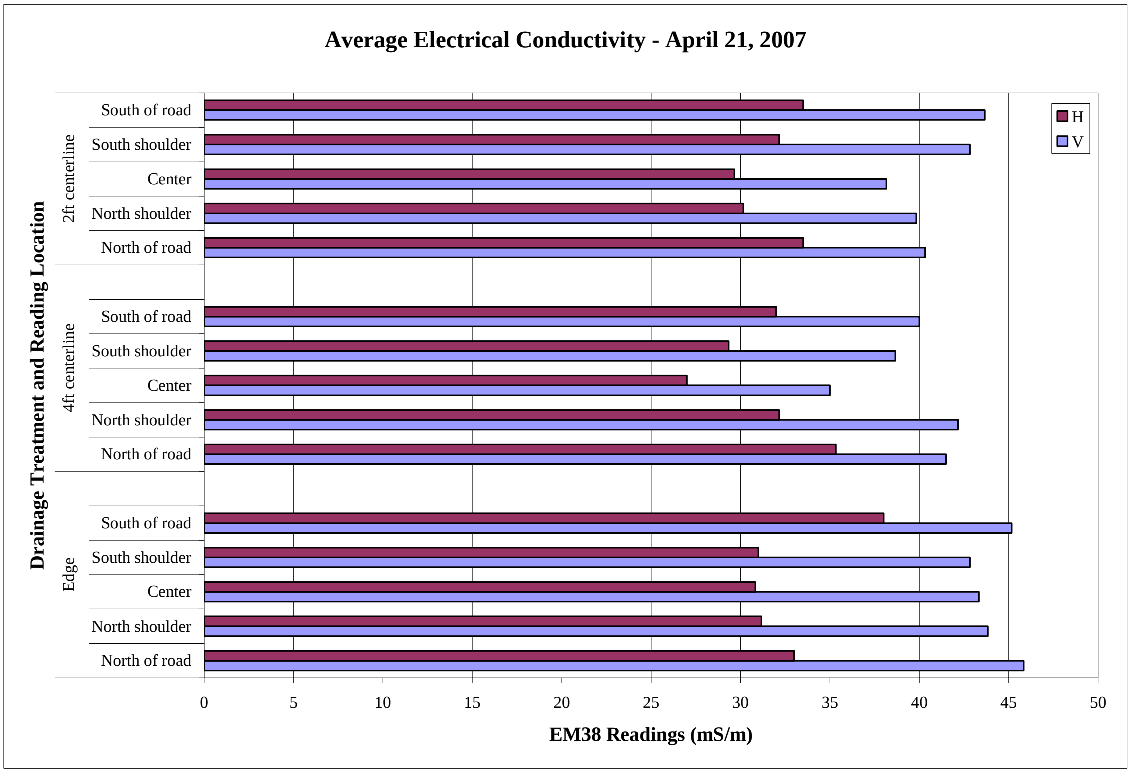

Figure 4.11 Average E.C. (mS/m) by treatment and location – April 21, 2007

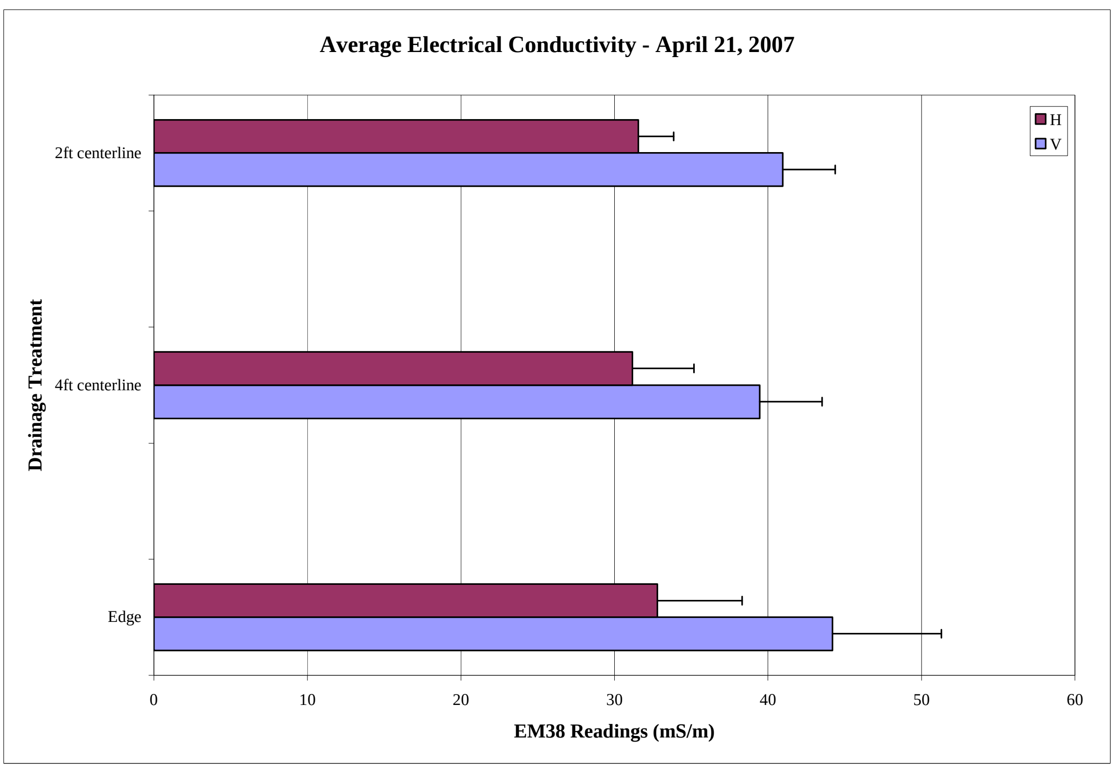

Figure 4.12 Average E.C. (mS/m) by treatment only – April 21, 2007

the edgedrain locations and just a little higher than those from both 4ft and 2ft centerline drains, which are very similar themselves.

May 14, 2007

Figure 4.13 shows the EM38 measurements from the three drainage treatments and the five measurement locations devised, while Figure 4.14 shows the EM38 measurements from the drainage treatments only, regardless of measurement locations. Results are presented for both the horizontal and vertical orientation of the EM38 instrument.

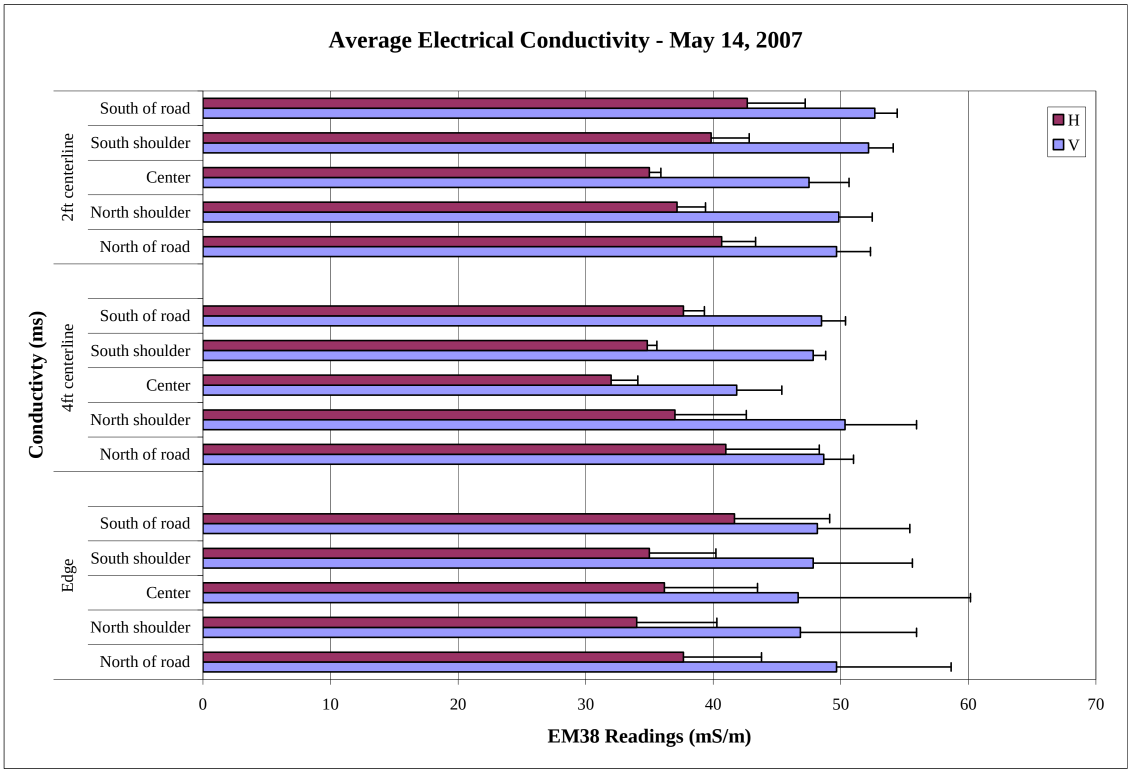

Figure 4.13 Average E.C. (mS/m) by treatment and location – May 14, 2007

Results show that, for all cases, the vertical measurements were higher than the horizontal ones. This was expected to be the case where the topmost layer is asphalt which behaves as a medium with essentially zero electrical conductivity. The measurement locations were similar for the three drainage treatments, showing mostly higher values in locations away from the center of the road. When locations are combined, measurements from the 2ft centerline drain locations were slightly higher than those from both the 4ft centerline and edgedrains, which were very similar themselves.

4.3 Summary

The electrical conductivity from different configurations of subsurface drain tiles installed on a newly constructed CSAH 35 located near Worthington, Minnesota is summarized. Measurements were taken on selected days when visiting to download data from the drainage

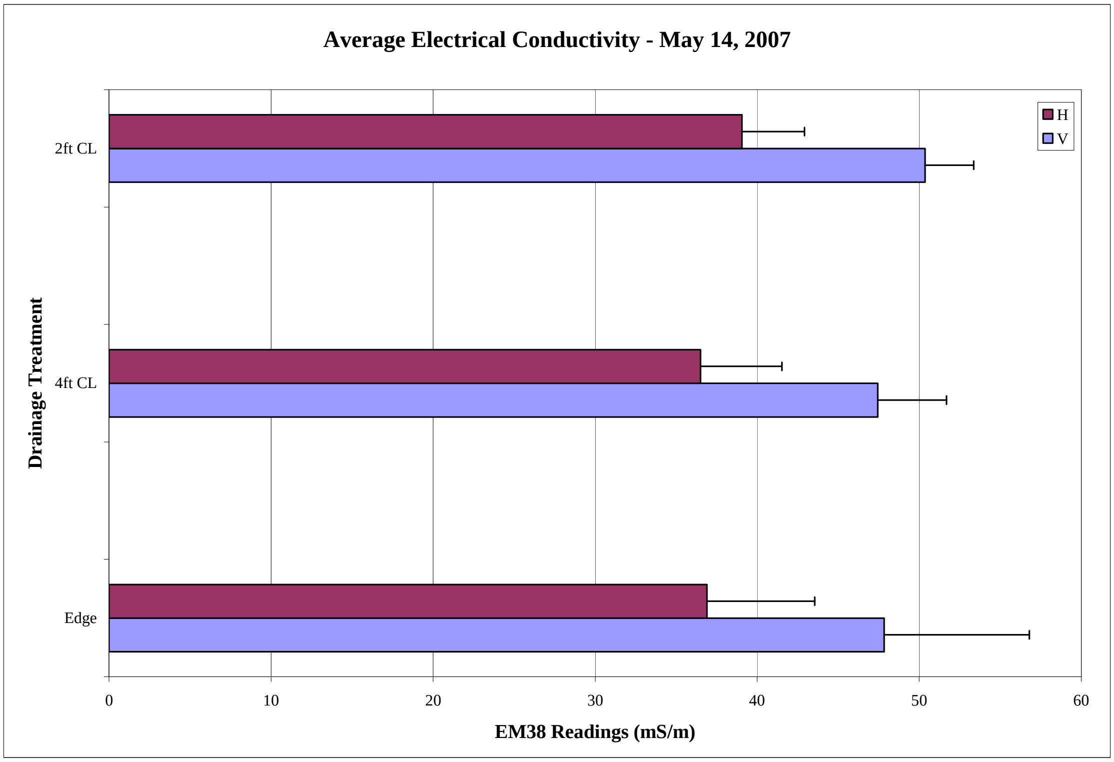

Figure 4.14 Average E.C. (mS/m) by treatment only – May 14, 2007

data logger systems, during the 2006-2007 period of time. The measurements were performed using an EM38 electromagnetic instrument for both conventional edgedrain and two centerline drain configurations. For all cases (dates, drainage treatment, and measurement locations), electrical conductivity measured with the vertical orientation of the EM38 were higher than those measured for the horizontal orientation of the instrument.

Electrical conductivity values for edgedrains were higher than those for the centerline drains for measurements taken in selected days of July and August of 2006, as well as April of 2007; values for both 2ft and 4ft centerline drains were very close one to another. For the measurements performed on May 2007, however, values of electrical conductivity were a little higher for the 2ft centerline drainage treatment, while values for both the edgedrains and the 4ft centerline drains were very similar.

When examining measurement locations for the selected days, values for measurements located away from the center of the road (either north of the road, or south of the road, or both) were, most of the time, higher than those obtained at the center of the road. The exceptions were measurements taken for the 2ft centerline on July 10, 2006, and both the 2ft and 4ft centerline drains on July 11, 2006, where the higher measurements were obtained right in the center of the road.

The edgedrains have two drains for each treatment location while the centerline drain configurations have only one drain at each location. So there is some question about whether there is a difference between edgedrains on one side of the road or the other.

Chapter 5

Statistical Analysis of Drainage Volume and Electrical Conductivity Measurements

5.1 Introduction

The statistical analysis presented in this chapter will be used to: 1) Compare the effectiveness of drainage of base and sub-grade materials where drain configuration is either the conventional edge-drain or centerline drain; 2) Compare the effectiveness of drainage of base and sub-grade materials where drain configuration is either the location of drains along the entire roadway or only in the low points; 3) Assess the capability of the EM38 electromagnetic measurement device to estimate relative moisture content of base and sub-grade material for both unpaved and paved surfaces.

Due to the different comparisons to be performed, most of the sections of this chapter begin with a brief introduction describing the data analysis tool to be used and stating the hypothesis to be tested. Section 5.2 presents the statistical analysis of drained volume by drainage treatment, using the *One-Way ANOVA test*. Section 5.3 shows the statistical analysis of drained volume by edgedrain orientation, using the *t-test* and the *F-test*. Section 5.4 presents the statistical analysis for drained volume by drain elevation, using the *t-test* and the *F-test*. Section 5.5 deals with the statistical analysis of electrical conductivity by drainage treatment and EM38 orientation, using the *Two-Way ANOVA with replication*. Section 5.6 presents the statistical analysis of electrical conductivity by surface type and EM38 orientation, using the *Two-Way ANOVA with replication*.

The statistical tests used are fully described in Bluman (2001) and Montgomery and Runger (2003). Details of the data collected can be found in Appendix C.

5.2 Statistical Analysis of Drained Volume by Drainage Treatment

5.2.1 Data analysis tool: one-way analysis of variance

For this case, the analysis of variance (*ANOVA*) is required because more than two treatments, or means, are being compared: edgedrains, 4-ft centerline drain, and 2-ft centerline drain. The one-way option of the analysis of variance (*One-way ANOVA*) test is used because there is only one independent variable to be considered: drainage treatment. In our case, the analysis of variance is used to test the hypothesis that the means of the three drainage treatment are equal.

H_0: $\mu_1 = \mu_2 = \mu_3$
H_1: At least one mean is different from the others.

In our case, the null hypothesis states that the mean values of drained volume collected for edgedrains, 4-ft centerline drain, and 2-ft centerline drain are equals; on the contrary, the alternative hypothesis states that at least one of those mean values is different.

If the null hypothesis is rejected, then an additional test is required to determine which treatment is causing the difference. The *Tukey test* is one of the tests available for this purpose. In our case, the *Tukey test* will include three comparisons: edgedrain vs. 4-ft centerline drain, edgedrain vs. 2-ft centerline drain, and 4-ft vs. 2-ft centerline drain.

5.2.2 Data analysis results

2006

Table 5.1 presents the results of the *one-way ANOVA test* performed to compare the three drainage treatments. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Tukey test* is performed (Table 5.2), and the results obtained (*q1 & q2 > q critical*) indicate that there are significant differences between the edgedrain treatment and both the 4-ft and 2-ft centerline drain treatments. There is no significant difference between the two centerline drain treatments.

Table 5.1 *One-way ANOVA test* for drainage treatment - 2006

SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Edgedrains	9	22496.54	2499.62	8096322.92		
4-ft Centerline Drain	9	28.38	3.15	22.02		
2-ft Centerline Drain	9	666.83	74.09	20328.78		
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Between Groups	36361558.18	2	18180779.09	6.72	0.00	3.40
Within Groups	64933389.68	24	2705557.90			
Total	101294947.86	26				

Table 5.2 *Tukey test* for drainage treatment - 2006

Comparison	***Average***	***MS W.G.***	***n***	***q***	***q critical***
Edge / 4-ft Centerline	2499.62	2705557.90	9	4.55	3.53
Edge / 2-ft Centerline	3.15			4.42	
4-ft / 2-ft Centerline	74.09			-.13	

2007

Table 5.3 presents the results of the *one-way ANOVA test* performed to compare the three drainage treatments. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Tukey test* is performed (Table 5.4), and the results obtained (*q1 & q2 > q critical*) indicate that there are significant differences between the edgedrain treatment and both the 4-ft and 2-ft centerline drain treatments. There is no significant difference between the two centerline drain treatments.

Table 5.3 *One-way ANOVA test* for drainage treatment - 2007

SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Edgedrains	9	44154.26	4906.03	35707221.80		
4-ft Centerline Drain	9	5431.88	603.54	615990.54		
2-ft Centerline Drain	9	2559.00	284.33	262102.26		
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Between Groups	119920066.92	2	59960033.46	4.92	0.02	3.40
Within Groups	292682516.80	24	12195104.87			
Total	412602583.72	26				

Table 5.4 *Tukey test* for drainage treatment - 2007

Comparison	***Average***	***MS W.G.***	***n***	***q***	***q critical***
Edge / 4-ft Centerline	4906.03	12195104.87	9	3.70	3.53
Edge / 2-ft Centerline	603.54			3.97	
4-ft / 2-ft Centerline	284.33			.27	

2006-07

Table 5.5 presents the results of the *one-way ANOVA test* performed to compare the three drainage treatments. According to the results obtained ($F > F$ *critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the Tukey test is performed (Table 5.6), and the results obtained ($q1$ & $q2 > q$ *critical*) indicate that there are significant differences between the edgedrain treatment and both the 4-ft and 2-ft centerline drain treatments. There is no significant difference between the two centerline drain treatments.

5.3 Statistical Analysis of Drained Volume by Edgedrain Orientation

5.3.1 Data analysis tool: *t-test*

For this comparison, the *t-test*, also know as *Student-test*, is required, which compares means for two groups of cases, or treatments In our case, the *t-test* is used to test the hypothesis that the means of the two drain orientations are equal.

H_0: $\mu_1 = \mu_2$
H_1: The two means are different.

Table 5.5 *One-Way ANOVA test* for drainage treatment – 2006-07

SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Edgedrains	9	33325.39	3702.82	18300222.93		
4-ft Centerline Drain	9	2730.14	303.35	155003.10		
2-ft Centerline Drain	9	1612.92	179.21	81454.65		
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Between Groups	71962898.39	2	35981449.20	5.82	0.01	3.40
Within Groups	148293445.43	24	6178893.56			
Total	220256343.82	26				

Table 5.6 *Tukey test* for drainage treatment – 2006-07

Comparison	***Average***	***MS W.G.***	***n***	***q***	***q critical***
Edge / 4-ft Centerline	3702.82	6178893.56	9	4.10	3.53
Edge / 2-ft Centerline	303.35			4.25	
4-ft / 2-ft Centerline	179.21			.145	

The null hypothesis states that the mean values of drained volume collected from drains located on the north side of the road are equal to those collected from drains located on the south side of the road; on the contrary, the alternative hypothesis states that the mean values are different.

Now, the *t-test* can be applied to perform comparisons when the variances of the population are either equal or unequal. In view of this, an *F-test* is required, before the *t-test*, to determine whether the variances are equal or not.

H_0: $\sigma_1 = \sigma_2$
H_1: The two variances are different.

In this case, the null hypothesis states that the variance of the volume collected by the drains located in the north side of the road is equal to the variance of the volume collected from drains located on the south side of the road; the alternative hypothesis, on the contrary, states that the two variances are different

5.3.2 Data analysis results

2006

Table 5.7 presents the results of the *F-test* performed to compare the variances of the two treatments (north/south side). According to the results obtained (*F > F critical, two-tails*), the null hypothesis is rejected, which means that the variances are different. In view of this, the *t-test, unequal variance* test is performed (Table 5.8), and the results obtained (*t stat < t critical, two-tails)* indicate that there are not significant differences between drains located at either side of the road.

Table 5.7 *F-test* for north/south drains - 2006

F-TEST	**NORTH**	**SOUTH**
Mean	1458.77	1040.85
Variance	5080958.64	876592.34
Observations	9	9
Df	8	8
F	5.80	
P (F<=f) right-tail	0.01	
F Critical right-tail	3.44	
P (f<=F) left-tail	0.99	
F Critical left-tail	0.29	
P two-tail	0.02	
F Critical two-tail	0.23	4.43

Table 5.8 *t-test* (unequal variance) for north/south edgedrains - 2006

	NORTH	**SOUTH**
Mean	1458.77	1040.85
Variance	5080958.64	876592.34
Observations	9	9
Hypothesized Mean Difference	0	
Observed Mean Difference	417.91	
Df	10.68	
t Stat	0.51	
P (T<=t) one-tail	0.31	
t Critical one-tail	1.80	
P (T<=t) two-tail	0.62	
t Critical two-tail	2.21	

2007

Table 5.9 presents the results of the *F-test* performed to compare the variances of the two treatments (north/south side). According to the results obtained (*F critical, left, two-tails < F < F critical, right, two-tails*), the null hypothesis cannot be rejected, which means that the variances are equal. In view of this, the *t-test, equal variance* test is performed (Table 5.10), and the results obtained (*t stat < t critical, two-tails)* indicate that there are not significant differences between drains located at either side of the road.

2006-07

Table 5.11 presents the results of the *F-test* performed to compare the variances of the two treatments (north/south side). According to the results obtained (*F critical, left, two-tails < F < F critical, right, two-tails*) the null hypothesis cannot be rejected, which means that the variances are equal. In view of this, the *t-test, equal variance* test is performed (Table 5.12), and the results obtained (*t stat < t critical, two-tails)* indicate that there are not significant differences between drains located at either side of the road.

Table 5.9 *F-test* for north/south drains - 2007

F-TEST	NORTH	SOUTH
Mean	2886.13	2262.58
Variance	10506854.07	9838001.99
Observations	9	9
Df	8	8
F	1.07	
P (F<=f) right-tail	0.46	
F Critical right-tail	3.44	
P (f<=F) left-tail	0.54	
F Critical left-tail	0.29	
P two-tail	0.93	
F Critical two-tail	0.23	4.43

Table 5.10 *t-test* (equal variance) for north/south edgedrains - 2007

	NORTH	SOUTH
Mean	2886.13	2262.58
Variance	10506854.07	9838001.99
Observations	9	9
Pooled Variance	10172428.03	
Hypothesized Mean Difference	0	
Observed Mean Difference	623.56	
Df	16	
t Stat	0.41	
P (T<=t) one-tail	0.34	
t Critical one-tail	1.75	
P (T<=t) two-tail	0.68	
t Critical two-tail	2.12	

Table 5.11 *F-test* for north/south edgedrains – 2006-07

F-TEST	NORTH	SOUTH
Mean	2172.44	1651.71
Variance	7401069.27	3135149.20
Observations	9	9
Df	8	8
F	2.36	
P (F<=f) right-tail	0.12	
F Critical right-tail	3.44	
P (f<=F) left-tail	0.88	
F Critical left-tail	0.29	
P two-tail	0.25	
F Critical two-tail	0.23	4.43

Table 5.12 *t-test* (equal variance) for north/south edgedrains - 2006-07

	NORTH	SOUTH
Mean	2172.44	1651.71
Variance	7401069.27	3135149.20
Observations	9	9
Pooled Variance	5268109.24	
Hypothesized Mean Difference	0	
Observed Mean Difference	520.72	
Df	16	
t Stat	0.48	
P (T<=t) one-tail	0.32	
t Critical one-tail	1.75	
P (T<=t) two-tail	0.64	
t Critical two-tail	2.12	

5.4 Statistical Analysis of Drained Volume by Drain Elevation

5.4.1 Data analysis tool: *t-test*

For this comparison, the approach to follow is similar to the one used when comparing the effects of drain orientation: the *t-test* is required, and an *F-test* is also required before the *t-test*, to determine whether the variances are equal or not.

5.4.2 Data analysis results

2006

Table 5.13 presents the results of the *F-test* performed to compare the variances of the treatments (high/low areas). According to the results obtained (*F critical, left, two-tails < F < F critical, right, two-tails*), the null hypothesis cannot be rejected, which means that the variances are equal. In view of this, a *t-test, equal variance* test is performed (Table 5.14), and the results obtained (*t stat < t critical, two-tails)* indicate that there are not significant differences between drains located at either high or low areas.

2007

Table 5.15 presents the results of the *F-test* performed to compare the variances of the treatments (high/low areas). According to the results obtained (*F critical, left, two-tails < F < F critical, right, two-tails*), the null hypothesis cannot be rejected, which means that the variances are equal. In view of this, a *t-test, equal variance* test is performed (Table 5.16), and the results obtained (*t stat < t critical, two-tails)* indicate that there are not significant differences between drains located at either high or low areas.

Table 5.13 *F-test* for high/low drained areas - 2006

F-TEST	HIGH	LOW
Mean	838.14	824.77
Variance	1153761.43	845154.60
Observations	9	9
Df	8	8
F	1.37	
P (F<=f) right-tail	0.34	
F Critical right-tail	3.44	
P (f<=F) left-tail	0.66	
F Critical left-tail	0.29	
P two-tail	0.67	
F Critical two-tail	0.23	4.43

Table 5.14 *t-test* (equal variance) for high/low drained areas - 2006

	HIGH	LOW
Mean	838.14	824.77
Variance	1153761.43	845154.60
Observations	9	9
Hypothesized Mean Difference	0	
Observed Mean Difference	13.37	
Df	15.63	
t Stat	0.03	
P (T<=t) one-tail	0.49	
t Critical one-tail	1.75	
P (T<=t) two-tail	0.98	
t Critical two-tail	2.12	

Table 5.15 *F-test* for high/low drained areas - 2007

F-TEST	HIGH	LOW
Mean	1848.78	2207.46
Variance	4646225.76	5056233.69
Observations	18	9
Df	17	8
F	0.92	
P (F<=f) right-tail	0.58	
F Critical right-tail	3.19	
P (f<=F) left-tail	0.42	
F Critical left-tail	0.39	
P two-tail	0.83	
F Critical two-tail	0.33	4.05

Table 5.16 *t-test* (equal variance) for high/low drained areas - 2007

	HIGH	LOW
Mean	1490.11	2207.46
Variance	4527535.92	5056233.69
Observations	9	9
Pooled Variance	4791884.80	
Hypothesized Mean Difference	0	
Observed Mean Difference	-717.35	
Df	16	
t Stat	-0.70	
P (T<=t) one-tail	0.25	
t Critical one-tail	1.75	
P (T<=t) two-tail	0.50	
t Critical two-tail	2.12	

2006-07

Table 5.17 presents the results of the *F-test* performed to compare the variances of the treatments (high/low areas). According to the results obtained (*F critical, left, two-tails < F < F critical, right, two-tails*), the null hypothesis cannot be rejected, which means that the variances are equal. In view of this, a *t-test, equal variance* test is performed (Table 5.18), and the results obtained (*t stat < t critical, two-tails)* indicate that there are not significant differences between drains located at either high or low areas.

Table 5.17 *F-test* for high/low drained areas 2006-07

F-TEST	HIGH	LOW
Mean	1164.13	1702.73
Variance	2482394.37	2248640.13
Observations	9	8
Df	8	7
F	1.10	
P (F<=f) right-tail	0.45	
F Critical right-tail	3.73	
P (f<=F) left-tail	0.55	
F Critical left-tail	0.29	
P two-tail	0.91	
F Critical two-tail	0.22	4.90

5.5 Statistical Analysis of E. C. by Drainage Treatment and EM38 Orientation

5.5.1 Data analysis tool: two-way analysis of variance

For this comparison, the *two-way analysis of variance (ANOVA) test* is required, because two independent variables are involved: drainage treatment (edgedrains, 4-ft centerline drain, and 2-ft centerline drain) and EM38 orientation (vertical and horizontal). The *two-way ANOVA test* will allow us to test the effects of the two independent variables in one dependent variable, which is

Table 5.18 *t-test* (equal variance) for high/low drained areas 2006-07

	HIGH	LOW
Mean	1164.13	1516.12
Variance	2482394.37	2280976.27
Observations	9	9
Pooled Variance	2381685.32	
Hypothesized Mean Difference	0	
Observed Mean Difference	-351.99	
Df	16	
t Stat	-0.48	
P (T<=t) one-tail	0.32	
t Critical one-tail	1.75	
P (T<=t) two-tail	0.64	
t Critical two-tail	2.12	

the electrical conductivity. Additionally, the interaction effect of the two variables can also be tested.

The *two-way ANOVA test* includes several null hypotheses, one for each independent variable, and one for the interaction between them.

1. The hypotheses for the drainage treatment are as follows:
   H_0: There is no difference between the means of the electrical conductivity measurements and the drainage treatment.
   H_1: There is a difference between the means of the electrical conductivity measurements and the drainage treatment.

2. The hypotheses for the EM 38 orientation are as follows:
   H_0: There is no difference between the means of the electrical conductivity measurements and the EM38 orientation.
   H_1: There is a difference between the means of the electrical conductivity measurements and the EM38 orientation.

3. The hypotheses for the interaction are as follow:
   H_0: There is no interaction between the drainage treatment and the EM38 orientation.
   H_1: There is an interaction between the drainage treatment and the EM38 orientation.

5.5.2 Data analysis results

July 10, 2006

Table 5.19 presents the results of the *two-way ANOVA test* performed to compare the treatments. According to the results obtained: 1) there is difference between the means of the electrical conductivity measurements and the drainage treatment ($F > F$ *critical*); 2) there is difference between the means of the electrical conductivity measurements and the EM38 orientation ($F > F$ *critical*); and, 3) there is no interaction between the drainage treatment and the EM38 orientation ($F < F$ *critical*)

Table 5.19 *Two-way ANOVA test* for drainage treatment and EM38 orientation – July 10, 2006

SUMMARY	Vertical	Horizontal	Total			
Edgedrains						
Count	5	5	10			
Sum	263.5	198.5	462			
Average	52.7	39.7	46.2			
Variance	29.575	66.7	89.7			
4-ft Centerline Drain						
Count	5	5	10			
Sum	241	183	424			
Average	48.2	36.6	42.4			
Variance	6.2	35.8	56.0			
2-ft Centerline Drain						
Count	5	5	10			
Sum	225.50	170.00	395.50			
Average	45.10	34.00	39.55			
Variance	14.43	33.63	55.58			
Total						
Count	15	15	30			
Sum	730.00	551.50	1281.50			
Average	48.67	36.77	42.72			
Variance	24.77	44.71	70.17			
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Drainage Treatment	222.62	2	111.31	3.58	0.04	3.40
EM38 Orientation	1062.07	1	1062.07	34.20	0.00	4.26
Interaction	4.85	2	2.43	0.08	0.93	3.40
Within	745.30	24	31.05			
Total	2034.84	29				

July 11, 2006

Table 5.20 presents the results of the *two-way ANOVA test* performed to compare the treatments. According to the results obtained: 1) there is difference between the means of the electrical conductivity measurements and the drainage treatment (*F* > *F critical*); 2) there is difference between the means of the electrical conductivity measurements and the EM38 orientation (*F* > *F critical*); and, 3) there is no interaction between the drainage treatment and the EM38 orientation (*F* < *F critical*)

Table 5.20 ***Two-way ANOVA test*** **for drainage treatment and EM38 orientation - July 11, 2006**

SUMMARY	**Column 1**	**Column 2**	**Total**			
Edgedrains						
Count	5	5	10			
Sum	285.00	213.50	498.50			
Average	57.00	42.70	49.85			
Variance	36.38	42.58	91.89			
4-ft Centerline Drain						
Count	5	5	10			
Sum	253.50	195.50	449.00			
Average	50.70	39.10	44.90			
Variance	5.95	10.30	44.60			
2-ft Centerline Drain						
Count	5	5	10			
Sum	263.50	203.50	467.00			
Average	52.70	40.70	46.70			
Variance	1.83	0.70	41.12			
Total						
Count	15	15	30			
Sum	802.00	612.50	1414.50			
Average	53.47	40.83	47.15			
Variance	20.02	17.63	59.45			
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Drainage Treatment	125.55	2	62.77	3.85	0.04	3.40
EM38 Orientation	1197.01	1	1197.01	73.49	0.00	4.26
Interaction	10.62	2	5.31	0.33	0.73	3.40
Within	390.90	24	16.29			
Total	1724.08	29				

July 10-11, 2006

Table 5.21 presents the results of the *two-way ANOVA test* performed to compare the treatments. According to the results obtained: 1) there is difference between the difference in means of the electrical conductivity measurements and the drainage treatment (*F* > *F critical*); 2) there is no difference between the difference in means of the electrical conductivity measurements and the EM38 orientation (*F* > *F critical*); and, 3) there is no interaction between the drainage treatment and the EM38 orientation (*F* < *F critical*)

Table 5.21 *Two-way ANOVA test* for drainage treatment and EM38 orientation - July 10-11, 2006

SUMMARY	Vertical	Horizontal	Total			
Edgedrains						
Count	5	5	10			
Sum	21.50	15.00	36.50			
Average	4.30	3.00	3.65			
Variance	0.57	9.88	5.11			
4-ft Centerline Drain						
Count	5	5	10			
Sum	12.50	12.50	25.00			
Average	2.50	2.50	2.50			
Variance	1.00	8.50	4.22			
2-ft Centerline Drain						
Count	5	5	10			
Sum	38.00	33.50	71.50			
Average	7.60	6.70	7.15			
Variance	14.80	26.82	18.72			
Total						
Count	15	15	30			
Sum	72.00	61.00	133.00			
Average	4.80	4.07	4.43			
Variance	9.46	16.67	12.75			
ANOVA						
Source of Variation	***SS***	***DF***	***MS***	***F***	***P-value***	***F critical***
Drainage Treatment	117.32	2.00	58.66	5.72	0.01	3.40
EM38 Orientation	4.03	1.00	4.03	0.39	0.54	4.26
Interaction	2.22	2.00	1.11	0.11	0.90	3.40
Within	246.30	24.00	10.26			
Total	369.87	29				

August 8, 2006

Table 5.22 presents the results of the *two-way ANOVA test* performed to compare the treatments. According to the results obtained: 1) there is difference between the means of the electrical conductivity measurements and the drainage treatment (*F* > *F critical*); 2) there is difference between the means of the electrical conductivity measurements and the EM38 orientation (*F* > *F critical*); and, 3) there is no interaction between the drainage treatment and the EM38 orientation (*F* < *F critic*

Table 5.22 *Two-way ANOVA test* for drainage treatment and EM38 orientation - August 8, 2006

SUMMARY	Vertical	Horizontal	Total			
Edgedrains						
Count	5	5	10			
Sum	287.70	220.00	507.70			
Average	57.54	44.00	50.77			
Variance	6.36	31.90	67.93			
4-ft Centerline Drain						
Count	5	5	10			
Sum	260.70	200.10	460.80			
Average	52.14	40.02	46.08			
Variance	1.77	13.84	47.74			
2-ft Centerline Drain						
Count	5	5	10			
Sum	275.80	215.00	490.80			
Average	55.16	43.00	49.08			
Variance	3.55	12.94	48.40			
Total						
Count	15	15	30			
Sum	824.20	635.10	1459.30			
Average	54.95	42.34	48.64			
Variance	8.57	19.82	54.81			
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Drainage Treatment	112.84	2	56.42	4.81	0.02	3.40
EM38 Orientation	1191.96	1	1191.96	101.65	0.00	4.26
Interaction	3.27	2	1.63	0.14	0.87	3.40
Within	281.42	24	11.73			
Total	1589.49	29				

April 21, 2007

Table 5.23 presents the results of the *two-way ANOVA test* performed to compare the treatments. According to the results obtained: 1) there is difference between the means of the electrical conductivity measurements and the drainage treatment (*F* > *F critical*); 2) there is difference between the means of the electrical conductivity measurements and the EM38 orientation (*F* > *F critical*); and, 3) there is no interaction between the drainage treatment and the EM38 orientation (*F* < *F critic*

Table 5.23 ***Two-way ANOVA test*** **for drainage treatment and EM38 orientation – April 21, 2007**

SUMMARY	**Vertical**	**Horizontal**	**Total**			
Edgedrains						
Count	5	5	10			
Sum	220.90	164.00	384.90			
Average	44.18	32.80	38.49			
Variance	1.62	9.22	40.79			
4-ft Centerline Drain						
Count	5	5	10			
Sum	197.40	155.80	353.20			
Average	39.48	31.16	35.32			
Variance	8.11	9.92	27.24			
2-ft Centerline Drain						
Count	5	5	10			
Sum	204.80	159.10	363.90			
Average	40.96	31.82	36.39			
Variance	5.07	3.23	26.89			
Total						
Count	15	15	30			
Sum	623.10	478.90	1102.00			
Average	41.54	31.93	36.73			
Variance	8.35	6.88	31.25			
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Drainage Treatment	52.01	2	26.01	4.20	0.03	3.40
EM38 Orientation	693.12	1	693.12	111.88	0.00	4.26
Interaction	12.54	2	6.27	1.01	0.38	3.40
Within	148.69	24	6.20			
Total	906.37	29				

May 14, 2007

Table 5.24 presents the results of the *two-way ANOVA test* performed to compare the treatments. According to the results obtained: 1) there is no difference between the means of the electrical conductivity measurements and the drainage treatment (*F* < *F critical*); 2) there is difference between the means of the electrical conductivity measurements and the EM38 orientation (*F* > *F critical*); and, 3) there is no interaction between the drainage treatment and the EM38 orientation (*F* < *F critic*

Table 5.24 *Two-way ANOVA test* for drainage treatment and EM38 orientation - May 14, 2007

SUMMARY	Vertical	Horizontal	Total			
Edgedrains						
Count	5	5	10			
Sum	239.20	184.60	423.80			
Average	47.84	36.92	42.38			
Variance	1.49	9.05	37.81			
4-ft Centerline Drain						
Count	5	5	10			
Sum	237.10	182.50	419.60			
Average	47.42	36.50	41.96			
Variance	10.71	11.27	42.89			
2-ft Centerline Drain						
Count	5	5	10			
Sum	251.90	195.40	447.30			
Average	50.38	39.08	44.73			
Variance	4.45	9.11	41.49			
Total						
Count	15	15	30			
Sum	728.20	562.50	1290.70			
Average	48.55	37.50	43.02			
Variance	6.59	9.78	39.46			
ANOVA						
Source of Variation	***SS***	***Df***	***MS***	***F***	***P-value***	***F critical***
Drainage Treatment	44.57	2	22.29	2.90	0.07	3.40
EM38 Orientation	915.22	1	915.22	119.19	0.00	4.26
Interaction	0.24	2	0.12	0.02	0.98	3.40
Within	184.28	24	7.68			
Total	1144.31	29				

5.6 Summary

Statistical analyses performed to compare collected drained water from different drainage treatments, different drain orientations, and different drain elevations, on a newly constructed CSAH 35 located near Worthington, Minnesota is summarized. Additionally, statistical analyses to compare the effect of both drainage treatment and EM38 orientation were also performed.

The drainage treatments were compared using the *one-way analysis of variance test*, because more than two means (3) were involved. The analysis of variance indicated differences in the treatments, so the *Tukey test* was used to determine the treatment that produced the difference.

For all the periods considered (2006, 2007, and the average of them) there was differences between the edgedrains and both the 4-ft and the 2-ft centerline drain. There was not significant difference between the two centerline drain treatments. According to these results, and because the edgedrains collected much more water than the other two treatments, it seems reasonable to conclude that edgedrains is the drainage treatment to recommend.

The orientation of the drains on both the north and south side of the road was compared using the *t-test* because there was only two means involved. This test was using in combination with the *F-test* to chose determine whether the variances were equal or unequal. For all the periods considered (2006, 2007, and the average of them) the results indicated that there was not significant differences between drains located at either side of the road. These results indicate that drains located at either side of the road collect approximately the same amount of water; therefore, both locations must have drains installed.

The location of the drain on both high and low areas of the road was compared using the same approach that was used for the comparison of the orientation of drains: the *t-test* combined with the *F-test*. In a similar way, for all the periods considered (2006, 2007, and the average of them) the results indicated that there was not significant differences between drains located at either high or low areas of the road. According to these results, drains placed in both high and low areas of the road collected similar amount of water; therefore, both elevations must have drains installed.

When comparing the effect of both the drainage treatment and the EM38 orientation on the values of the electrical conductivity measurements, the results show that: 1) for all cases, there was difference between the means of the electrical conductivity measurements and the EM38 orientation; 2) for all cases, there was no interaction between the drainage treatment and the EM38 orientation; and 3) for all but one case, there was difference between the means of the electrical conductivity measurements and the drainage treatment. These results suggest that, as it was concluded above, a specific drainage treatment should be used; likewise, the results indicate that additional study is needed for the EM38, so as to select the orientation of the device that best fit measurements of water content.

Chapter 6

Numerical Simulation of Flow to Drain Tiles Beneath Roadway Pavements

6.1 Introduction

This task report describes the numerical simulation of variably-saturated flows in the vicinity of and beneath highway pavements as affected by the presence of subsurface drainage tile. The purpose of the modeling exercise was to evaluate the efficiency of alternative drain tile placement configurations with respect to volumes of water removed and degree of reduction of water content beneath the pavement. Three different drainage treatments (edgedrains, 2ft centerline drains, and 4ft centerline drains) were considered. Also considered was the effect of the elevation of the landscape surrounding the roadway, as to whether that landscape is relatively flat or lower than the roadway pavement, or whether it is higher than the roadway pavement. The elevation of the surrounding landscape does help in determining the source of water impacting the roadway pavement foundation material. The objectives for this study were 1) to create adequate numerical models for various drainage configurations, and 2) to evaluate measured tile flow with numerical simulations.

6.2 Background on the Numerical Method

The Richards equation is the governing differential equation used almost universally for modeling the flow of water in variably-saturated porous media. The equation is derived from the combination of Darcy's law for unsaturated/saturated flow with the equation of mass conservation. For variably-saturated porous media liquid water flow occurs by the gradient of capillary forces and well as for the force of gravity. Of course, there is water flow by water vapor diffusion as well, but this is generally neglected when the flows are assumed to be isothermal. The pressure head based form of the Jacobs-Richards equation (Freeze, 1971) in two space dimensions for isotropic porous media is given by

$$\left(C + S_e S\right)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad (1)$$

where $h = h\left(S_e\right)$ is the water pressure head (m), C is the specific moisture capacity of the porous medium (m^{-1}), S_e is the effective saturation, $S = S\left(h\right)$ is the storage coefficient associated with the compressibility of the porous medium and the fluid (m^{-1}), $K = K\left(S_e\right)$ is the unsaturated hydraulic conductivity, and t is time. The coordinate system is the Cartesian system with coordinates x, y, z where z is taken to be oriented vertically upward. Equation (1) reduces to the classical Richards equation (Richards, 1931) if the compressibility storage term, S is assumed to be zero.

The relationships between pressure head and water saturation, and unsaturated hydraulic conductivity and water saturation can be described by the Mualem - van Genuchten (Mualem, 1976; van Genuchten, 1980) relations. These relations are given by

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} \left(1 + |\alpha h|^n\right)^{-m}, & h < 0 \\ 1, & h \geq 0 \end{cases} \qquad (2a)$$

$$C = C(h) = (\theta_s - \theta_r)\frac{dS_e}{dh} \qquad (2b)$$

$$K = K(S_e) = \begin{cases} K_s S_e^{0.5}\left(1 - \left(1 - S_e^{1/m}\right)\right)^2, & h < 0 \\ K_s, & h \geq 0 \end{cases} \qquad (2c)$$

$$m = 1 - 1/n$$

where $\theta = \theta(h)$ is the volumetric water content, θ_s is the saturated water content, θ_r is the residual water content, and n and m

6.2.1 Numerical solution procedure

The Jacobs-Richards equation given by equation (1) was solved for the case with $S = 0$, meaning that we were solving the classical Richards equation by assuming compressibility to be negligible. A finite element solution method was used since the finite element method is robust and provides for easy representation of relatively complex solution domain geometry. The finite element solution was facilitated by the commercial software COMSOL-MP (Comsol, 2007). This software provides complete flexibility to solve single physics equations, or multiphysics with coupled interactions. The solution of the Richards equation involves just one physic process. COMSOL-MP has an Earth Science module which directly solves the Richards equation with equations (2) as one of the alternative relations for unsaturated hydraulic properties.

For symmetric cases as in Figure 6.1, a no-flux boundary condition was used along the line of symmetry (the center line of the roadway). The pavement at the top of the flow region (the pavement is not shown explicitly in the diagram) was considered to be impermeable to incident rainfall, and runoff from the pavement flowed to the permeable shoulder where the runoff was assumed to infiltrate entirely. In a later section it is stated that based on borehole logs from nearby locations, clay is the predominant material found at depths below the top soil. Due to this condition the bottom was assumed to be effectively impermeable. However, we did also consider the case where the water pressure was fixed at a constant value at the bottom boundary, that is, for example the bottom boundary could be coincident with the water table. The right boundary represents the roadway ditch. For the case where the bottom boundary was taken to be impermeable the right boundary was treated as a seepage surface, while when the bottom boundary was a fixed pressure boundary the right boundary was treated as impermeable. The drain located either under the shoulder (as in this diagram), or along the centerline of the roadway was treated as a surface of seepage. Seepage occurs along the seepage boundary only when the soil is saturated and under positive pressure along the seepage surface. The COMSOL-

MP model accounts for the dynamic seepage conditions so that when the soil under the pavement is not saturated the drain tile will not discharge any water.

6.3 Description of Modeling Conditions

6.3.1 Geometry of flow regions

The flow region in this study is represented by typical two-dimensional road cross sections. Two different geometries were considered: *edgedrains* with a drain under the shoulder and *centerline drain* with a drain under the center of the road. All geometries were constructed using Nobles County project 32-02 SAP 53-632-05 (sheets 3, 4) as a guide. Copies of these sheets will be included in the appendix to the final report.

The pavement itself was considered impermeable to precipitation and was excluded from the modeling. This corresponds to a rather new condition for the pavement as there are no cracks present for promoting water infiltration through the pavement. The entire pavement surface from the centerline to pavement edge at the shoulder was assumed to contribute to inflow through the shoulder.

Edgedrains

A typical edgedrain geometry is depicted in Figure 6.1. Only one-half of the roadway cross section was considered for the cases where the surrounding landscape topography was sufficiently symmetric. By considering only one-half of the flow region we cut down significantly the required numerical computations. For cases where the surrounding landscape topography was severely asymmetric the entire roadway section was modeled. Such asymmetric conditions do exist at some of the monitoring sites along CR 35.

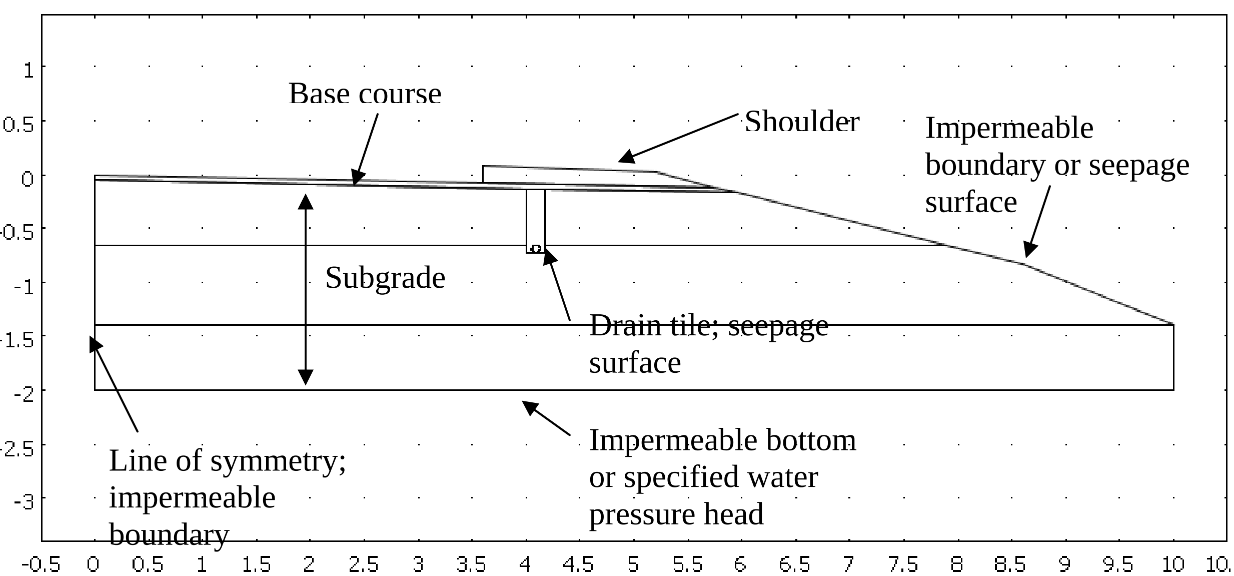

Figure 6.1 Typical cross-sectional view of edgedrain geometry

The pavement (not shown) above the base course sheds rainfall, and this rainfall flows to the shoulder where it is assumed to infiltrate into the shoulder. Seepage surfaces exist on the ditch boundary and along the surface of the tile drain located in the trench.

Centerline drains

Two types of centerline drains were modeled: drain tile at 2 feet below the base course and drain tile at 4 feet below the base course. The typical geometry of the cross section is shown in Figure 6.2. Only half of the road cross section was considered to reduce computational effort.

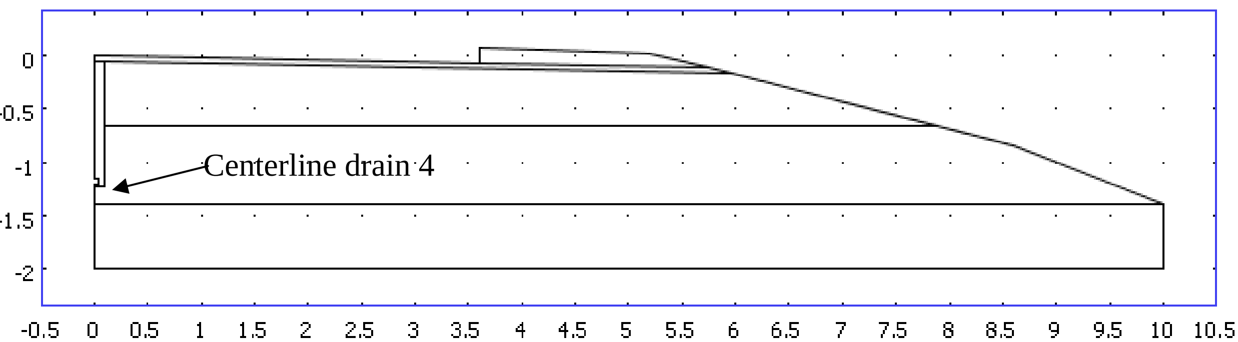

Figure 6.2 Typical cross-sectional view of centerline drain geometry; in this case the 4-ft depth drain. Other features pointed out in Figure 6.1 are the same for this drainage condition

6.3.2 Soil types

To estimate unsaturated soil parameters for the modeling activity we need to know what types of soils exist in the vicinity of CR 35. For soil information we used data available from the MN-DNR data deli. Soil properties including layers thicknesses, their depth and texture were found in Soil Survey of Nobles County (Lorenzen, 1975). Averaged unsaturated soil parameters (Carsel & Parrish, 1988) corresponding to different soil types were used in the models. Those parameters were slightly adjusted to represent the compaction of sub-grade materials, and also to provide for faster convergence of the numerical solution. Saturated hydraulic conductivity of sand trench backfill was estimated from experiment as 10 m/day. The trench backfill material had been collected during a drain tile reconnaissance conducted with the Nobles County Highway Department crew on November 15/16, 2008.

The predominant soil types found along CR 35 between Worthington and Rushmore was found to be composed of Prinsberg Silty Clay Loam and Clarion Loam. Hydraulic properties of these soils are summarized in the subsections to follow.

The County Well Index (CWI) database from the Minnesota Geological Survey was examined to assess hydraulic properties of the near-surface geology.. Mostly clay was found beneath soil (top five feet of material) profile (Well indexes: 00172148, 00223456, 00596019, 00623728, 00223457, 00223458).

Characteristics of some soil types found near the road according to the Soil Survey report are summarized further in the following sections.

Prinsburg silty clay loam

This soil type is found at location 100 hundred feet along the road from Rushmore to Worthington. Texture characteristics by layers, along with unsaturated parameters based on work by Carsel and Parrish (Carsel & Parrish, 1988).

Table 6.1 Soil layers properties for Prinsburg silty clay loam

Texture	Depth, IN	θ_r	θ_s	α, m^{-1}	n	$K_s, m/day$
Silty clay loam	19	0.089	0.43	1	1.23&	0.0168
Silt loam, silty clay loam	46	0.067	0.45	2	1.41	0.1080
Clay loam, loam	60	0.095	0.41	1.9	1.31	0.0624

&Simulations of the Richards equations behave poorly when n is less than 2.0. To fix this the n value is increased by 1.0.

Clarion loam

This type of soil is found at locations 330 and 335 hundred feet along the road from Rushmore to Worthington.

Table 6.2 Soil layers properties for Clarion loam

Texture	Depth, IN	θ_r	θ_s	α, m^{-1}	n	$K_s, m/day$
Loam	14	0.078	0.43	3.6	1.56&	0.2496
Loam	33	0.078	0.43	3.6	1.56	0.2496
Clay loam, Loam	60	0.095	0.41	1.9	1.31	0.0624

&Simulations of the Richards equations behave poorly when n is less than 2.0. To fix this the n value is increased by 1.0.

6.3.3 Topography

A Digital Elevation Model acquired from the MN/DNR was used to assess possible influence of land slope along the CR 35. The slope was evaluated along strips 2000 ft wide on either side of CR 35. Analysis of this DEM showed that 76% of the surface within the strips along the entire 8 mile length of roadway is nearly level with slopes less than 8%. Approximately 21% of the surface along the roadway is strongly sloping (8%-16%).

6.3.4 Rainfall

Weather data was taken from National Climatic Data Center. The nearest weather station was found to be Worthington 2 NNE (COOP ID 219170). An average daily amount of precipitation for the most rain intensive months March-June 2007 was found to be 2.29 mm or approximately 0.09 inch. The hyetograph for the most rain intensive months is shown in Figure 6.3.

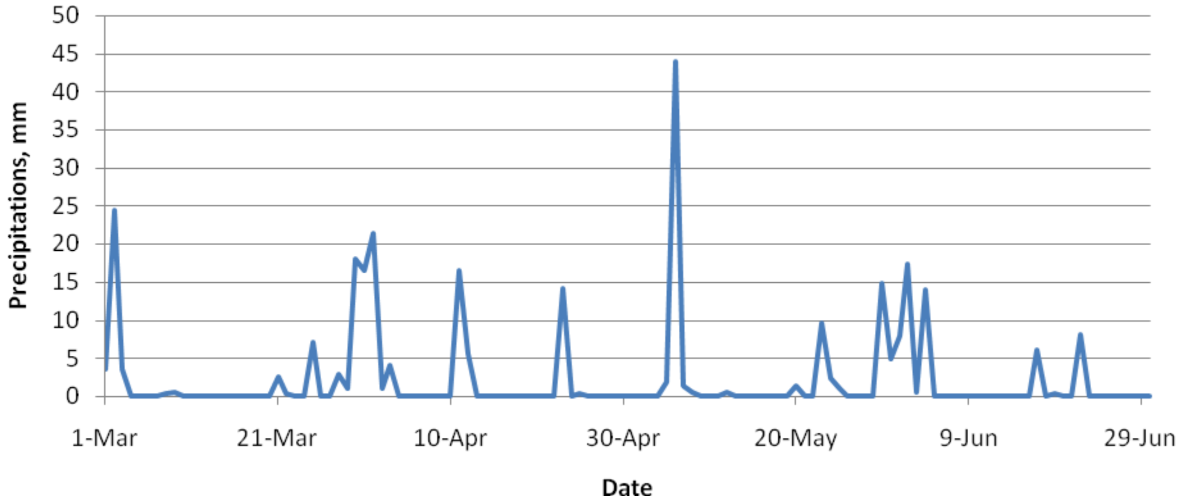

Figure 6.3 Hyetograph from March 2007 to June 2007

With the rainfall fluxes given in Figure 6.3, and assuming the pavement to be completely impermeable such that 100% of the rainfall is shed by the pavement, the corresponding amount of water that enters the road shoulder on a daily basis is shown in Figure 6.4. This amount includes that rainfall that is shed by the pavement and the rainfall that falls directly on the shoulder. The unit is given as cubic meters per m of roadway. It is assumed that this water is distributed uniformly over the surface of the permeable shoulder.

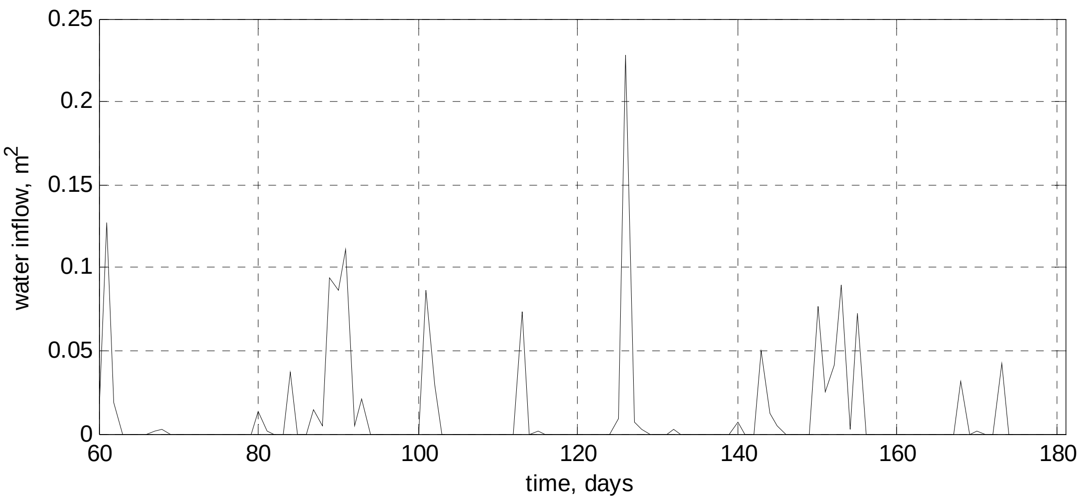

Figure 6.4 Rate of water infiltrating into the roadway shoulder (m^3 water /m roadway)

6.3.5 Boundary and initial conditions

To fully describe the model for the numerical solution we need to assign boundary conditions and initial conditions. The following assumptions were considered in setting those conditions. Boundary conditions were already described previously but some repetition in description will follow.

The entire pavement was considered impermeable which corresponds to the relatively new condition of the road. The infiltration of precipitation occurred through the road shoulder only. Two landscape classes were considered: one with noticeable height differences and the other without any height difference between the roadway and the landscape.

In the case of a nearly level landscape, only one-half of entire cross section of the road was modeled. Infiltration was assumed to be uniform nearby the location of such modeled road cross section. That means the no-flux boundary condition was applied along the sides of the modeled domain corresponding to the roadway ditch, and along the axis of symmetry (the boundary corresponding to the centerline of the road).

For modeled locations along the road with noticeable landscape height differences on its sides the entire cross section was considered. Hills with elevated depressions were considered as a source of shallow underground water, while low areas along the road were considered as sinks. To account for that far field influence, the following boundary condition was used

$$-n \cdot K\left(\frac{\partial h}{\partial x}+\frac{\partial h}{\partial z}+1\right)=R_b\left(\left[h_b-h\right]+\left(z_b-z\right)\right) \qquad (3)$$

where h_b is the reference pressure head at distant location of water source or sink (that is, it is the far-field pressure head), R_b is the empirical conductance parameter that was taken proportional to the saturated hydraulic conductivity of soil located between the road and the distant location and reverse proportional to the distance to that location, and z_b is the elevation of the point of the reference pressure head.

To model the flow of water entering the drain tile a pressure dependent boundary condition was set up so that

$$-n \cdot K\left(\frac{\partial h}{\partial x}+\frac{\partial h}{\partial z}+1\right)=\begin{cases} R_b\left(h_b-h\right),\ h \geq 0 \\ 0, \quad h<0 \end{cases} \qquad (4)$$

where h_b is the reference pressure head just next to the boundary of the drain tile (and is set equal to zero). The first equation in (4) indicates that flow occurs when the water pressure at the drain boundary is equal to or greater than zero pressure head. The second of the equations indicates that when the pressure along the boundary of the drain is less than zero, the flux through the drain boundary will be zero. It is assumed here that all water that enters the tile is readily drained away, that is, there is no back pressure on the drain.

The higher the value of R_b implies the more permeable the interface is. From numerical experiments it was found that if R_b is greater than some value it virtually does not influence the result. Figure 6.5 shows one of the simulation results for different values of R_b parameter. For values exceeding $R_b = 86.4/day$ there is hardly any visible difference. In this study $R_b = 864/day$ was used.

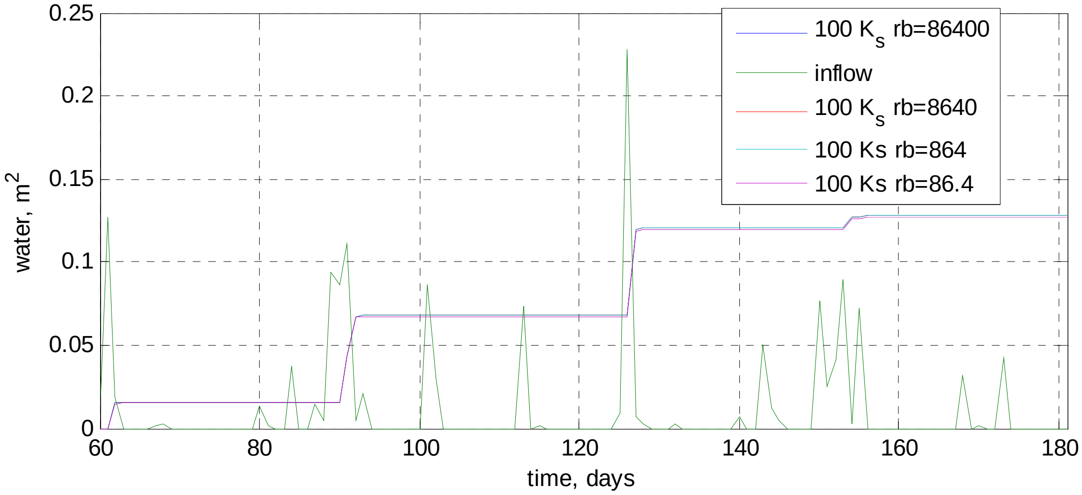

Figure 6.5 Simulation results for different values of empirical conductance parameter

Two different boundary conditions were considered for the bottom of the modeled domain: 1) constant pressure head and 2) impermeable bottom. For the case of impermeable bottom, seepage was allowed through the side slopes of the road. Constant pressure head at the bottom corresponds to the case where somewhat highly easily permeable material exists below the soil profile, allowing for an almost constant water table level. Imposing a no-flux boundary condition corresponds to the presence of dense impermeable materials.

The initial conditions for the simulations corresponded to a condition where the soil is very close to saturation, a condition that might exist shortly after snowmelt or frost thawing in the spring. This initial condition was used because it was found that when the initial condition is drier, for instance a condition of field capacity, the centerline drains never responded for the short period (180 days) considered for the rainfall. Had longer periods of simulation been considered, with periods of freeze/thaw for instance, the effect of the initial condition would have been negligible.

6.3.6 Effects of subgrade compaction

The simulations described in the above outline were all for the native subgrade material, not accounting for compaction for stabilization. It is of interest to know what impact this compaction might have on the drain flow for each of the configurations, and for each of the soil types. In the analysis to follow it was assumed that the top 0.6 m (2 ft) of the subgrade material was compacted to optimum moisture density. For these soils that will be approximately 110 – 120 pcf (or about 1900 kg/m^3).

The influence of compaction was modeled according to Assouline (2006) with the relations,

$$\theta_{sc} = \theta_s \frac{\rho_s - \rho_c}{\rho_s - \rho}$$

$$K_{sc} = K_s \left(\frac{\rho_s - \rho_c}{\rho_s - \rho} \right)^3 \left(\frac{\rho_c}{\rho} \right)^{-3}$$

where θ_s is volumetric water content at saturation for the native soil, K_s is hydraulic conductivity at saturation for the native soil, ρ is a bulk density, ρ_s is a density of solid particles (was averaged as 2.7 g/cc), ρ_c is a density of compacted material (approximately 1900 kg/ m^3 for our application), and θ_{sc} and K_{sc} are the saturated water content and the saturated hydraulic conductivity for the compacted soil.

6.4 Results

6.4.1 Dependence of outflow from treatment used

Several treatments were modeled for ***Prinsburg silty clay loam*** soil type which is found near the bucket located at 100 hundred feet along the test road from Rushmore to Worthington. Modeled treatments include edgedrain and centerline drains at 2 feet and 4 feet beneath the pavement. Two boundary conditions for the bottom of the domain were considered: pressure head $h = -0.5m$ and the impermeable condition. Simulation results corresponding to constant pressure head are shown in Figure 6.6. Both centerline drains yielded less outflow compared to the edgedrain configuration. The centerline drain at 4 feet is the least efficient for this case.

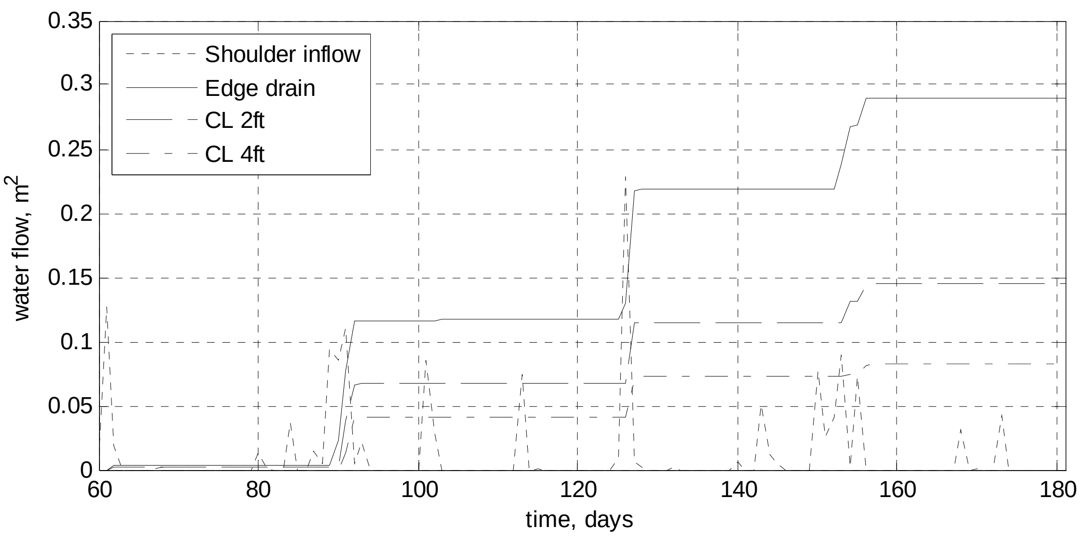

Figure 6.6 Cumulative water outflow (m^3 water /m roadway) from the three drain configurations for the case where the pressure is fixed at the bottom of the soil profile for the Prinsberg silty clay loam soil

The infiltration into the shoulder is also shown in Figre 6.6, but is given as daily water flux m^3 water /m roadway.

For the case of impermeable bottom of the domain the results are different from the previous case (Figure 6.7). This would be the case where the material underlying the soil profile is for instance a very dense clay. For this case the centerline drain at 4 feet appeared to be the most efficient treatment.

Thus the efficiency of the treatment is heavily dependent on properties of the layers. For the case of dense and almost impermeable clay, the centerline drain at 4 feet appeared to be the most efficient. This is due to the fact that the depth to the impermeable boundary was in this case set to about 2 m (about 6 ft), and the 4-ft depth drain will have greater access to the water that flows deeper into the profile than either the 2-ft centerline drain or the edgedrain. If the edgedrain had been constructed deeper into the profile, maybe as much as 4 ft, it is expected that it would exceed the performance of the 4-ft centerline drain. Of if the impermeable boundary were much shallower, for example at 3 ft, then it is expected that the edgedrain would outperform both of the centerline drain configurations.

In the case of a fixed bottom boundary pressure (highly permeable bottom layers) the edgedrain is the most efficient. This is probably due to the fact that for the edgedrain configuration the drain is closer to the source of the infiltrating water than for either of the centerline drain configurations.

6.4.2 Dependence of edgedrain outflow on landscape

It was found from our field monitoring work that under some conditions the landscape height differences can result in different amounts of water outflow on different sides of the road with edgedrains. The influence of landscape on the difference in water outflow from the north and south edgedrains (CR 35 is oriented east-west) was modeled for the ***Clarion loam*** soil type. This soil type is commonly found at the location of 33,500 feet along the road from Rushmore to Worthington. The elevation profile at one of the drain monitoring sites near this location is shown in Figure 6.8. The influence of the elevation difference was modeled through the application of boundary condition expressed by equation (3) on the sides of the domain. The bottom of the flow domain had to be considered impermeable for the flows from the sideslopes to be at all influential.

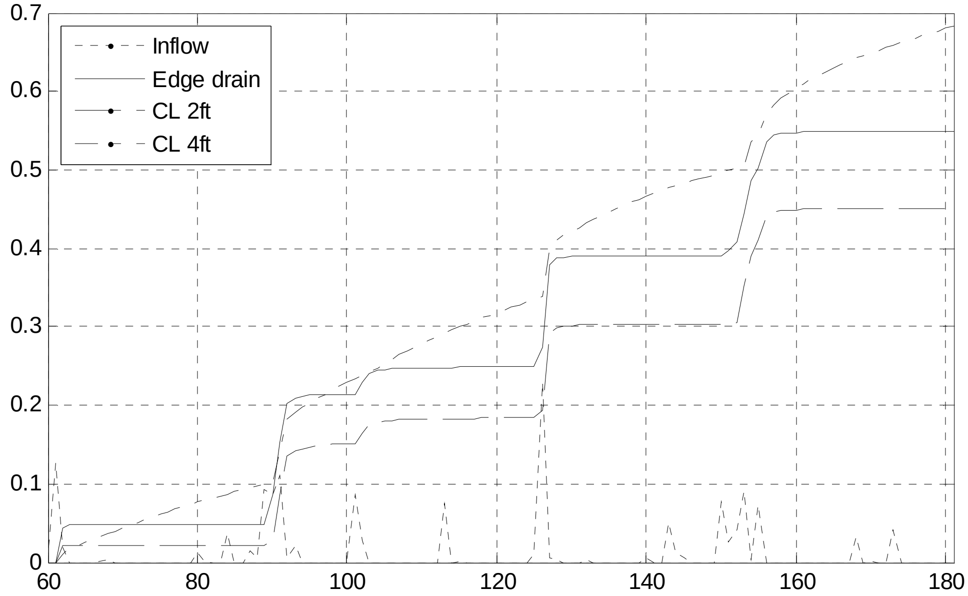

Figure 6.7 Cumulative water flux (m^3 water /m roadway) from the three drain configurations for the case where the bottom of the soil profile is an impermeable boundary for the Prinsberg silty clay loam soil

The infiltration into the shoulder is also shown in Figure 6.7, but is given as a daily water flux m^3 water / m roadway.

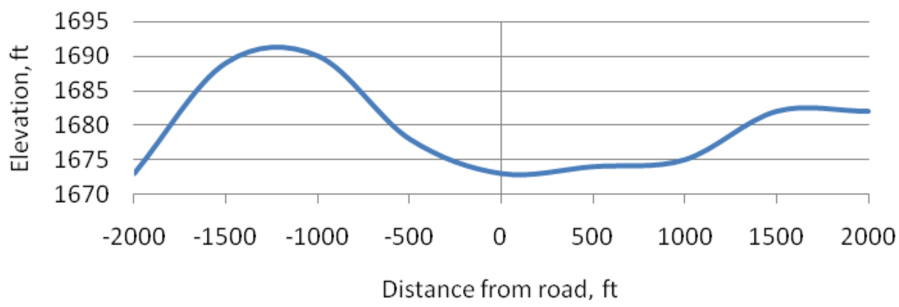

Figure 6.8 Elevation profile across the road at about 6.5 miles east of Rushmore. The south side of the road is to the left of the origin in the graphical plot

Simulation results for this case are shown in Figure 6.9. From the plot it is observed that the cumulative discharge is higher for the south edgedrain than for the north edgedrain. This is the result of there being a higher reference water pressure on the south side of the road, than on the north side of the road. The reference pressure is manifested directly by the elevation of the landscape on the side of the road. Figure 6.8 shows that at this location the elevation is much higher on the south side of the road.

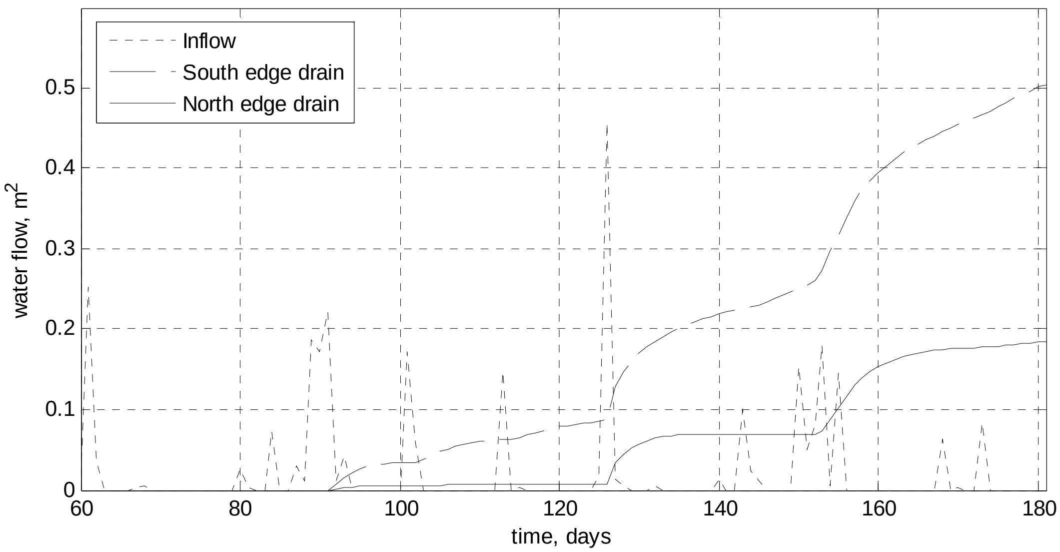

Figure 6.9 Cumulative water flux (m^3 water /m roadway) from the edgedrain configuration for the north and south side edgedrains

This simulation reflects the effect of lateral flow in from areas along the roadway that have higher elevation than the roadway. For this case the bottom boundary of the soil profile was assumed to be impermeable to downward water flow, thereby forcing water to move laterally toward the roadway. In the figure the infiltration into the shoulder is also shown but is given as a daily water flux ($m^3\ water / m\ roadway / day$).

6.4.3 Impact of subgrade compaction

A total of twelve simulations were performed to cover all the different cases of drain configurations (edgedrain, centerline 2 foot, centerline 4 foot), compaction conditions (compacted, not compacted), and soil types (Prinsburg, Clarion).

The cumulative drain outflow for the different cases are illustrated in Figure 6.10. The daily inflow to the subsurface from rainfall is not shown on the graph to avoid confusion, as the graph is busy enough already. The inflow has the same distribution as that shown in Figure 6.9.

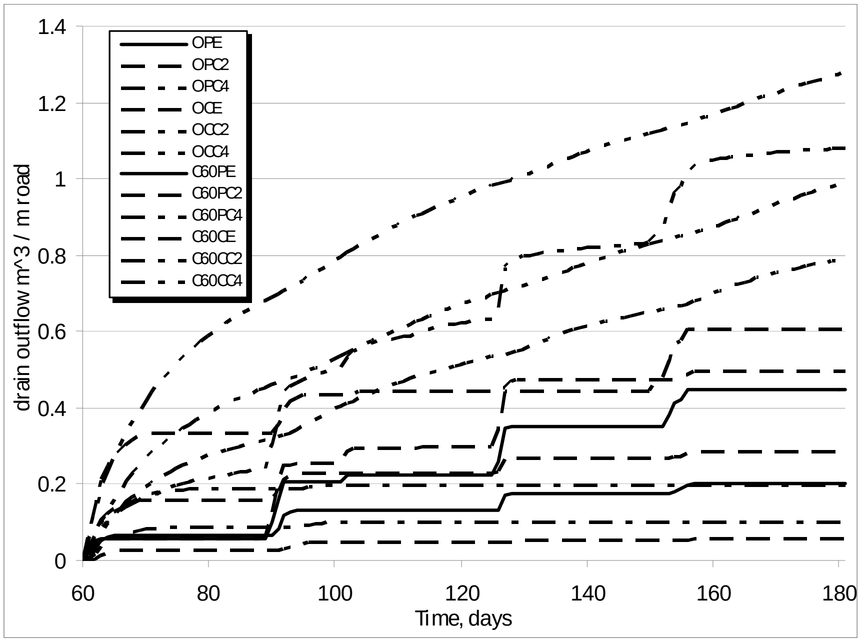

Figure 6.10 Cumulative drain outflow for the different drain configurations, subgrade soil types, and compaction condition

For the legend of Figure 6.10: OP - uncompacted Prinsburg soil; C60P - compacted Prinsburg soil; OC – uncompacted Clarion soil; C60C – compacted Clarion soil; E – edgedrain configuration; C2 – centerline drain, 2 foot depth; C4 – centerline drain, 4 foot depth.

It is interesting to see that that centerline drains hardly register any effect from the rainfall events, while the edgedrains show the rainfall input clearly.

The drainage configuration with the drain tile located under the center line of the road was found to be the most effective. This is mostly the result of assuming a nearly saturated profile as the initial condition. As mentioned earlier, for other simulations performed with much drier initial conditions the centerline drains responded very little if at all to the rainfall of this short period.

The total outflow volumes for the different simulation cases are summarized in Figure 6.11. The result for the compaction of the top 30 cm of the subgrade is also shown along with the 60 cm compaction condition. Here it is seen that the compaction of the top layers of the Prinsburg soil results in an increase of drain tile outflow, whereas compaction of top layer of the Clarion soil type results in a decrease of total drain tile outflow.

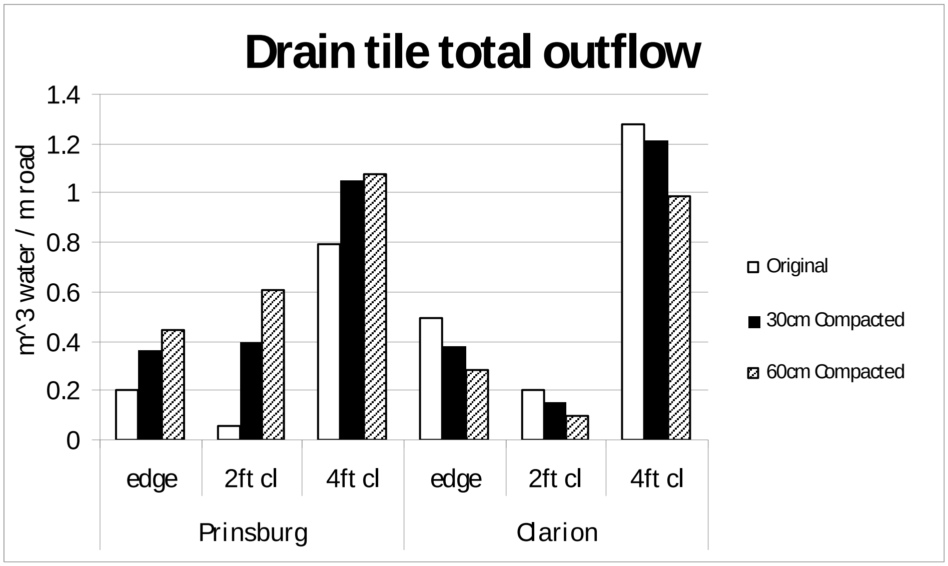

Figure 6.11 Effect of compaction on total drain outflow for different subgrade materials and compaction conditions

Results for a 30 cm compaction layer are also given in addition to the result for the 60 cm compaction.

All of the draining water does not need to go through the drain, but it also has the opportunity to seep laterally into the roadway ditch. When the resistance to flow toward the drain increases because of compaction, or because of subgrade soil type, the relative amount of water that flows outward into the ditch will increase. A summary of the cumulative flow into the drains and into the ditch for the different conditions considered is presented in Figure 6.12.

To explain the compaction and soil interaction effect it is beneficial to examine the simulated outflow volumes for the edgedrain configuration. The cumulative outflow through drains is presented in Figure 6.13. As it was shown above, compaction resulted in an increase in outflow for the Prinsburg soil type, whereas decreased outflow for Clarion soil. The top layers of the Prinsburg soil type have smaller saturated hydraulic conductivity compared to those of the Clarion type soil. That is why water was turned to drain trench top and tile when the very top layer was compacted, and top layer's conductivity was decreased as a consequence. Wheareas for Clarion soil type, water entered drain trench all along the walls of the trench for the uncompacted case, and the decrease of top layer's conductivity resulted in a reduced flux of water entering the drain trench through the trench sides.

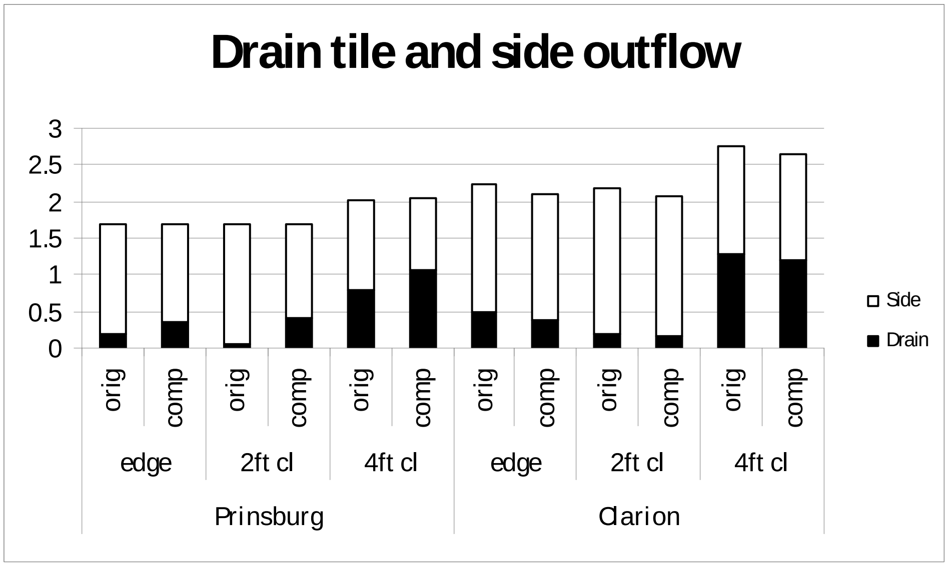

Figure 6.12 Total water outflow through drain tile and side of the domain for the various configurations

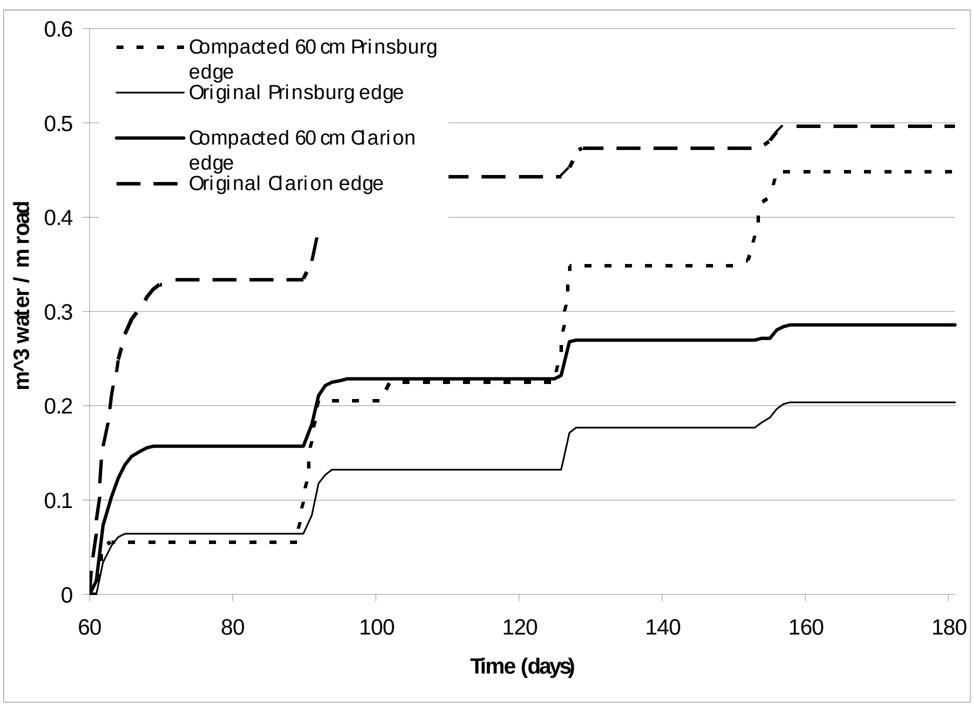

Figure 6.13 Cumulative drainage outflow for the two soil types and the two compaction conditions

6.5 Summary and Discussion

The finite element solution using the COMSOL-MP software has been applied to the situation involving variably-saturated flow toward subsurface drains placed beneath roadway pavements. Three configurations were considered, edgedrains, centerline drains places at 2 ft depth, and centerline drains placed at 4 ft depth.

The numerical solutions were found to be fairly robust in execution although there were cases where the numerical simulations abruptly terminated before completion. Being that the problems being solved are highly nonlinear it is expected that numerical convergence problems would arise; this is not atypical of what is reported in the literature, and is the experience of the PI working with other finite element codes, including his own.

The results displayed by the limited number of cases examined showed that the 4-ft depth centerline drain will remove more of the infiltrated water when the soil beneath the pavement subgrade is essentially impermeable. For the case where the lower boundary is not impermeable the results show that the edgedrain is the most effective at removing excess water. In the area where CR 35 is located this impermeable condition is probably more the rule than the exception, at least we can say that based on the limited number of borehole logs we had available for our analysis.

The results presented were for cases where the subsurface materials began at a fairly wet condition, such as would exist immediately after spring thaw. If the conditions are drier it turns out that the edgedrain is the most effective for all conditions.

Notation

$C=(\theta_s-\theta_r)\frac{dS_e}{dh}$	Specific water capacity, m^{-1}
S_e	Effective saturation
θ	Water fraction
θ_r	Residual water content
θ_s	Saturated water content
S	Storage term due to fluid and porous medium compressibility, m^{-1}
h	Pressure head, m
K	Unsaturated hydraulic conductivity, m/day
z	Vertical coordinate axis, elevation, m
K_s	Saturated hydraulic conductivity, m/day
$\vec{n}$	Outward normal

Chapter 7

Assessment of Crushed Concrete on Edgedrain Condition

7.1 Introduction

The objective of this task of the project was to assess the potential impact of the quantity of crushed concrete used in base course materials on drain tile condition. The concern is that when an excessive amount of crushed concrete is used in the base course, there exists the potential that carbonate dissolution will lead to deposits of carbonate onto the geofabric of the drain tile, thereby plugging the entries to the drain. Mn/DOT has a guideline, based on laboratory experimental evidence, that the maximum amount of crushed concrete to place into the base course should not exceed the equivalent of 2 inches of the base course material.

To assess this concern in the field we selected two road sections in Nobles County, one on CR 32, and the other on CR 35. These two county roads are oriented east-west. The sections of highway sampled for the assessment for both county roads were between CR 10 and CR 13, both north-south oriented highways.

CR 32 was used as a control in this assessment because it did not have any crushed concrete placed in the base course or in the permeable unpaved shoulder. CR 32 had been reconstructed around 1998. Contrasting with CR 32 is CR 35, which when reconstructed in 2004, had crushed concrete utilized throughout the entire permeable unpaved shoulder. Crushed concrete was not used in the base course of CR 35.

The hypothesis is then that the crushed concrete in the shoulder of CR 35 could potentially lead to precipitation of carbonate onto the geofabric of the edgedrains. One limitation of any comparison made here is that the two roadways are not of the same age. But not having alternative study sites we had to do with these two sites.

7.2 Sample Collection

In November 2007, three Nobles County maintenance crew members took samples of drain tile at three locations on each of the roads. They accomplished this by trenching down to the sand-filled trench over the edgedrain at each location using a tracked backhoe. A hand shovel was then used to dig out the sand to expose the geofabric covered drain tile. A 2-3’ section of the drain tile was cut out with a hole saw and then the tile was spliced back together with a section of new tile.

A photograph of the backhoe equipment is shown in Figure 7.1 and a photograph of the excavation down to the level of the sand-filled trench is shown in Figure 7.2. Excavation of the sand is shown in Figure 7.3, and the exposed tile is shown in Figure 7.4. The cutout of the tile is shown in Figure 7.5, and the spliced tile is shown in Figure 7.6.

Figure 7.1 Illustration of the tracked backhoe machine used to excavate through the unpaved shoulder to access the edgedrain tile on Nobles County CR 32 and CR 35

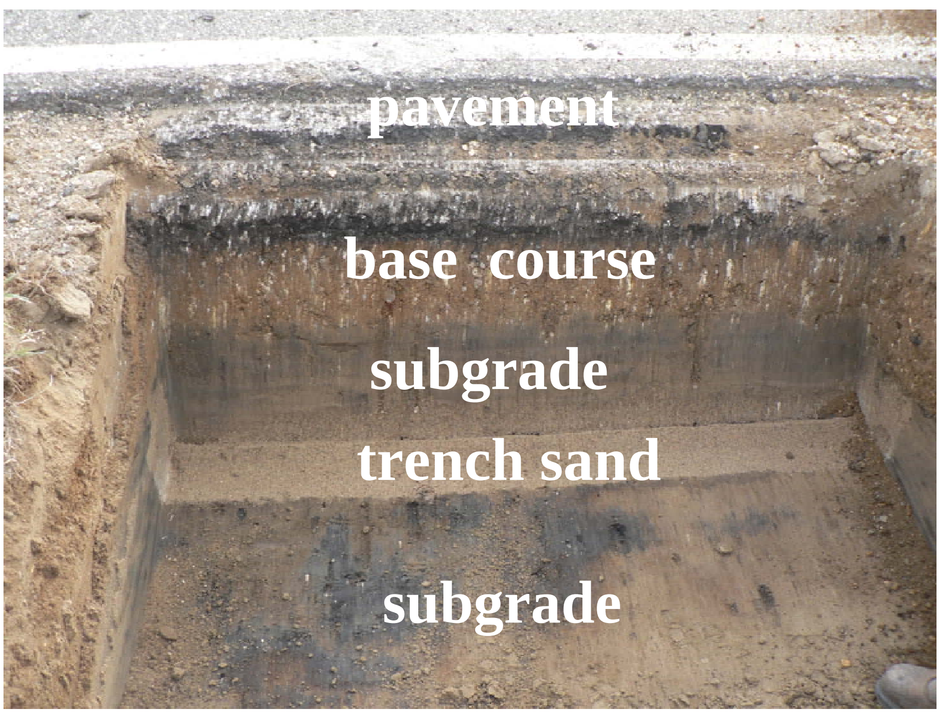

Figure 7.2 Illustration showing the excavated pit down to the level just above the edgedrain elevation

In the photograph (Figure 7.2) one can make out the sand filled trench, the pavement, the base course, and the subgrade material.

Figure 7.3 Exposing the edgedrain by shoveling out the trench sand

Figure 7.4 Exposed edgedrain at the bottom of the edgedrain trench

Figure 7.5 Edgedrain with tile sample removed

Figure 7.6 The edgedrain with the splice in place

The tile samples were collected and catalogued, and in addition a sample (over 4 pounds) of the trench sand was bagged, and the bags were marked by sample location. The sample locations were given designations of 32A, 32B, and 32C for CR 32, and 35A, 35B and 35C for CR 35.

The tile samples and the samples of the trench sand were transported back to the Soil and Water Laboratory at the University of Minnesota for analysis. The analysis consisted of conducting visual inspections (with photographs) of the drain tile and the filter fabric, and the measurement of the relative amount of carbonate precipitates on the fabric and in the sand samples.

The test of the relative amount of carbonate precipitates was conducted by using an eyedropper to apply drops of 1 M HCL solution onto the collected materials. The HCL solution was applied to the geofabric and to the sand. The idea was that if carbonate precipitates are present on the geofabric or in the trench sand, the application of the acid solution would lead to fizzing/bubbling of the applied drop.

7.3 Visual Observations

Photographs of the tile samples, showing the geofabric and the interior of the tiles are presented in Figures 7.7 through 7.18.

Figure 7.7 The geofabric of the edgedrain at site A on CR 32

Figure 7.8 The interior of the drain tile at site A of CR 32. Note the deposits on the interior

Figure 7.9 The geofabric of the edgedrain at site B on CR 32

Figure 7.10 The interior of the drain tile at site B of CR 32. Note the deposits
.

Figure 7.11 The geofabric of the edgedrain at site C on CR 32. Appears to be significant deposits on the fabric material

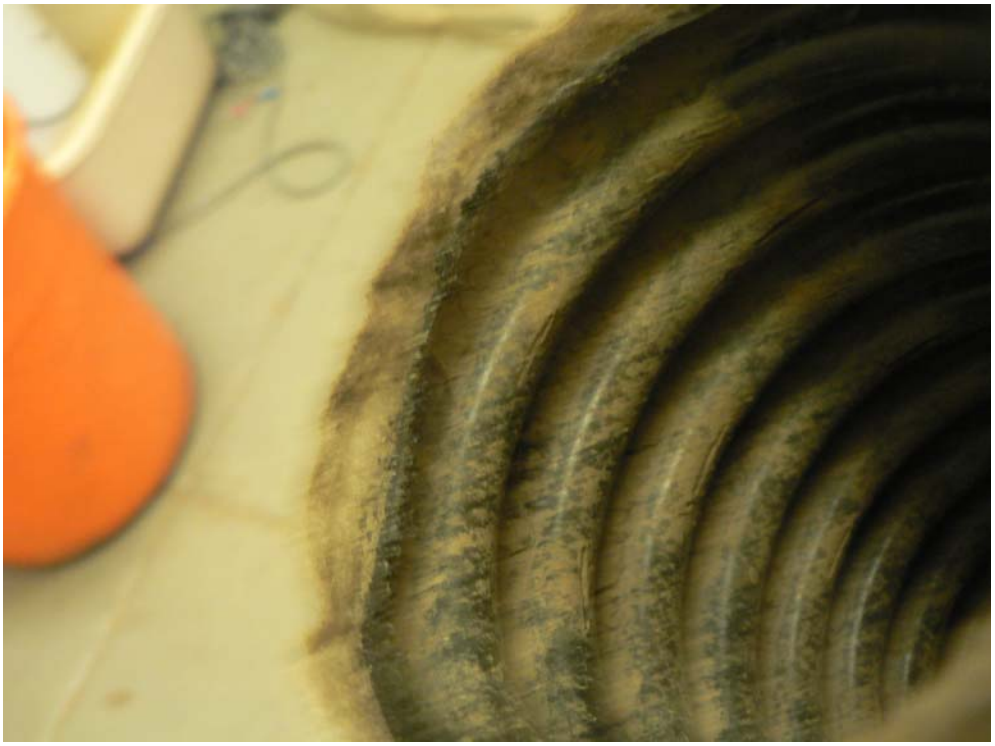

Figure 7.12 The interior of the drain tile at site C of CR 32. Note the deposits

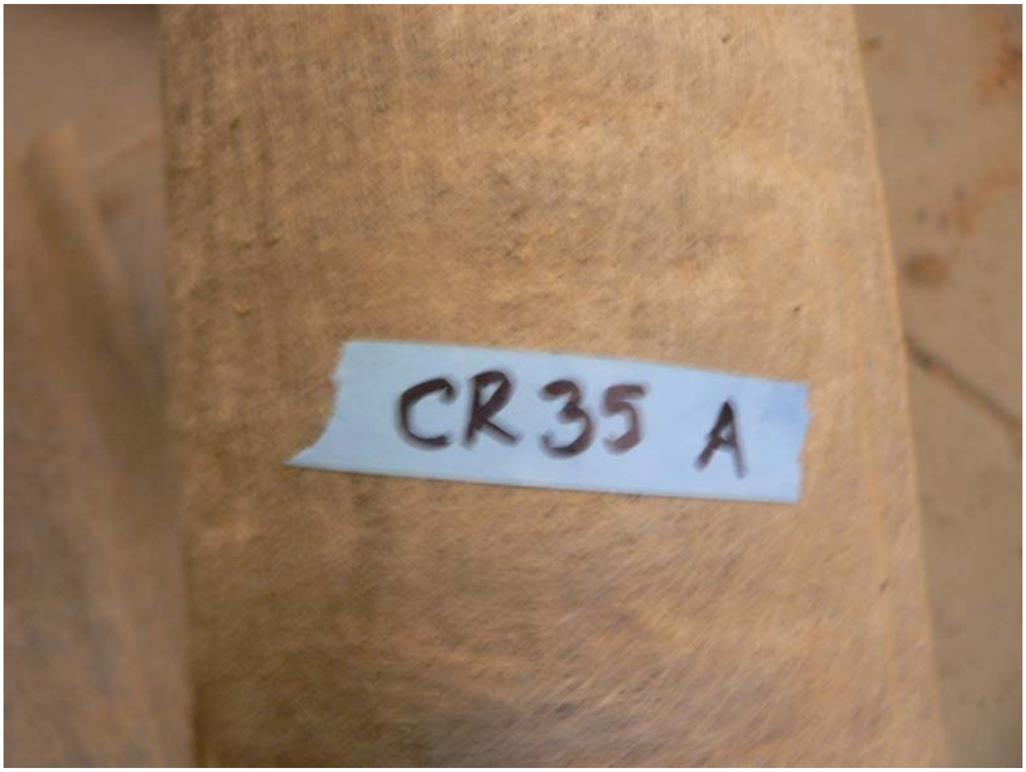

Figure 7.13 The geofabric of the edgedrain at site A on CR 35

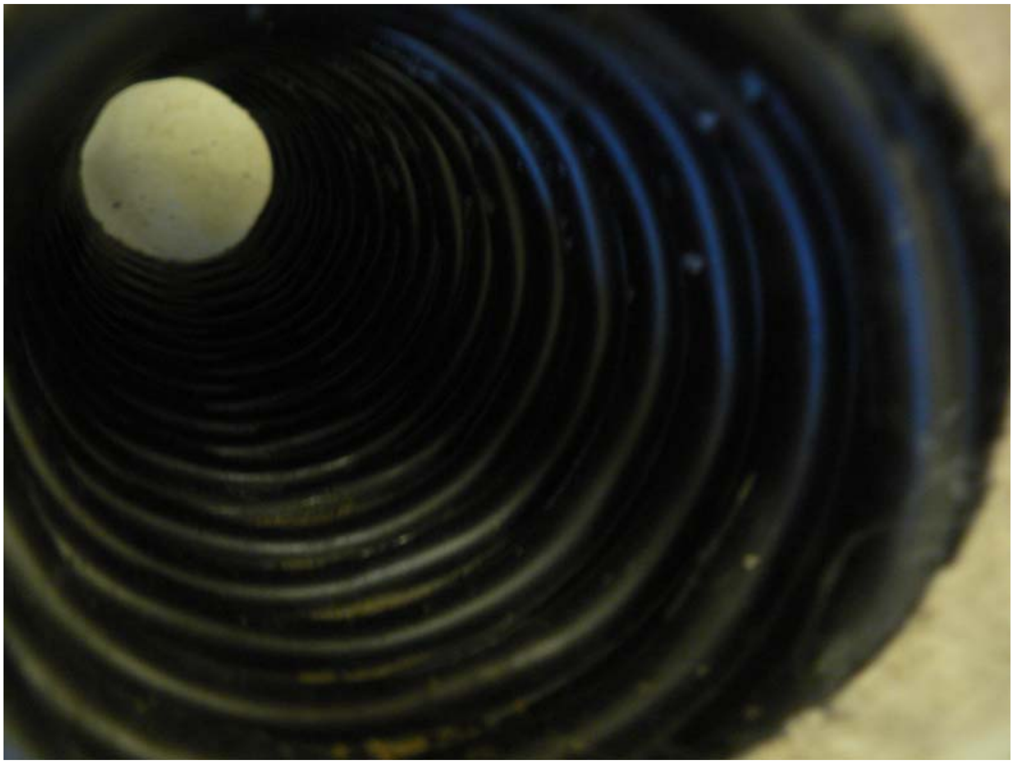

Figure 7.14 The interior of the drain tile at site A of CR 35. There are some deposits on the interior of the drain, but it is quite clean overall

Figure 7.15 The geofabric of the edgedrain at site B on CR 35

Figure 7.16 The interior of the drain tile at site B of CR 35. Note the deposits

Figure 7.17 The geofabric of the edgedrain at site C on CR 35

Figure 7.18 The interior of the drain tile at site C of CR 35. Note the deposits

7.4 Acid Test

One or more drops of 1 M HCL was applied with an eye dropper to the geofabric and to the trench sand originating from each of the sample sites. The results of the acid test are summarized in Table 7.1.

The distinction between the two sites is remarkable. For the samples from CR 35, all the geofabric samples, and two of the three trench sand samples showed no fizzing/bubbling action in response to application of the acid. For the trench sand sample that did show some reaction to the application of the acid, the reaction was moderate.

In contrast to the results for CR 35, the samples from CR 32 all showed strong reaction to application of the acid. This strong reaction is an indication of presence of calcium carbonate in both the geofabric samples as well as in the sand.

The results are interesting although they are somewhat contrary to what might have been expected. Certainly it would have been expected that the CR 32 samples would not have shown any reaction to the application of the acid because there is no crushed concrete in the shoulder or in the base course material. One would expect to see more reaction to the acid for the samples from CR 35 because at least along that roadway a significant amount of crushed concrete was used in the shoulder. It might be that since the conditions for CR 35 have only been in place for about 4 years there has not been sufficient time for migration of significant amounts of calcium carbonate to the tile geofabric or the trench sand.

It is not clear what the source of the calcium carbonate is for the samples derived from CR 32. It might be that the trench sand used for the CR 32 tile installation is carbonate sand, in which case the reaction to the acid would be expected.

Table 7.1 Results of the acid test for carbonate deposit presence on the geofabric and grains of the trench sand

Roadway	CR 32			CR 35		
Location	A	B	C	A	B	C
Tile Geofabric	Heavy[&]	Heavy	Heavy	None	Moderate	None
Trench Backfill Sand	Heavy	Heavy	Heavy	None	None	None

[&]Terms (heavy, moderate, none) refer to the degree of fizziness/bubbling resulting from application of the 1 M HCL acid.

Chapter 8

Assessment of Open Graded Base Drainage Systems using the EM38

8.1. Introduction

The soils in within the borders of the City of Worthington, Minnesota are subject to frequent conditions of high water table. It has been the experience of the city public works department that many of the residential streets within the city have not endured these high water table conditions, but developed transverse cracks and alligator cracking within just a few years in many instances. It was realized that the cause of this rapid pavement degradation was caused by the high water table conditions.

The city now uses open graded base drainage systems to control the potentially high water table conditions. This drainage system has a high permeable base course material separated from the underlying fine-grained subgrade material with a geotextile fabric to prevent migration of fines into the base course.

The objective of the work presented in this chapter is to evaluate the moisture conditions beneath selected sections of residential streets in Worthington to evaluate the performance of the current design in comparison to previous designs. The EM38 instrument was selected for conducting the measurements to provide some index of relative moisture conditions beneath the pavements. Four city street sections were selected based on the suggestion of Mr. Dwayne Haffield, Worthington City Engineer.

Readings were taken in the city of Worthington (Figure 8.1), located in Nobles County, close to the southwest corner of the State of Minnesota, at 43^{0}37’12” N and 95^{0}35’47” W.

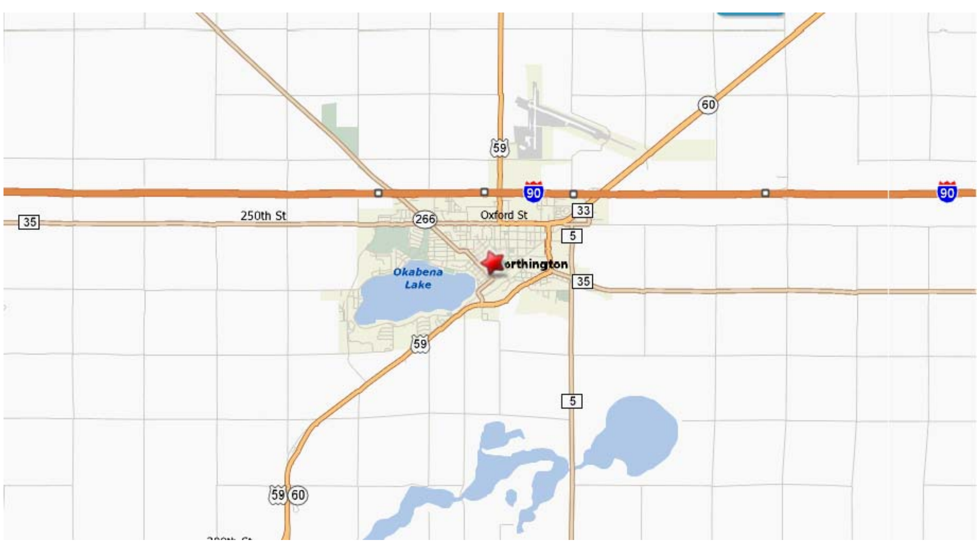

Figure 8.1 Map of the city of Worthington (Mapquest, 2008)

Electrical conductivity readings were taken in two specific locations in the city. One location was in the vicinity of the intersections of Pleasant Street and Eckerson Drive (Figures 8.2 and 8.3), located southwest of downtown Worthington and south of Okabena Lake. Eckerson Drive is a street with the new type of open graded base to promote good drainage, while Pleasant Street is of the former type that does not have enhanced drainage conditions.

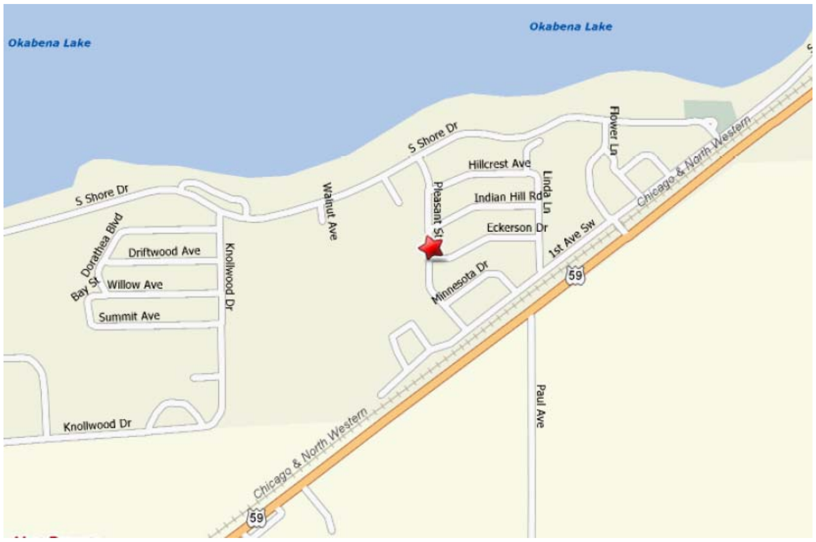

Figure 8.2 Location for EM-38 readings at the intersection of Pleasant Street and Eckerson Drive. (Mapquest, 2008)

Figure 8.3 Intersection of Eckerson Drive and Pleasant Street

The condition of Pleasant Street is illustrated in photographs presented in Figures 8.4 and 8.5. One observes that there is significant longitudinal and transverse cracking in the pavement, and some alligator cracking. This type of cracking was absent from the Eckerson Drive pavement.

Figure 8.4 View of pavement of Pleasant Street showing the cracking pattern in the street

Figure 8.5 Closeup view of cracking on Pleasant Street

The other street location for measurements was at the intersection of Cecillee Street and Spring Avenue (Figures 8.6 and 8.7), northeast of downtown Worthington, close to the State Road 60 underpass for Interstate 90. For this location, Cecillee Street was constructed using the open graded base for enhanced drainage, while Spring Avenue is similar in construction to Pleasant Street.

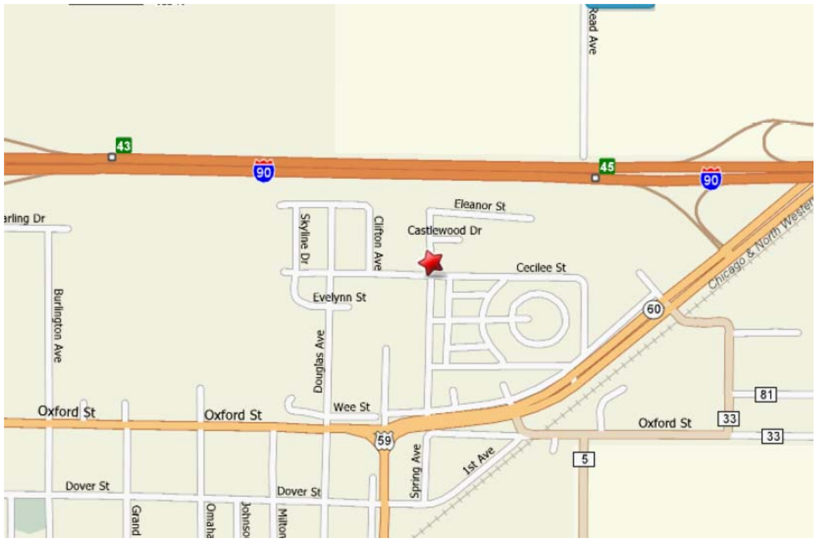

Figure 8.6 Location for EM-38 readings at the intersection of Cecillee Street and Spring Avenue (Mapquest, 2008)

Figure 8.7 Intersection of N. Spring Avenue. and Cecillee Street

The conditions of Spring Ave and Cecillee Dr are illustrated in photographs presented in Figures 8.8 - 8.11. A visual comparison of these two street sections in terms of pavement quality related to cracking shows that the distinction is not as clear as it is for the Pleasant Street versus Eckerson Drive comparison since both Spring Avenue and Cecillee Street have some evidence of cracking. However, Spring Avenue has much lower pavement quality as observed in Figures 8.8 and 8.9, where longitudinal and transverse cracks and also alligator cracking is present. Cecillee Street had some transverse cracks, but no alligator cracking (Figures 8.10 and 8.11).

Figure 8.8 View of pavement of N. Spring Avenue, looking south of the intersection with Cecillee Street, showing the cracking pattern in the street

In Figure 8.8, one sees fine alligator cracking in the background, and some larger crack patterns in the foreground.

Figure 8.9 Cracking pattern in pavement on N. Spring Ave

There were four cross-sectional readings on each road, with the exception of Eckerson Drive, where only three cross-sectional readings were taken; the cross section were separated 50 ft from each other. Each cross section had five points of reading, one at the middle of the road, and two at each side of it; each reading point was separated 8ft from the adjacent one. Readings at each point were taken using both the horizontal and the vertical orientation of the EM38 electromagnetic instrument.

Figure 8.10 View of pavement of Cecillee Street looking east of the intersection with Spring Avenue, showing the presence of some longitudinal and transverse cracks

Alligator cracking was not present.

Figure 8.11 View of pavement of Cecillee Street looking west of the intersection with Spring Avenue, showing the cracking pattern in the street

Readings from two dates (June 22 and July 20 of 2007) are presented in this chapter. Readings on other dates were taken as well, but those are not included in the report. The values obtained for the June 22 and July 20 dates are presented in Tables 8.1 and 8.2, respectively.

In the following sections several statistical tests are performed in an attempt to discover existing differences between the two pavement conditions.

Table 8.1 EC (mS/m) by road and EM38 orientation – June 22, 2007

Cecillee Street		**W 50**		**W 100**		**E 50**		**E 100**	
		V	**H**	**V**	**H**	**V**	**H**	**V**	**H**
	N 1	80	50	71	38	86	48	87	49
	N 8	78	59	69	45	77	53	78	50
	N 16	60	46	67	44	79	57	75	53
	N 24	51	37	66	44	82	60	77	55
	N 31	54	31	68	41	86	58	81	52
Eckerson Drive		**E 50**		**E 100**		**E 150**			
		V	**H**	**V**	**H**	**V**	**H**		
	N 1	85	41	56	37	59	37		
	N 8	69	38	54	37	50	38		
	C 16	58	31	53	32	47	36		
	S 24	51	29	53	33	46	34		
	S 31	50	27	53	33	45	31		
Pleasant Street		**N 50**		**N 100**		**S 50**		**S 100**	
		V	**H**	**V**	**H**	**V**	**H**	**V**	**H**
	W 1	50	36	51	33	47	30	37	29
	W 8	61	42	53	41	50	40	43	34
	C 16	61	43	54	41	51	39	46	35
	E 24	59	40	54	41	55	43	47	36
	E 31	60	46	57	32	53	42	40	31
Spring Avenue		**N 50**		**N 100**		**S 50**		**S 100**	
		V	**H**	**V**	**H**	**V**	**H**	**V**	**H**
	W 1	81	56	77	54	72	49	71	50
	W 8	84	58	78	58	70	50	71	49
	C 16	87	71	78	58	69	53	70	60
	E 24	85	64	77	53	68	50	68	51
	E 31	79	48	74	50	68	49	69	47

Table 8.2 EC (mS/m) by road and EM38 orientation – July 20, 2007

Cecillee Street		**W 50**		**W 100**		**E 50**		**E 100**	
		V	**H**	**V**	**H**	**V**	**H**	**V**	**H**
	N 1	74	38	62	26	78	37	78	37
	N 8	72	48	58	36	70	43	69	37
	N 16	53	35	56	36	73	46	68	41
	N 24	41	24	56	34	75	51	70	43
	N 31	43	19	57	31	79	47	73	40
Eckerson Drive		**E 50**		**E 100**		**E 150**			
		V	**H**	**V**	**H**	**V**	**H**		
	N 1	83	37	48	29	52	28		
	N 8	65	33	46	29	44	28		
	C 16	53	26	42	23	40	27		
	S 24	48	23	41	25	38	24		
	S 31	45	20	42	24	36	22		
Pleasant Street		**N 50**		**N 100**		**S 50**		**S 100**	
		V	**H**	**V**	**H**	**V**	**H**	**V**	**H**
	W 1	42	24	42	21	36	21	28	16
	W 8	49	33	44	29	42	29	32	22
	C 16	48	35	44	29	43	30	34	24
	E 24	48	32	45	28	46	34	34	25
	E 31	48	44	48	20	45	32	30	19
Spring Avenue		**N 50**		**N 100**		**S 50**		**S 100**	
		V	**H**	**V**	**H**	**V**	**H**	**V**	**H**
	W 1	68	45	66	43	60	38	62	41
	W 8	70	49	66	47	59	39	61	40
	C 16	74	65	67	46	58	44	61	49
	E 24	71	54	66	43	57	38	59	40
	E 31	65	39	61	39	58	36	59	37

8.2. Statistical Analysis of Electrical Conductivity Readings by Road and EM38 Orientation

8.2.1 Data analysis tool: two-way analysis of variance

For this comparison, the *two-way analysis of variance (ANOVA) test* because two independent variables are involved: road (Cecillee Street, Eckerson Drive, Pleasant Street , and Spring Ave) and EM38 orientation (vertical and horizontal).

The null hypotheses to be tested, one for each independent variable, and one for the interaction between them are:

1. The hypotheses for the road are as follows:
    H_0: There is no difference between the means of the electrical conductivity measurements and the roads where the readings were taken.
    H_1: There is a difference between the means of the electrical conductivity measurements and the roads.

2. The hypotheses for the EM 38 orientation are as follows:
    H_0: There is no difference between the means of the electrical conductivity measurements and the EM38 orientation.
    H_1: There is a difference between the means of the electrical conductivity measurements and the EM38 orientation.

3. The hypotheses for the interaction are as follow:
    H_0: There is no interaction between the roads were the electrical conductivity readings were taken and the EM38 orientation.
    H_1: There is an interaction between the roads and the EM38 orientation.

8.2.2 Data analysis results

June 22, 2007

Table 8.3 shows the results of the *two-way ANOVA test* performed to compare the four treatments: 1) there is difference between the means of the electrical conductivity measurements and the road where the reading was taken (*F > F critical*); 2) there is difference between the means of the electrical conductivity readings and the EM38 orientation (*F > F critical*); and, 3) there is interaction between the road and the EM38 orientation (*F > F critical*)

July 20, 2007

Table 8.4 shows results of the *two-way ANOVA test* performed to compare the four treatments: 1) there is difference between the means of the electrical conductivity measurements and the road (*F > F critical*); 2) there is difference between the means of the electrical conductivity measurements and the EM38 orientation (*F > F critical*); and, 3) there is interaction between the road and the EM38 orientation (*F > F critical*)

Table 8.3 *Two-way ANOVA test* for road and EM38 orientation – June 22, 2007

SUMMARY	**Vertical**	**Horizontal**	Total			
Cecillee Street						
Count	5	5	10			
Sum	368.10	242.6	610.7			
Average	73.62	48.52	61.07			
Variance	23.03	6.81	188.26			
Eckerson Drive						
Count	5	5	10			
Sum	276.40	171.30	447.70			
Average	55.28	34.26	44.77			
Variance	51.64	12.63	151.30			
Pleasant Street						
Count	5	5	10			
Sum	257.40	188.60	446.00			
Average	51.48	37.72	44.60			
Variance	8.92	10.90	61.40			
Spring Avenue						
Count	5	5	10			
Sum	374.10	269.60	643.70			
Average	74.82	53.92	64.37			
Variance	2.02	18.91	130.64			
Total						
Count	20	20	40			
Sum	1276.00	872.10	2148.10			
Average	63.80	43.61	53.70			
Variance	134.40	76.82	207.48			
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Roads	3307.21	3	1102.40	65.40	0.00	2.90
Orientation	4078.38	1	4078.38	241.95	0.00	4.15
Interaction	166.61	3	55.54	3.29	0.03	2.90
Within	539.41	32	16.86			
Total	8091.61	39				

Table 8.4 ***Two-way ANOVA test*** **for road and EM38 orientation - July 20, 2007**

SUMMARY	**Vertical**	**Horizontal**	**Total**			
Cecillee Street						
Count	5	5	10			
Sum	326.30	187.30	513.60			
Average	65.26	37.46	51.36			
Variance	24.86	8.93	229.70			
Eckerson Drive						
Count	5	5	10			
Sum	241.00	132.60	373.60			
Average	48.20	26.52	37.36			
Variance	68.25	15.81	167.92			
Pleasant Street						
Count	5	5	10			
Sum	207.20	136.90	344.10			
Average	41.44	27.38	34.41			
Variance	6.47	15.14	64.52			
Spring Avenue						
Count	5	5	10			
Sum	317.10	218.20	535.30			
Average	63.42	43.64	53.53			
Variance	2.51	22.93	119.99			
Total						
Count	20	20	40			
Sum	1091.60	675.00	1766.60			
Average	54.58	33.75	44.17			
Variance	128.22	67.02	206.37			
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Road	2809.39	3	936.46	45.43	0.00	2.90
Orientation	4338.89	1	4338.89	210.50	0.00	4.15
Interaction	240.60	3	80.20	3.89	0.02	2.90
Within	659.59	32	20.61			
Total	8048.47	39				

8.3. Statistical Analysis of EM38 Readings by Road (Averaging Cross Sections)

8.3.1 Data analysis tool: one-way analysis of variance

For this comparison, the *one-way analysis of variance (ANOVA) test* will be used because there is one independent variable to be considered with more than two treatments or means: EM38 readings from city road (Cecillee Street, Eckerson Drive, Pleasant Street, and Spring Avenue). The analysis of variance is used to test the hypothesis that the means of EM readings from the four roads are equal. The EC values to use are the five readings from the averaged cross sections; vertical and horizontal readings are treated independently.

H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$
H_1: At least one mean is different from the others.

In our case, the null hypothesis states that the mean values of EM38 readings from the four roads are equals; on the contrary, the alternative hypothesis states that at least one of those mean values is different. If the null hypothesis is rejected, then an additional test is required to determine which treatment is causing the difference. The *Tukey test* is one of the tests available for this purpose and, in our case, it will include six comparisons: Cecillee Street vs. Eckerson Drive, Cecillee Street vs. Pleasant Street, Cecillee Street vs. Spring Avenue, Eckerson Drive vs. Pleasant Street, vs. Spring Avenue, and Pleasant Street vs. Spring Avenue.

8.3.2 Data analysis results

June 22, 2007, Vertical Orientation of EM38

Table 8.5 shows the results of the *one-way ANOVA test* performed to compare the four roads, using only the readings from the vertical orientation of the EM38 on June 22, 2007. According to the results obtained ($F > F$ *critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Tukey test* is performed (Table 8.6), and the results obtained indicate that there are significant differences ($q > q$ *critical*) among all the roads, with the exception to those roads that are located close to each other (Cecillee Street vs. Spring Avenue, and Pleasant Street vs. Eckerson Drive), which shows no significant differences.

June 22, Horizontal Orientation of EM38

Table 8.7 presents the results of the *one-way ANOVA test* performed to compare the four roads, using only readings from the horizontal orientation of the EM38 taken on June 22, 2007. According to the results obtained ($F > F$ *critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Tukey test* is performed (Table 8.8), and the results obtained indicate that, there are significant differences ($q > q$ *critical*) among all the roads, with the exception of those roads that are located close to each other (Cecillee Street vs. Spring Avenue, and Pleasant Street vs. Eckerson Drive), which show no significant differences.

Table 8.5 *One-way ANOVA test* for vertical readings – June 22, 2007

SUMMARY						
Groups	Count	Sum	Average	Variance		
Cecillee Street	5	368.1	73.62	23.03		
Eckerson Drive	5	276.4	55.28	51.64		
Pleasant Street	5	257.4	51.48	8.92		
Spring Avenue	5	374.1	74.82	2.02		
ANOVA						
Source of Variation	SS	Df	MS	F	P-value	F critical
Between Groups	2211.23	3	737.08	34.44	0.00	3.24
Within Groups	342.41	16	21.40			
Total	2553.64	19				

Table 8.6 *Tukey test* for EM38 vertical readings – June 22, 2007

COMPARISON	***MS W.G.***	***N***	***Q***	***Q CRITICAL***
Cecillee Street vs. Eckerson Drive	21.40	5	8.86	4.05
Cecillee Street vs. Pleasant Street			10.70	
Cecillee Street vs. Spring Avenue			0.58	
Eckerson Drive vs. Pleasant Street			1.84	
Eckerson Drive vs. Spring Avenue			9.45	
Pleasant Dr vs. Spring Avenue			11.28	

Table 8.7 *One-way ANOVA test* for EM38 horizontal readings – June 22, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	5	242.6	48.52	6.81		
Eckerson Drive	5	171.3	34.26	12.63		
Pleasant Street	5	188.6	37.72	10.90		
Spring Avenue	5	269.6	53.92	18.91		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	1262.59	3	420.86	34.18	0.00	3.24
Within Groups	197.00	16	12.31			
Total	1459.59	19				

Table 8.8 *Tukey test* for EM38 horizontal readings – June 22, 2007

COMPARISON	***MS W.G.***	***N***	***Q***	***Q CRITICAL***
Cecillee Street vs. Eckerson Drive	12.31	5	9.09	4.05
Cecillee Street vs. Pleasant Street			6.88	
Cecillee Street vs. Spring Avenue			3.44	
Eckerson Drive vs. Pleasant Street			2.21	
Eckerson Drive vs. Spring Avenue			12.53	
Pleasant Dr vs. Spring Avenue			10.32	

July 20, 2007, Vertical Orientation of EM38

Table 8.9 presents the results of the *one-way ANOVA test* performed to compare the four roads, using only readings from the vertical orientation of the EM38 taken on July 20, 2007. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Tukey test* is performed (Table 8.10), and the results obtained indicate that there are significant differences (*q > q critical*) among all the roads, with the exception of those roads that are located close to each other (Cecillee Street vs. Spring Avenue, and Pleasant Street vs. Eckerson Drive), which show no significant differences.

Table 8.9 *One-way ANOVA test* for EM38 vertical readings – July 20, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	5	326.3	65.26	24.86		
Eckerson Drive	5	241	48.20	68.25		
Pleasant Street	5	207.2	41.44	6.47		
Spring Avenue	5	317.1	63.42	2.51		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	2027.86	3	675.95	26.48	0.00	3.24
Within Groups	408.372	16	25.52			
Total	2436.232	19				

Table 8.10 *Tukey test* for EM38 vertical readings – July 20, 2007

COMPARISON	***MS W.G.***	***N***	***Q***	***Q CRITICAL***
Cecillee Street vs. Eckerson Drive	21.40	5	7.57	4.05
Cecillee Street vs. Pleasant Street			10.56	
Cecillee Street vs. Spring Avenue			0.82	
Eckerson Drive vs. Pleasant Street			3.00	
Eckerson Drive vs. Spring Avenue			6.75	
Pleasant Dr vs. Spring Avenue			9.75	

July 20, Horizontal Orientation of EM38

Table 8.11 shows the results of the *one-way ANOVA test* performed to compare the four roads, using only readings from the horizontal orientation of the EM38 taken on July 20, 2007. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Tukey test* is performed (Table 8.12), and the results obtained indicate that there are significant differences (*q > q critical*) among all the roads, with the exception of those roads that are located close to each other (Cecillee Street vs. Spring Avenue, and Pleasant Street vs. Eckerson Drive), which show no significant differences.

Table 8.11 *One-way ANOVA test* for EM38 horizontal readings – July 20, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	5	187.3	37.46	8.93		
Eckerson Drive	5	132.6	26.52	15.81		
Pleasant Street	5	136.9	27.38	15.14		
Spring Avenue	5	218.2	43.64	22.93		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	1022.13	3	340.71	21.70	0.00	3.24
Within Groups	251.22	16	15.70			
Total	1273.35	19				

Table 8.12 *Tukey test* for EM38 horizontal readings – July 20, 2007

COMPARISON	***MS W.G.***	***N***	***Q***	***Q CRITICAL***
Cecillee Street vs. Eckerson Drive	15.70	5	6.17	4.05
Cecillee Street vs. Pleasant Street			5.69	
Cecillee Street vs. Spring Avenue			3.49	
Eckerson Drive vs. Pleasant Street			0.49	
Eckerson Drive vs. Spring Avenue			9.66	
Pleasant Dr vs. Spring Avenue			9.18	

8.4. Statistical Analysis of EM38 Readings by Road (Averaging Points)

8.4.1 Data analysis tool: one-way analysis of variance

For this comparison, the *one-way analysis of variance (ANOVA) test* will be used because there is only one independent variable to be considered, with more than two treatments or means: EM38 readings from city road (Cecillee Street, Eckerson Drive, Pleasant Street , and Spring Avenue). The analysis of variance is used to test the hypothesis that the means of EM readings from the four roads are equal. The EC values to use are the five readings from the averaged points in each cross section, and vertical and horizontal readings are treated independently.

H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$
H_1: At least one mean is different from the others.

In our case, the null hypothesis states that the mean values of EM38 readings from the four roads are equals; on the contrary, the alternative hypothesis states that at least one of those mean values is different. If the null hypothesis is rejected, then an additional test is required to determine which treatment is causing the difference. In this case, because the groups have different size, the *Scheffé test* is available for this purpose, and will include six comparisons: Cecillee Street vs. Eckerson Drive, Cecillee Street vs. Pleasant Street , Cecillee Street vs. Spring Avenue, Eckerson Drive vs. Pleasant Street , Eckerson Drive vs. Spring Avenue, and Pleasant Street vs. Spring Avenue.

8.4.2 Data analysis results

June 22, 2007, Vertical Orientation of EM38

Table 8.12 shows the results of the *one-way ANOVA test* performed to compare the four roads, using only the readings from the vertical orientation of the EM38 on June 22, 2007. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Scheffé test* is performed (Table 8.14), and the results obtained indicate that there are significant differences (*F' > F critical*) among all the roads, with the exception to those roads that are located close to each other (Cecillee Street vs. Spring Avenue, and Pleasant Street vs. Eckerson Drive), which shows no significant differences.

Table 8.13 *One-way ANOVA test* for vertical readings – June 22, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	4	294.4	73.6	72.24		
Eckerson Drive	3	165.8	55.27	45.17		
Pleasant Street	4	207.2	51.80	35.39		
Spring Avenue	4	299.2	74.80	42.91		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	1656.47	3	552.16	11.21	0.00	3.59
Within Groups	541.95	11	49.27			
Total	2198.42	14				

Table 8.14 *Scheffé test* for EM38 vertical readings – June 22, 2007

COMPARISON	*MS W.G.*	N_1	N_2	*F'*	*F CRITICAL*
Cecillee Street vs. Eckerson Drive	49.27	4	3	11.69	10.68
Cecillee Street vs. Pleasant Street		4	4	19.29	
Cecillee Street vs. Spring Avenue		4	4	0.06	
Eckerson Drive vs. Pleasant Street		3	4	0.42	
Eckerson Drive vs. Spring Avenue		3	4	13.27	
Pleasant Dr vs. Spring Avenue		4	4	21.47	

June 22, Horizontal Orientation of EM38

Table 8.15 presents the results of the *one-way ANOVA test* performed to compare the four roads, using only readings from the horizontal orientation of the EM38 taken on June 22, 2007. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Scheffé test* is performed (Table 8.16), and the results obtained indicate that, there are significant differences (*F' > F critical*) among all the roads, with the exception, again, of those roads that are located close to each other (Cecillee Street vs. Spring Avenue, and Pleasant Street vs. Eckerson Drive), which show no significant differences.

Table 8.15 *One-way ANOVA test* for EM38 horizontal readings – June 22, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	4	194	48.50	36.07		
Eckerson Drive	3	102.8	34.27	1.01		
Pleasant Street	4	151.8	37.95	9.45		
Spring Avenue	4	215.6	53.90	16.89		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	902.49	3	300.83	17.48	0.00	3.59
Within Groups	189.26	11	17.21			
Total	1091.74	14				

Table 8.16 *Scheffé test* for EM38 horizontal readings – June 22, 2007

COMPARISON	*MS W.G.*	N_1	N_2	*F'*	*F CRITICAL*
Cecillee Street vs. Eckerson Drive	12.31	4	3	20.17	11.02
Cecillee Street vs. Pleasant Street		4	4	12.93	
Cecillee Street vs. Spring Avenue		4	4	3.39	
Eckerson Drive vs. Pleasant Street		3	4	1.35	
Eckerson Drive vs. Spring Avenue		3	4	38.38	
Pleasant Dr vs. Spring Avenue		4	4	29.56	

July 20, 2007, Vertical Orientation of EM38

Table 8.17 presents the results of the *one-way ANOVA test* performed to compare the four roads, using only readings from the vertical orientation of the EM38 taken on July 20, 2007. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Scheffé test* is performed (Table 8.18), and the results obtained indicate that there are not significant differences (*F' < F critical*) among the roads, with the exception of both Cecillee Street vs. Pleasant Street and Pleasant Street vs. Spring Avenue), which do show significant differences.

Table 8.17 *One-way ANOVA test* for EM38 vertical readings – July 20, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	4	261	65.25	88.57		
Eckerson Drive	3	144.6	48.2	85.08		
Pleasant Street	4	165.6	41.4	46.21		
Spring Avenue	4	253.6	63.4	25.23		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	1581.05	3	527.02	8.92	0.00	3.59
Within Groups	650.19	11	59.11			
Total	2231.24	14				

Table 8.18 *Scheffé test* for EM38 vertical readings – July 20, 2007

COMPARISON	***MS W.G.***	N_1	N_2	***F'***	***F CRITICAL***
Cecillee Street vs. Eckerson Drive	59.11	4	3	8.43	11.07
Cecillee Street vs. Pleasant Street		4	4	19.25	
Cecillee Street vs. Spring Avenue		4	4	0.12	
Eckerson Drive vs. Pleasant Street		3	4	1.34	
Eckerson Drive vs. Spring Avenue		3	4	6.70	
Pleasant Dr vs. Spring Avenue		4	4	16.38	

July 20, Horizontal Orientation of EM38

Table 8.19 shows the results of the *one-way ANOVA test* performed to compare the four roads, using only readings from the horizontal orientation of the EM38 taken on July 20, 2007. According to the results obtained (*F > F critical*), the null hypothesis is rejected, which means that there are statistical differences among the treatments. In view of this, the *Scheffé test* is performed (Table 8.20), and the results obtained indicate that there are not significant differences (*F' < F critical*) among the roads, with the exception of both Eckerson Drive vs. Spring Avenue and Pleasant Street vs. Spring Avenue), which do show significant differences.

Table 8.19 *One-way ANOVA test* for EM38 horizontal readings – July 20, 2007

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
Cecillee Street	4	149.8	37.45	34.60		
Eckerson Drive	3	79.6	26.53	1.21		
Pleasanr St	4	109.4	27.35	28.04		
Spring Avenue	4	174.4	43.60	24.08		
ANOVA						
Source of Variation	**SS**	**Df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	759.71	3	253.24	10.61	0.00	3.59
Within Groups	262.57	11	23.87			
Total	1022.28	14				

Table 8.20 *Scheffé test* for EM38 horizontal readings – July 20, 2007

COMPARISON	***MS W.G.***	N_1	N_2	***F'***	***F CRITICAL***
Cecillee Street vs. Eckerson Drive	23.87	4	3	8.56	11.07
Cecillee Street vs. Pleasant Street		4	4	8.55	
Cecillee Street vs. Spring Avenue		4	4	3.17	
Eckerson Drive vs. Pleasant Street		3	4	0.05	
Eckerson Drive vs. Spring Avenue		3	4	20.93	
Pleasant Dr vs. Spring Avenue		4	4	22.13	

8.5. Summary

Subsurface drainage conditions for four streets in the city of Worthington were compared using electrical conductivity readings taken with the EM38 electromagnetic device. Both vertical and horizontal orientations of the EM38 were used. The roads evaluated were Pleasant Street and Eckerson Drive, in the southwest part of Worthington, and Cecillee Street and Spring Avenue, in the northeast part of the city. Four cross sections, separated 50ft, were considered in each road, with the exception of Eckerson Drive, with only three cross sections. Five readings were taken per cross section, separated 7-8 ft apart.

Readings were taken for two dates: June 22 and July 20, 2007. It could be observed that, for both orientations of the EM38, values collected on July 20 (mid-summer) were lower than those that were collected on June 22. This is probably due to drier conditions following drainage after spring. Likewise, values of electrical conductivity corresponding to the vertical orientation of the EM38 were consistently higher than those corresponding to the horizontal orientation. The higher reading are expected to occur because the vertical orientation reads to larger depths and therefore more metallic utilities will be sensed within the vertical readings. It was also observed that, for most cases, values of EC for both Cecillee Street and Spring Avenue were higher than those collected from both Pleasant Street and Eckerson Drive. Values of EC from Spring Avenue were, in general, higher than those from Cecillee Street.

Regarding the statistical analysis, a *two-way ANOVA test* with replications was performed to compare two treatments: the drainage system (roads) and the EM38 orientation. Average readings for all cross sections in each road were used. For the two dates considered, results showed that: 1) there was a difference between the means of the electrical conductivity measurements and the drainage conditions; 2) there was a difference between the means of the electrical conductivity measurements and the EM38 orientation; and, 3) there was interaction between the road and the EM38 orientation.

In view of these results, two *one-way ANOVA tests* were performed for each of the EM38 orientations, using as treatment the drainage conditions (roads), readings from both June 22 and July 20. The first test used electrical conductivity values from the average of the cross sections. The second test used values from the average of the five points in each cross section. For all cases (EM38 orientation and date of reading), the results indicated that the treatments (roads) were different.

Next, a *Tukey test* was performed on the results of the first *one-way ANOVA test* (average cross sections) to make pair comparisons among the treatments and determine which one made the difference. A *Tukey test* was used because the samples to compare had the same size: 4 treatments (roads) with 5 values each. For all cases (EM38 orientation and date or reading), the results indicated that there was statistical difference among all the roads compared, with the exception of those pairs located close to each other: Pleasant Street vs Eckerson Drive and Cecillee Street vs. Spring Avenue.

Finally, a *Scheffé test* was performed on the results of the second one-way ANOVA *test* (average readings on each cross section). A *Scheffé test* was required because the size of the samples was different (Eckerson Drive had only 3 cross sections, while the other roads had 4). For the June 22 readings, and for the two orientations of the EM38, the results again showed differences among all comparisons, with the exception of those performed on roads located close to each other: Pleasant Street vs. Eckerson Drive and Cecillee Street vs. Spring Avenue, where there was no statistical difference. On July 20, however, the results of the *Scheffé test* showed statistical difference only when comparing Cecillee Street vs. Eckerson Drive and Pleasant Street vs. Spring Avenue, for the vertical orientation of the EM38; for the horizontal orientation, there were significant differences in Eckerson Drive vs. Spring Avenue and Pleasant Street vs. Spring Avenue.

The four roads selected were located in two locations with different drainage conditions, such as type of soil, condition of the road surface, age of the road, etc. That explains not only the difference in absolute values of EC among those two groups of roads, but also the strong significant differences found when performing the statistical analysis for each reading date. Spring Avenue seems to be the road with a least effective drainage system, followed by Cecillee Street. Both Pleasant Street and Eckerson Drive perform in a pretty similar way. In the case of Spring Avenue, cracks were noticed in the road surface. Values of electrical conductivity were lower for the July 20 readings than they were for the June 22 readings, which was expected due to the fact that July 20 correspond with mid-summer when the soil profile should be drier.

Based on the knowledge about the type of drainage system underlying each of the streets, and also the observations of the pavement stress (in terms of cracking) for each street section, one would have expected that the bulk electrical conductivities of the streets would be higher for Spring Avenue and Pleasant Street, than for Cecillee Street and Eckerson Drive. Some distinction was found as a result of the statistical analysis of the data, but for the data analyzed the distinctions did not come out fully as expected. However, the data analyzed were for early summer and mid-summer periods, and it might be better to use bulk electrical conductivity measurements from the period immediately after spring thaw, or late in the fall following period of heavy rain to test for distinctions. It is expected that if the drainage systems perform as they should that the distinctions would come out as hypothesized.

Chapter 9

Summary and Conclusions

This project involved the evaluation of the efficacy of drainage systems for drainage of roadway base materials. The objectives of the study were to:

1. Evaluate three types of subsurface drain configurations for ability to drain the roadway subsurface materials.
2. Conduct simulation modeling of drainage configurations using a numerical solution for solving the variably-saturated flow associated with water flow in the subsurface beneath the roadway pavement.
3. Evaluate the effect of crushed concrete in roadway permeable shoulders and/or base course on deposition of carbonates onto insitu drain tile materials.
4. Evaluate the differences in moisture conditions beneath two types of subsurface drainage systems for city streets.

The first objective was met by installing replicates of three drainage treatments including conventional edgedrains, 2-ft deep centerline drains, and 4-ft deep centerline drains. Drainage outflow from the treatments was measured with tipping buckets installed at the tile outlet points. The length of tile drained by each treatment was 500 feet. The purpose of this part of the study was to determine the difference in drainage efficiency of these drain configurations. Mixed in with the treatments was the effect of topographic position of the road.

In addition to measuring drain outflows, an index to moisture conditions beneath the roadway within each treatment was quantified using an electromagnetic induction instrument. The instrument, Geonics EM38, measured the bulk electrical conductivity of the materials underlying the road, thereby providing an indirect measure of bulk moisture content.

Data (flow and bulk electrical conductivity) was collected from the treatments for the periods of March – November in 2006, 2007 and 2008. In this report data is analyzed only for the 2006 and 2007 periods. The 2008 data is available for additional analysis.

The drain flow data and the bulk electrical conductivity data were subjected to statistical analysis to assess differences in treatment, and also effects of topographic position.

Analyses showed that the edgedrain treatment yielded by far the greatest volume of drainage water during the two-year period of monitoring, 2006-2007. The monitored drainage volume from the centerline drain configurations showed that the 2-ft configuration yielded greater yields in 2006, while in 2007 neither of the drain configurations had a consistently higher drainage volume. Statistical analysis of the flow data showed that the edgedrains yielded significantly more drain flow than either the 2-ft or the 4-ft treatments. This would indicate that the edgedrain treatment is the recommended one to use, but in some specific instances, particularly if the source of water is an artesian ground water source the centerline drains could have an advantage over the edgedrain treatment.

For the edgedrains, those drains located on the north side of the road, which runs east-west, had higher average volumes drained for March and April monitoring periods, but that during the rest of the drainage seasons the drained volumes for the north side were comparable to those on the south side. Results of the statistical testing indicated that the drainage from the north and south sides of the roads were not significantly different over the full drainage season.

Regarding road elevation, considering all drain treatments, drains at relatively low elevations had a higher drain volume during the March and April monitoring periods, but during the rest of the year the drainage volumes did not have a tendency to depend on elevation. This result is expected because the March/April period would involve drainage of snowmelt and water from thawing soils, while later in the year the water source would mainly be from rainfall events. Overall, statistical testing showed that drains at all roadway elevations yielded similar drainage volumes, thereby indicating that all elevations should be drained.

Measurements with the EM38 instrument were conducted for all drainage treatments, using the instrument in both vertical and horizontal orientations. For all cases (dates, drainage treatment, and measurement locations), bulk electrical conductivity measured with the vertical orientation of the EM38 was higher than those measured for the horizontal orientation. This would be expected because the vertical orientation puts more weight on moisture deeper in the soil profile, and it is expected that moisture contents will be higher at larger depths.

Bulk electrical conductivity for edgedrains were higher than those for the centerline drains for measurements taken in selected days of July and August of 2006, as well as April of 2007; values for both 2-ft and 4-ft centerline drains were very close one to another. For the measurements performed in May 2007, however, values of electrical conductivity were a little higher for the 2-ft centerline drainage treatment, while values for both the edgedrains and the 4-ft centerline drains were very similar.

Results of the statistical analysis showed overall the edgedrain treatments had lower bulk electrical conductivity, indicating a lower moisture content beneath the pavement. The statistical tests showed that the orientation of the instrument did not affect this outcome. It is not clear at this point which orientation will be the best to use in distinguishing moisture conditions beneath roadways. Additional work under controlled conditions should be conducted to make this assessment.

To meet the second objective a finite-element numerical model using the COMSOL-MP software was applied to the situation involving variably-saturated flow toward subsurface drains placed beneath roadway pavements. The three drain configurations were considered. The numerical solutions were found to be fairly robust in execution although there were cases where the numerical simulations abruptly terminated before completion. Being that the problems being solved are highly nonlinear it is expected that numerical convergence problems would arise..

The results displayed by the limited number of cases examined showed that the 4-ft depth centerline drain will remove more of the infiltrated water when the soil beneath the pavement subgrade is essentially impermeable and the initial condition is that of essentially saturated matierals. For the case where the initial condition is that of fully drained profile, the edgedrains do best at removing water coming from rainfall infiltration through the permeable shoulder. Simulations were also performed for other conditions, such as the condition of free vertical drainage, and the condition of a static water table beneath the roadway. For these conditions the results are completely different from results for the case with the impermeable boundary. With regard to the applicability of the simulation results to the field site studied here, the impermeable condition is probably more the rule than the exception based on the limited number of borehole logs available for examination.

The numerical solution results do clearly show that the outcome of a given drain configuration depends heavily on the hydraulic properties of the native subgrade material, the depth and degree of compaction of the subgrade material, and the depth of the drain. Even slight variations in geometry can have a dramatic impact on the outcome. Some effects are outlined in this report, but additional analysis is needed to more fully comprehend the full extent of the possible effects.

To accomplish the third objective of the project, samples of drain tile with geotextile fabric, and trench backfill sand were collected from two road sections in Nobles County, CR 32 and the CR 35, both located longitudinally west of Rushmore and east of Adrian. The edgedrain system for CR 32 was about 12 years old, while that for CR 35 was about four years old. The permeable shoulder for CR 35 was constructed with crushed concrete, while that for CR 32 was constructed without crushed concrete.

To test for the presence of carbonate precipitates on the geofabric or in the trench backfill sand, drops of 1 M HCL solution were applied onto the collected materials. The results from the test indicated no presence of carbonates on the samples for CR 35, but for CR 32 there was strong evidence for the presence of carbonates on the geofabric and the trench sand.

The results are interesting although they are somewhat contrary to what might have been expected. Certainly it would have been expected that the CR 32 samples would not have shown any reaction to the application of the acid because there is no crushed concrete in the shoulder or in the base course material. One would expect to see more reaction to the acid for the samples from CR 35 because at least along that roadway a significant amount of crushed concrete was used in the shoulder. It might be that since the conditions for CR 35 have only been in place for about 4 years there has not been sufficient time for migration of significant amounts of calcium carbonate to the tile geofabric or the trench sand.

It is not clear what the source of the calcium carbonate is for the samples derived from CR 32. It might be that the trench sand used for the CR 32 tile installation is carbonate sand, in which case the reaction to the acid would be expected.

To accomplish the fourth objective, bulk electrical conductivity measurements were conducted on four street sections within the city of Worthington using the EM38 instrument. Both vertical and horizontal orientations of the EM38 were used. The roads evaluated were Pleasant Street and Eckerson Drive, in the southwest part of Worthington, and Cecillee Street and Spring Avenue, in the northwest part of the city. Data from two measurement dates, June 22, 2007 and July 20, 2007, were analyzed although data for other dates were collected for the project and are available for further analysis.

Among those streets, Cecillee and Eckerson are both constructed with open graded base for enhanced subsurface drainage, while Pleasant and Spring are both older construction with a less efficient subsurface drainage system. Based on this information one would expect higher bulk electrical conductivity readings for Pleasant and Spring, than for Cecillee and Eckerson.

For both orientations of the EM38, values of bulk electrical conductivity measured on July 20 were lower than those that were collected on June 22. This would be expected because the July date would represent a longer drainage period since spring thaw. Likewise, values corresponding to the vertical orientation of the EM38 were consistently higher than those corresponding to the horizontal orientation. The higher values for vertical orientation are thought to be due not only to higher bulk moisture content, but also due to the presence of public utilities beneath the roads. The horizontal orientation of the instrument would sense less effect from those public utilities.

It was also observed that, for most cases, values of bulk electrical conductivity for both Cecillee Street and Spring Avenue were higher than those collected from both Pleasant Street and Eckerson Drive. Values of bulk electrical conductivity from Spring Avenue were, in general, higher than those from Cecillee Street. The statistical analysis supported these differences as being significant, and the result is that Spring Avenue appears to have the lowest performance with regard to drainage. This result is expected because of what is known about the drainage system. Surface cracking on the street also has patterns that are typically manifest on pavements that have inadequate subsurface drainage.

The distinction in terms of bulk electrical conductivity measurements were not so clear as to distinguish Eckerson Drive from Pleasant Street, or Cecillee Street from Spring Avenue. It is expected that measurements early after spring thaw or late in the fall after period of heavy rain should help to make these distinctions better defined.

The electromagnetic method for indexing the bulk moisture content beneath pavements has high potential for success. Controlled experiments to help in better calibrating the method for paved surfaces should help to increase the utility of the method for future studies and possible practical implementation by highway departments.

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Appendix A

Additional Information on the Experimental Design

Figure A.1 The inventory of tipping buckets constructed for the project

The tipping buckets were all calibrated for flow in the Land and Water Laboratory of the Department of Bioproducts and Biosystems Engineering.

The tipping buckets were installed in March of 2006 before the spring thaw of that year. A series of photos in Figures 4-8 illustrate the installation process.

Figure A.2 Preparing materials for installation at a site

Figure A.3 Preparing the tipping bucket housing and placement of tipping bucket into the housing. Preparation of the tipping bucket in the housing includes the leveling of the tipping bucket

Figure A.4 Levelled tipping bucket ready for connection to the drain outlet from the pavement

Figure A.5 Tipping bucket after connection to the drain

Figure A.6 Closing and the tipping bucket housing. The housing cover is locked to deter vandalism

A few example hydrographs along with the rainfall distribution in the area obtained early in the 2006 season are illustrated in Figure 9a – 9d. A summary of the total volume of water drained for the various treatments is presented in Table 5.

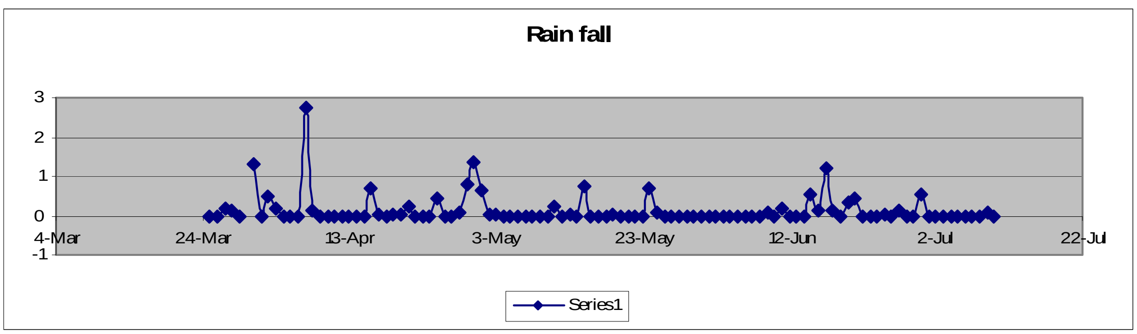

Figure A-7 Rainfall distribution at the experimental site early in the 2006 drainage season

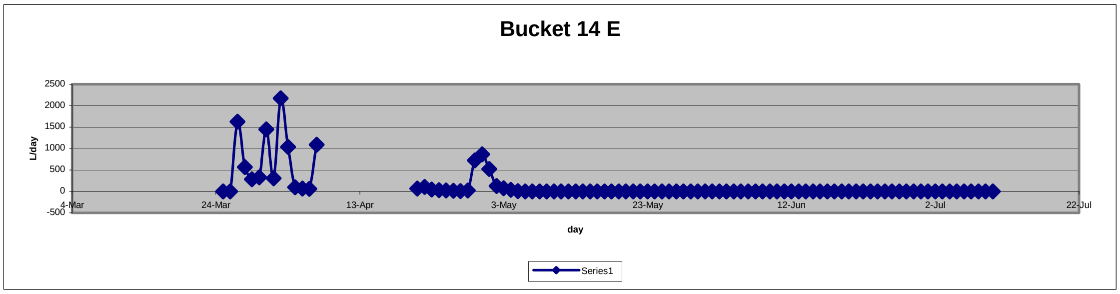

Figure A.8 Distribution of drainage for one of the edgedrain treatments for the early part of the 2006 season

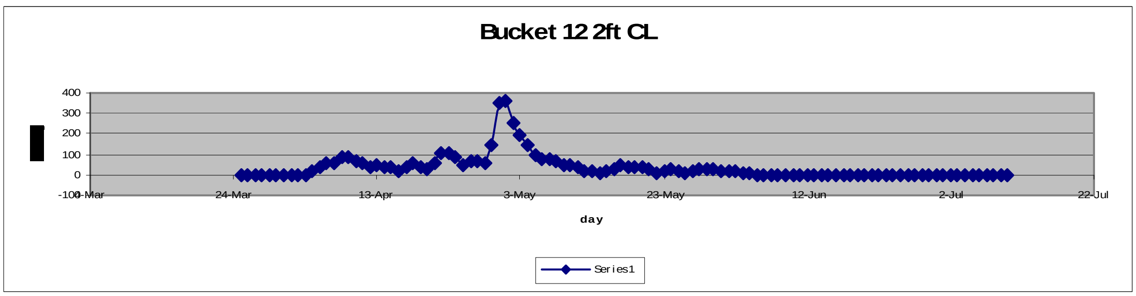

Figure A.9 Distribution of drainage for one of the 2 foot centerline drain treatments for the early part of the 2006 season

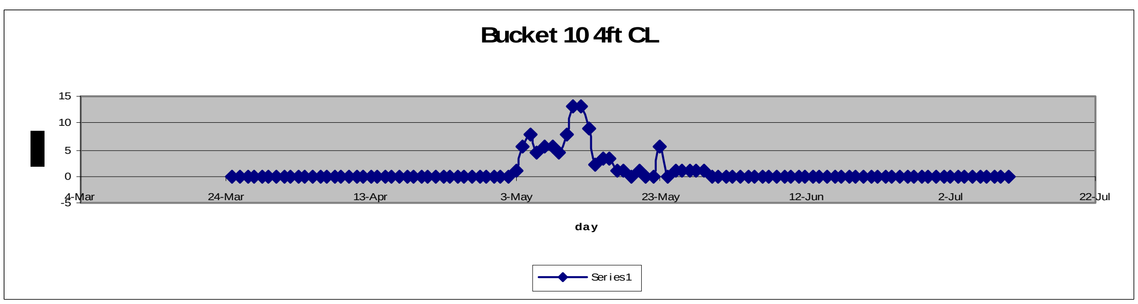

Figure A.10 Distribution of drainage for one of the 4 foot centerline drain treatments for the early part of the 2006 season

Table A-1 Summary of total volume of water drained by each drainage treatment during the early part of the 2006 drainage season

Config	side of roa	bucket #	2 tip vol L		March*	April	May	June
Edge	North	**14**	2.23		4251.4	6732.4	778.3	0.0
Edge	South	**21**	2.89		0.0		0.0	30.3
Edge	North	**13**	2.47		5955.2	7338.1	890.4	0.0
Edge	South	**6**	2.75		1241.6	0.0	0.0	0.0
Edge	South	**3**	2.25		8702.5	7650.0	1820.2	1741.5
Edge	North	**15**	2.3		1.2	4.6	0.0	15.0
Edge	South	**7**	2.405		inc	7320.8	2477.1	913.9
Edge	North	**4**	2.94		8311.2	8239.4	1374.5	477.8
Edge	North	**18**	2.375		1505.8	2523.8	598.5	0.0
Edge	South	**20**	2.3		0.0		0.0	0.0
Edge	North	**19**	2.305		9392.9	9392.9	0.0	618.4
Edge	South	**17**	2.36		0.0	0.0	0.0	3118.7
4 ft CL	South	**22**	2.16		1.1	0.0	4.3	0.0
4 ft CL	South	**1**	2.6		19.5	61.1	5.2	0.0
4 ft CL	South	**16**	2.265		0.0	4.5	0.0	0.0
4 ft CL	North	**9**	2.295		0.0	1.1	0.0	1.1
4 ft CL	South	**10**	2.21		0.0	0.0	100.6	0.0
4 ft CL	North	**8**	2.355		0.0	1.2	1.2	0.0
2 ft CL	North	**23**	2.7		27.0	10.8	0.0	1.4
2 ft CL	South	**12**	2.55		0.0	1895.4	1892.1	49.7
2 ft CL	South	**2**	2.295		0.0	2.3	34.4	0.0
2 ft CL	North	**24**	2.11		0.0	30.6	8.4	0.0
2 ft CL	North	**5**	2.96		1.5	0.0	0.0	1.5
2 ft CL	South	**11**	2.2		523.6	3960.0	35.2	35.2
		Rain fall			2.2	7.25	2.47	3.68

Measurement of base moisture with EM38

The EM38 is an electromagnetic induction instrument for measuring the electrical conductivity of earth materials. Since the electrical conductivity of those materials are related to the moisture (as well as other state variables) of those materials, the EM38 should be able to detect differences in drainage beneath roadway pavements.

A first test of the EM38 was conducted on the agronomy fields north of the St. Paul campus in May 2005. At the site EM38 readings were taken and gravimetric soil moisture samples were taken from the soil profile at several 6 inch increments down to 36 inches. The measurements were taken from several different locations in the field. A plot of the EM38 readings and the corresponding soil moisture measurement for the 0-6 inch depth is illustrated in Figures A-11. Plots for other depths are also available but not shown here. Note that the EM38 has two measurement orientations; vertical and horizontal. These give different readings for the instrument because the depth sensitivity of the generated electromagnetic field is different for these two orientations.

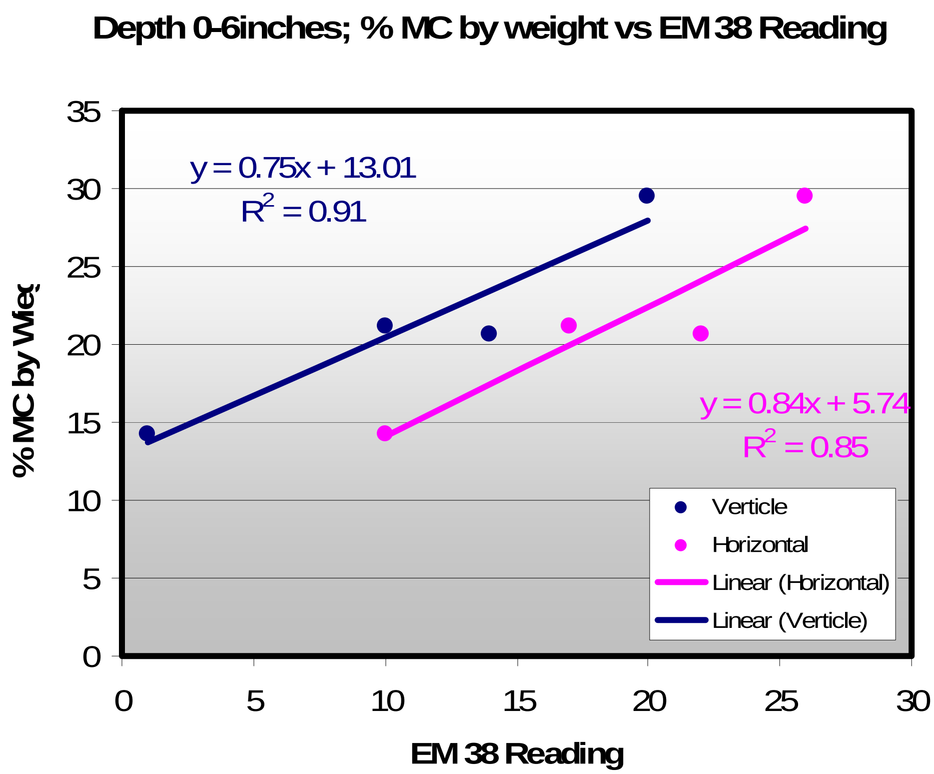

Figure A.11 EM38 reading for vertical and horizontal orientation of the instrument and the moisture content taken from the 0-6 inch depth increment

Four locations in the field are represented by the different data points. At each location in the field a horizontal and vertical orientation measurement was taken.

The scheme for measurement with the EM38 at the Nobles Co. Rd. 35 site is illustrated in Figure A-12. There are ten measurements made at each site according to the scheme shown. The instrument with operator is illustrated in Figures 12 and 13.

An illustration of the type of data collected in the early part of 2006 is presented in Figure 14. These data, along with additional data collected subsequently need to be analyzed to quantify differences. The readings do make sense, however it remains to be determined whether the difference observed are significantly different.

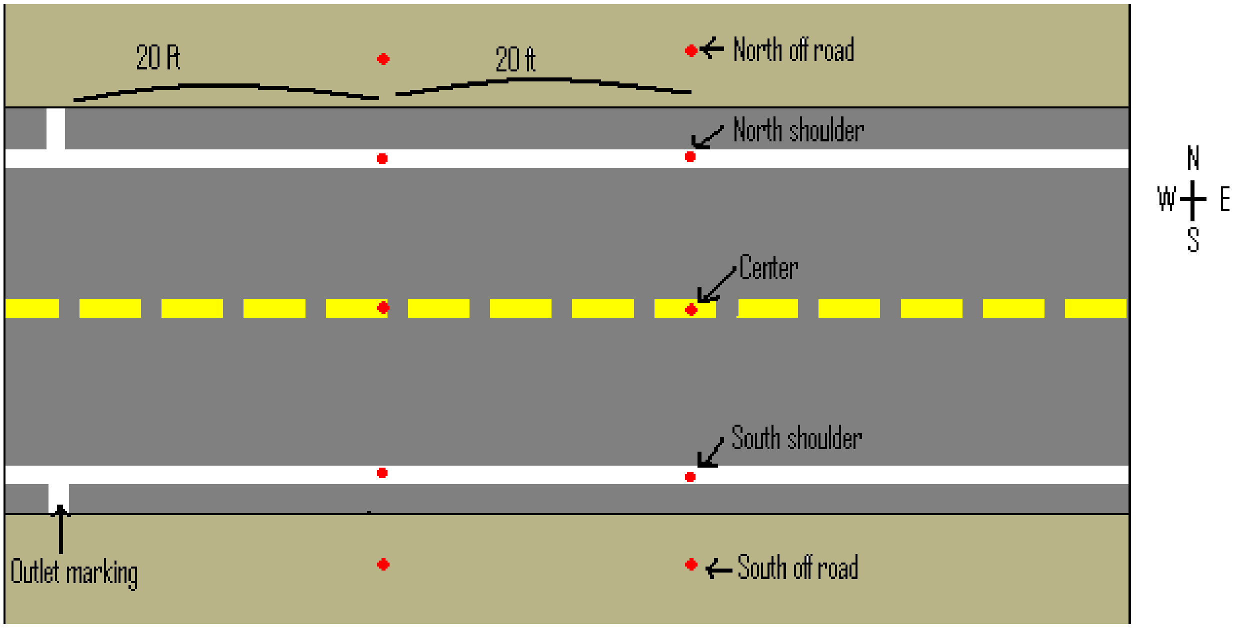

Figure A.12 Measurement scheme for the EM38 instrument at the Noble Co. Rd 35 site

The location of the drain outlet is clearly marked on the road at each drainage outlet. Measurements are then made with the EM38 at the locations indicated by the solid circles (north of road, north shoulder, centerline, south shoulder, and south of road) and along two transects for each drain site.

Figure A.13 The EM38 instrument and the insulation enclosure made for the instrument to shield it from environmental temperature fluctuations


Figure A.14 The EM38 instrument in use

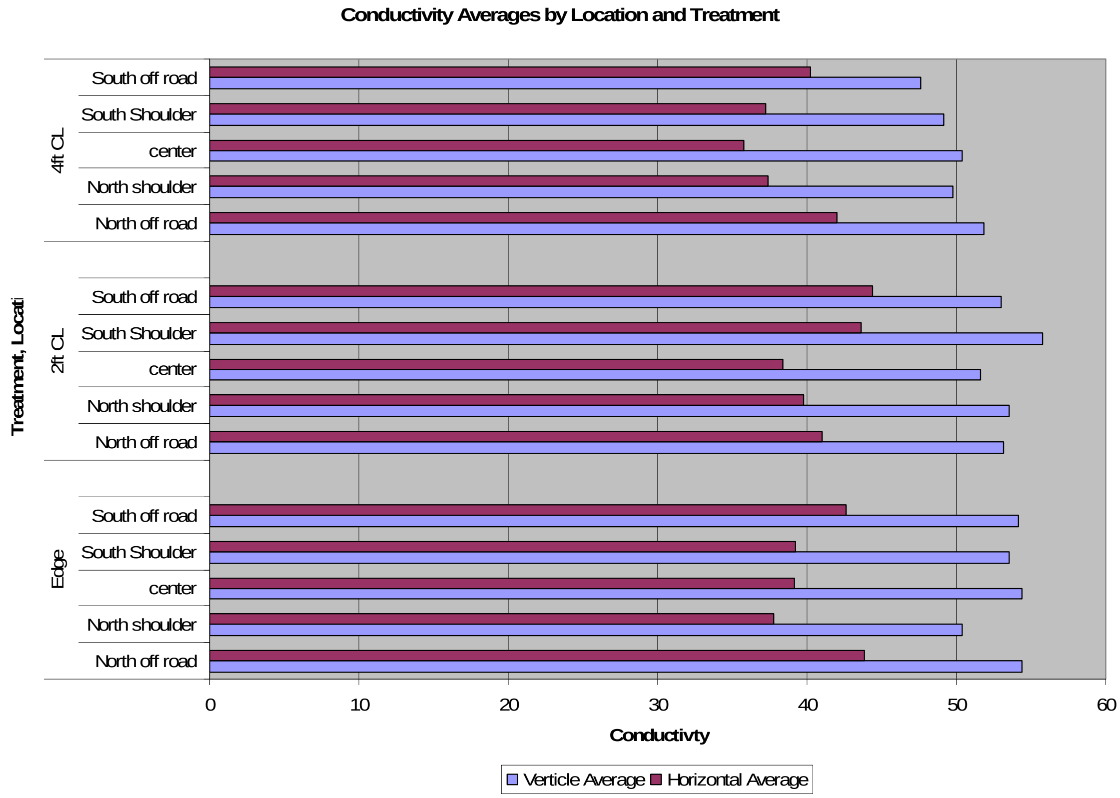

Figure A.15 Electrical conductivity readings from the EM38 for the various drainage treatments for both vertical and horizontal configuration

Appendix B

Additional Information on Monitoring Drainage Outflow

Table B.1 Cumulative volume drained from edge/centerline drains (l) – 2006

TREAT	BUCKET	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEP.	OCT.	NOV.
Edge	14, 21	3473.2	5056.5	651.2	10.12	5.78	0.00	0.00	0.00	0.00
Edge	13, 6	7093.7	7358.1	886.7	1.15	0.00	0.00	0.00	0.00	0.00
Edge	3, 15	6397.9	7650.0	1820.3	1749.43	1.15	2451.88	5357.25	57.38	0.00
Edge	7, 4	11980.50	13152.59	3254.34	1245.74	0.00	1839.83	1562.05	2.41	0.00
Edge	18, 20	1505.75	2487.31	598.50	---	---	---	---	---	---
Edge	19, 17	9391.72	9392.88	0.00	3701.19	0.00	13035.26	4435.51	233.96	0.00
4 ft CL	22	0.00	0.00	1.08	0.00	0.00	0.00	0.00	0.00	0.00
4 ft CL	1	18.20	58.50	5.20	0.00	0.00	0.00	10.40	0.00	0.00
4 ft CL	16	0.00	4.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 ft CL	9	0.00	1.15	0.00	2.30	0.00	0.00	0.00	0.00	0.00
4 ft CL	10	0.00	0.00	61.88	0.00	0.00	0.00	0.00	0.00	0.00
4 ft CL	8	0.00	1.18	1.18	1.17	2.35	0.00	1.17	0.00	0.00
						0.00				
2 ft CL	23	10.80	10.80	0.00	1.35	0.00	0.00	0.00	0.00	0.00
2 ft CL	12	0.00	1895.93	1892.10	49.73	0.00	0.00	0.00	0.00	0.00
2 ft CL	2	0.00	2.30	32.13	0.00	0.00	0.00	0.00	0.00	0.00
2 ft CL	24	0.00	29.54	8.44	0.00	0.00	0.00	0.00	0.00	0.00
2 ft CL	5	1.48	0.00	0.00	1.48	0.00	0.00	0.00	0.00	0.00
2 ft CL	11	0.00	0.00	34.10	30.80	0.00	0.00	0.00	0.00	0.00

Table B.2 Cumulative volume drained from edge/centerline drains (l) – 2007

TREAT	BUCKET	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEP.	OCT.	NOV.
Edge	9, 5	1810.37	1830.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Edge	2, 1	15278.85	14994.20	499.95	574.20	0.00	191.70	0.00	1795.50	0.00
Edge	17, 6	28589.70	15502.42	4009.73	3598.46	0.00	2977.68	846.83	3566.85	0.00
Edge	3, 8	14573.04	14910.68	5723.96	2452.42	0.00	3221.40	1083.58	0.00	0.00
Edge	24, 13	31138.68	18278.66	12802.49	4217.34	0.00	9772.14	8399.70	9049.36	0.00
4ft CL	22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4ft CL	1	125.79	32.95	17.97	5.99	0.00	62.90	0.00	35.94	0.00
4ft CL	16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4ft CL	9	1667.96	1875.29	345.29	0.00	0.00	0.00	0.00	0.00	0.00
4ft CL	10	168.90	9587.89	4931.88	0.00	0.00	0.00	1624.26	11029.17	371.58
4ft CL	8	544.06	158.83	4.67	0.00	0.00	0.00	0.00	0.00	0.00
2ft CL	23	1449.60	2613.81	770.10	491.51	2.27	0.00	0.00	0.00	0.00
2ft CL	12	0.00	0.00	0.00	60.71	0.00	0.00	0.00	0.00	0.00
2ft CL	2	1475.69	722.48	0.00	4.59	0.00	0.00	0.00	0.00	0.00
2ft CL	24	0.00	29.52	0.00	0.00	0.00	4.92	0.00	0.00	0.00
2ft CL	5	3771.14	1377.43	2.32	0.00	0.00	0.00	0.00	0.00	0.00
2ft CL	11	1436.33	1141.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B.3 Cumulative volume drained from high/low areas (l) - 2006

TREAT	BUCKET	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEP.	OCT.	NOV.
Edge	14, 21	3473.23	5056.53	651.16	10.12	5.78	0.00	0.00	0.00	0.00
Edge	13, 6	7093.67	7358.13	886.73	1.15	0.00	0.00	0.00	0.00	0.00
Edge	3, 15	6397.88	7650.00	1820.25	1749.43	1.15	2451.88	5357.25	57.38	0.00
Edge	7, 4	11980.50	13152.59	3254.34	1245.74	0.00	1839.83	1562.05	2.41	0.00
Edge	18, 20	1505.75	2487.31	598.50	---	---	---	---	---	---
Edge	19, 17	9391.72	9392.88	0.00	3701.19	0.00	13035.26	4435.51	233.96	0.00
4 ft CL	22	0.00	0.00	1.08	0.00	0.00	0.00	0.00	0.00	0.00
4 ft CL	1	18.20	58.50	5.20	0.00	0.00	0.00	10.40	0.00	0.00
4 ft CL	16	0.00	4.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 ft CL	9	0.00	1.15	0.00	2.30	0.00	0.00	0.00	0.00	0.00
4 ft CL	10	0.00	0.00	61.88	0.00	0.00	0.00	0.00	0.00	0.00
4 ft CL	8	0.00	1.18	1.18	1.17	2.35	0.00	1.17	0.00	0.00
						0.00				
2 ft CL	23	10.80	10.80	0.00	1.35	0.00	0.00	0.00	0.00	0.00
2 ft CL	12	0.00	1895.93	1892.10	49.73	0.00	0.00	0.00	0.00	0.00
2 ft CL	2	0.00	2.30	32.13	0.00	0.00	0.00	0.00	0.00	0.00
2 ft CL	24	0.00	29.54	8.44	0.00	0.00	0.00	0.00	0.00	0.00
2 ft CL	5	1.48	0.00	0.00	1.48	0.00	0.00	0.00	0.00	0.00
2 ft CL	11	0.00	0.00	34.10	30.80	0.00	0.00	0.00	0.00	0.00

Table B.4 Cumulative volume drained from high/low areas (l)- 2007

TREAT	BUCKET	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEP.	OCT.	NOV.
Edge	9, 5	1810.37	1830.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Edge	2, 1	15278.85	14994.20	499.95	574.20	0.00	191.70	0.00	1795.50	0.00
Edge	17, 6	28589.70	15502.42	4009.73	3598.46	0.00	2977.68	846.83	3566.85	0.00
Edge	3, 8	14573.04	14910.68	5723.96	2452.42	0.00	3221.40	1083.58	0.00	0.00
Edge	24, 13	31138.68	18278.66	12802.49	4217.34	0.00	9772.14	8399.70	9049.36	0.00
4ft CL	22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4ft CL	1	125.79	32.95	17.97	5.99	0.00	62.90	0.00	35.94	0.00
4ft CL	16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4ft CL	9	1667.96	1875.29	345.29	0.00	0.00	0.00	0.00	0.00	0.00
4ft CL	10	168.90	9587.89	4931.88	0.00	0.00	0.00	1624.26	11029.17	371.58
4ft CL	8	544.06	158.83	4.67	0.00	0.00	0.00	0.00	0.00	0.00
2ft CL	23	1449.60	2613.81	770.10	491.51	2.27	0.00	0.00	0.00	0.00
2ft CL	12	0.00	0.00	0.00	60.71	0.00	0.00	0.00	0.00	0.00
2ft CL	2	1475.69	722.48	0.00	4.59	0.00	0.00	0.00	0.00	0.00
2ft CL	24	0.00	29.52	0.00	0.00	0.00	4.92	0.00	0.00	0.00
2ft CL	5	3771.14	1377.43	2.32	0.00	0.00	0.00	0.00	0.00	0.00
2ft CL	11	1436.33	1141.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00

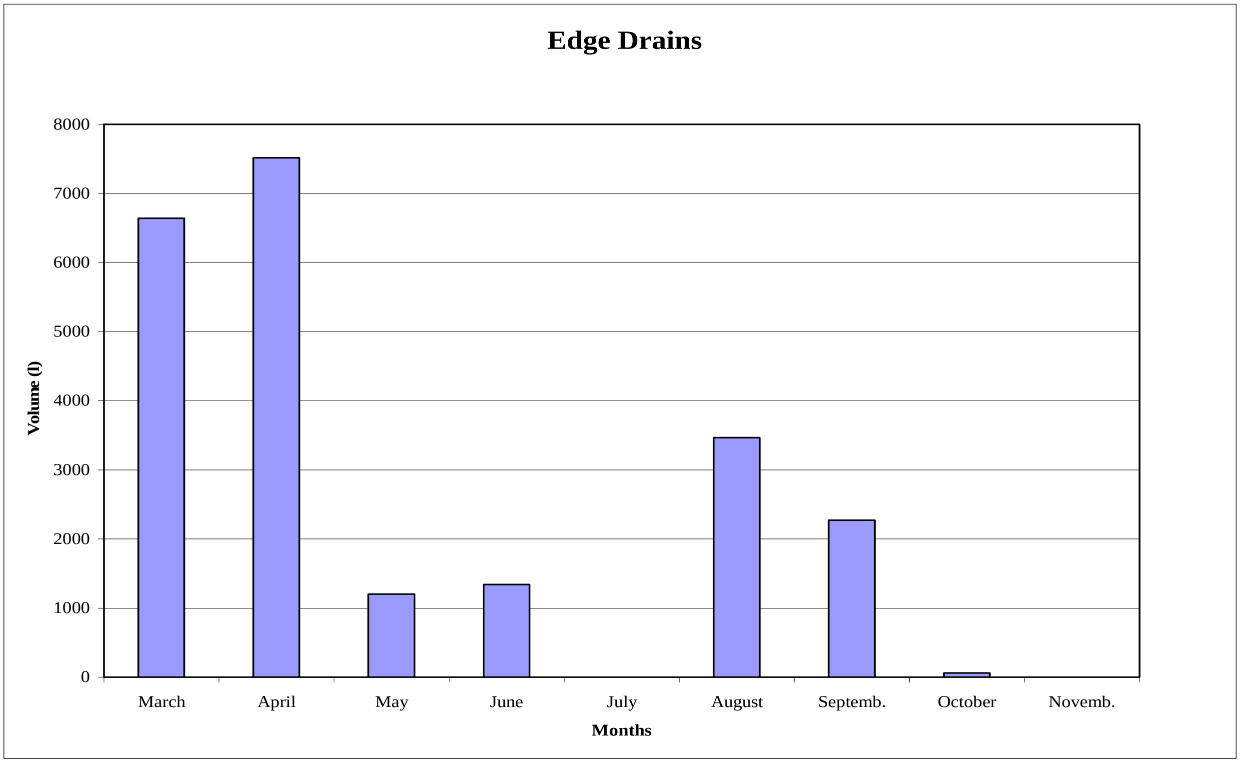

Figure B.1 Average volume drained from edgedrains (l) - 2006

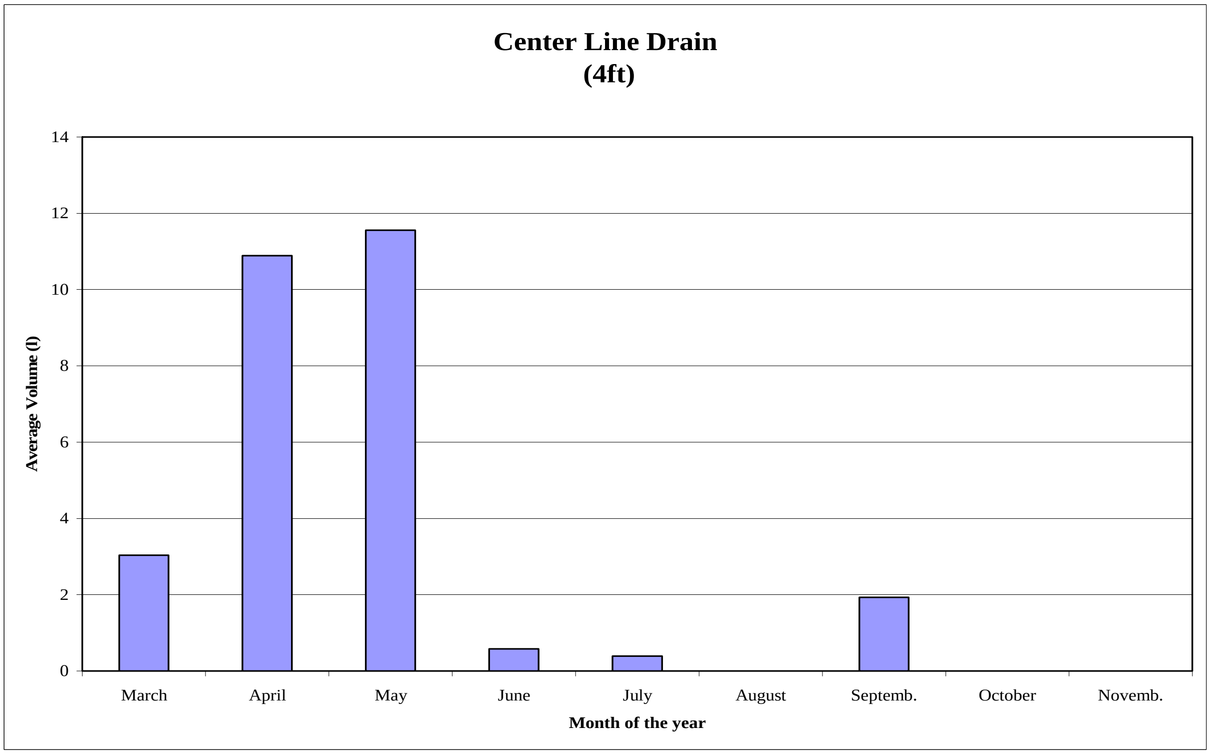

Figure B.2 Average volume drained from 4-ft centerline drains (l) - 2006

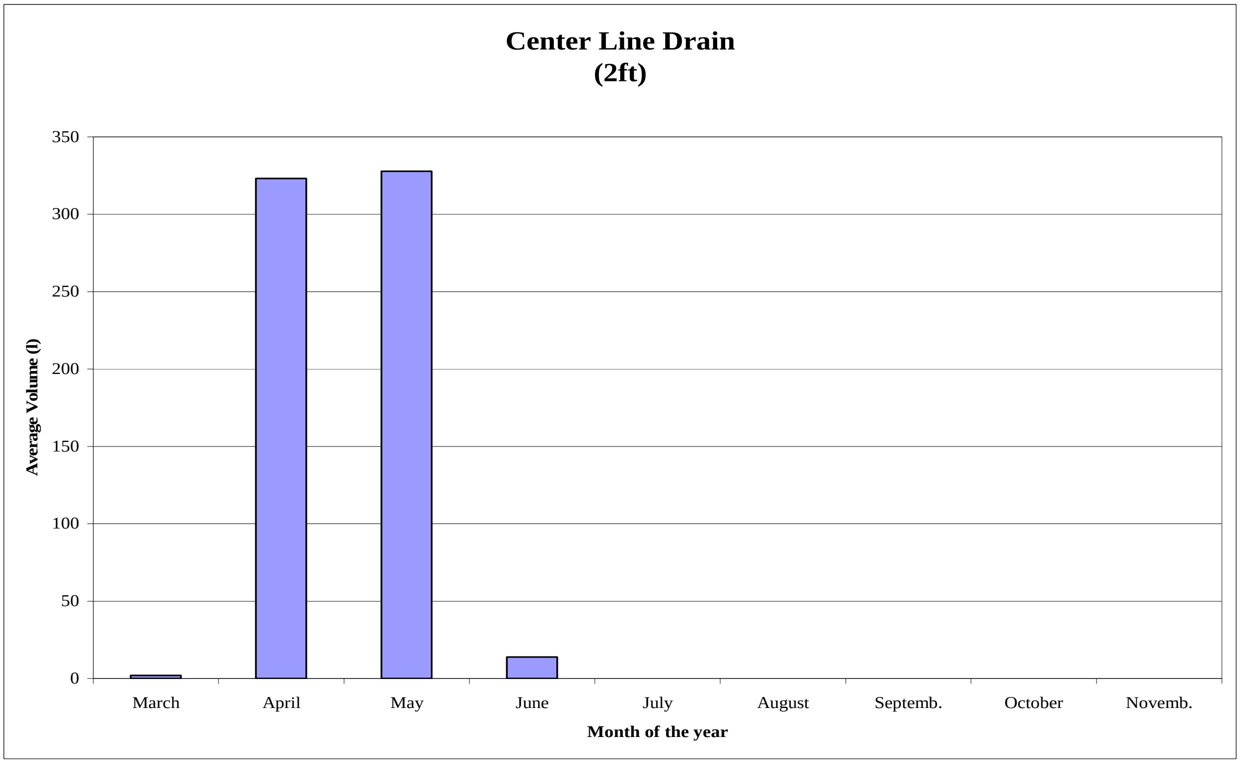

Figure B.3 Average volume drained from 2-ft centerline drains (l) – 2006

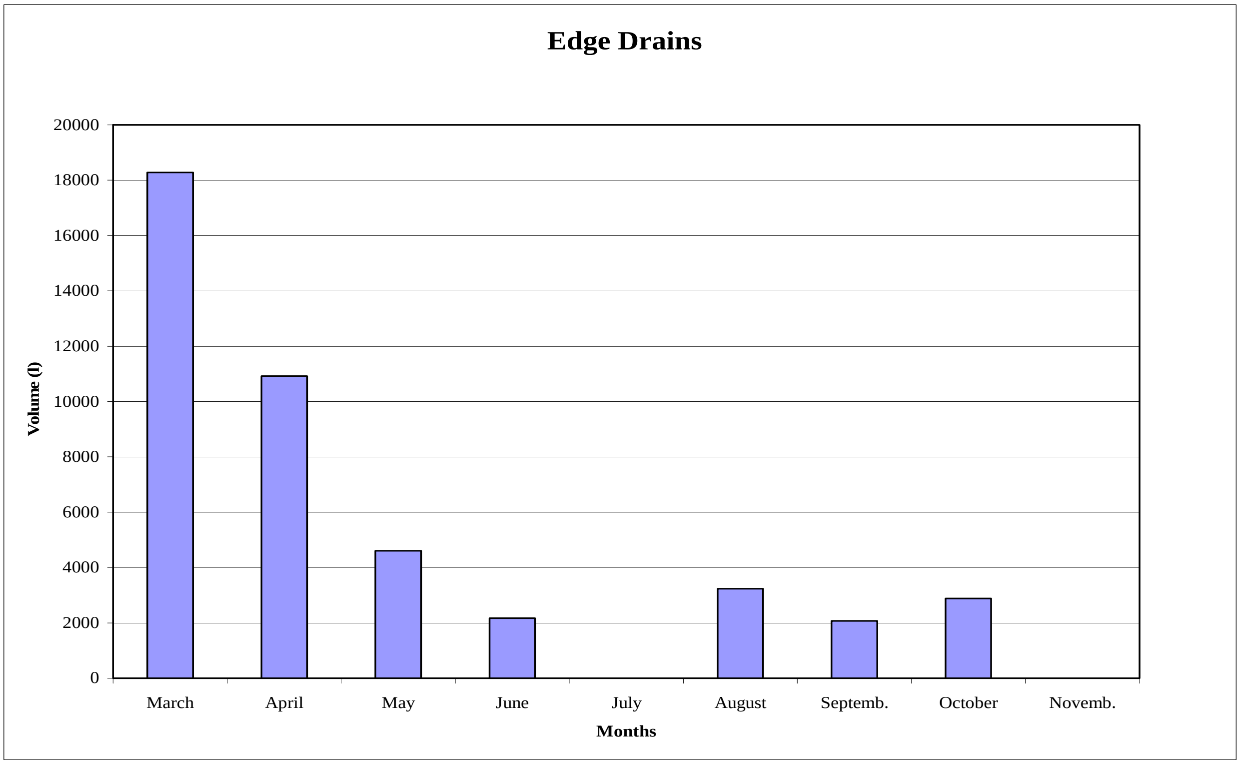

Figure B.4 Average volume drained from edgedrains (l) – 2007

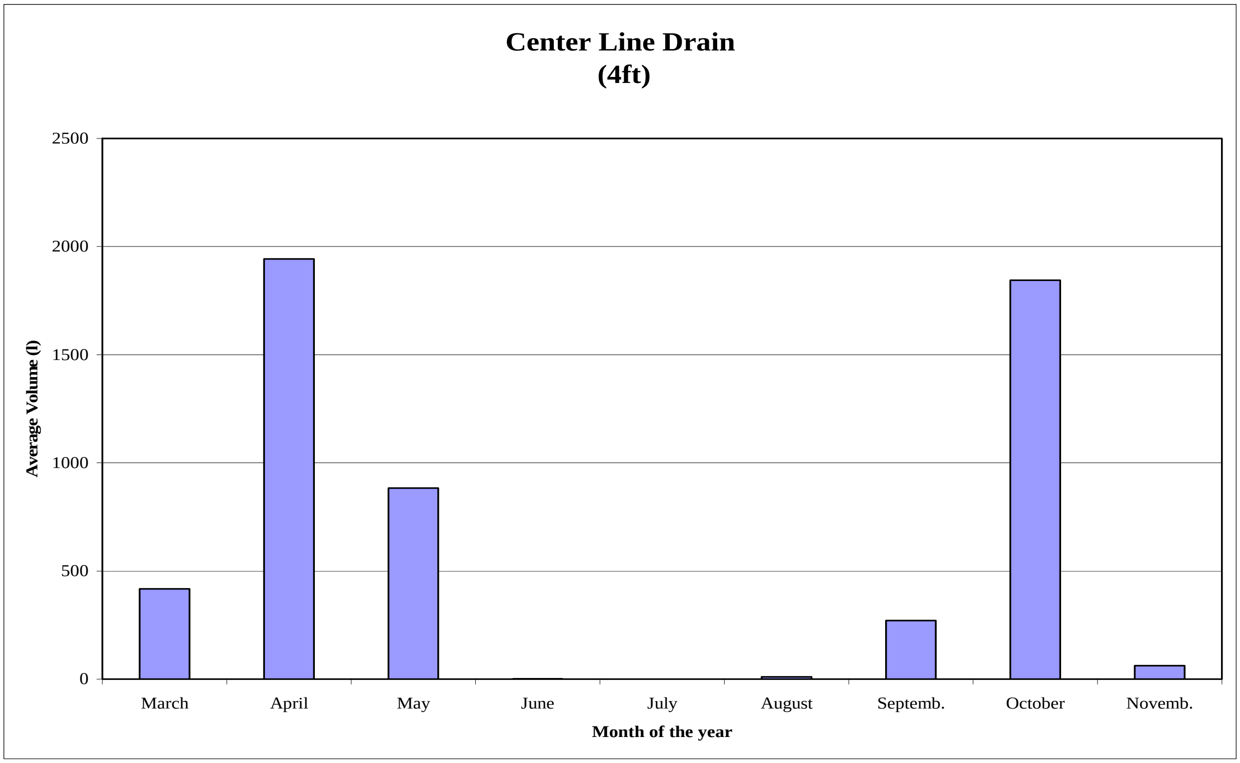

Figure B.5 Average volume drained from 4-ft centerline drains (l) – 2007

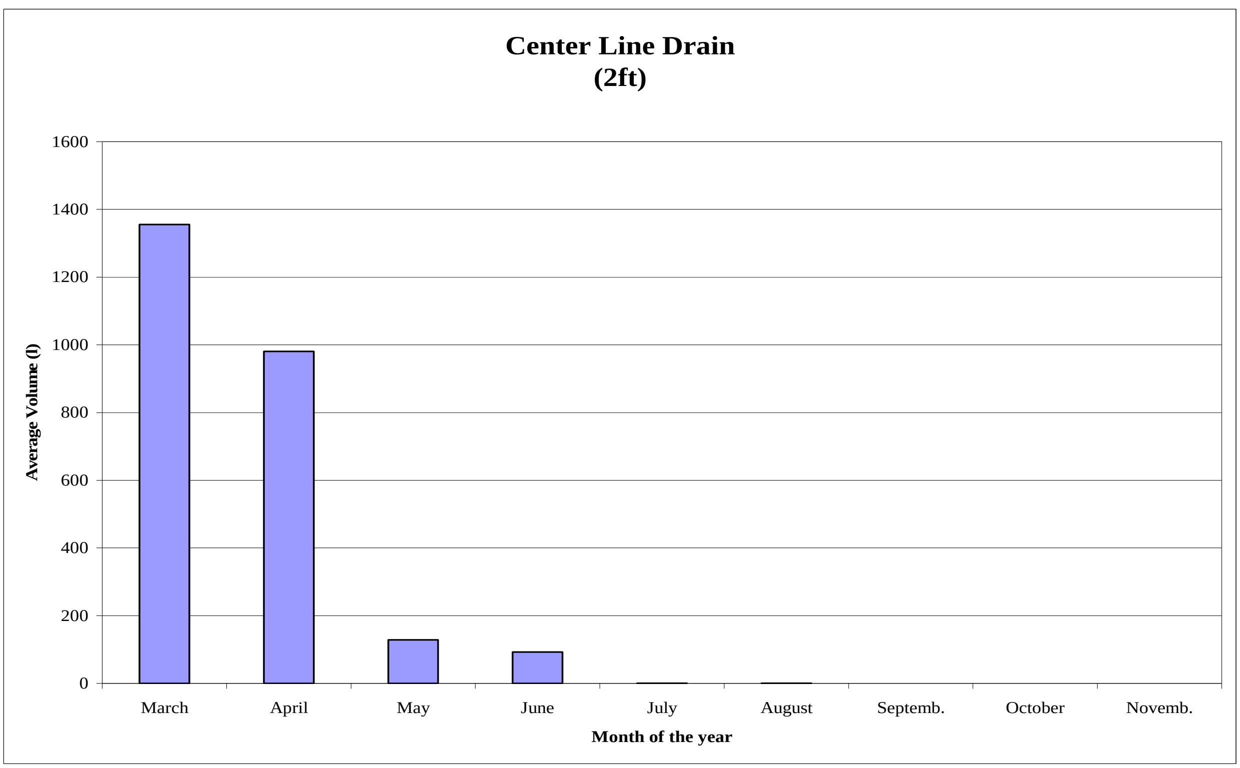

Figure B.6 Average volume drained from 2-ft centerline drains (l) – 2007

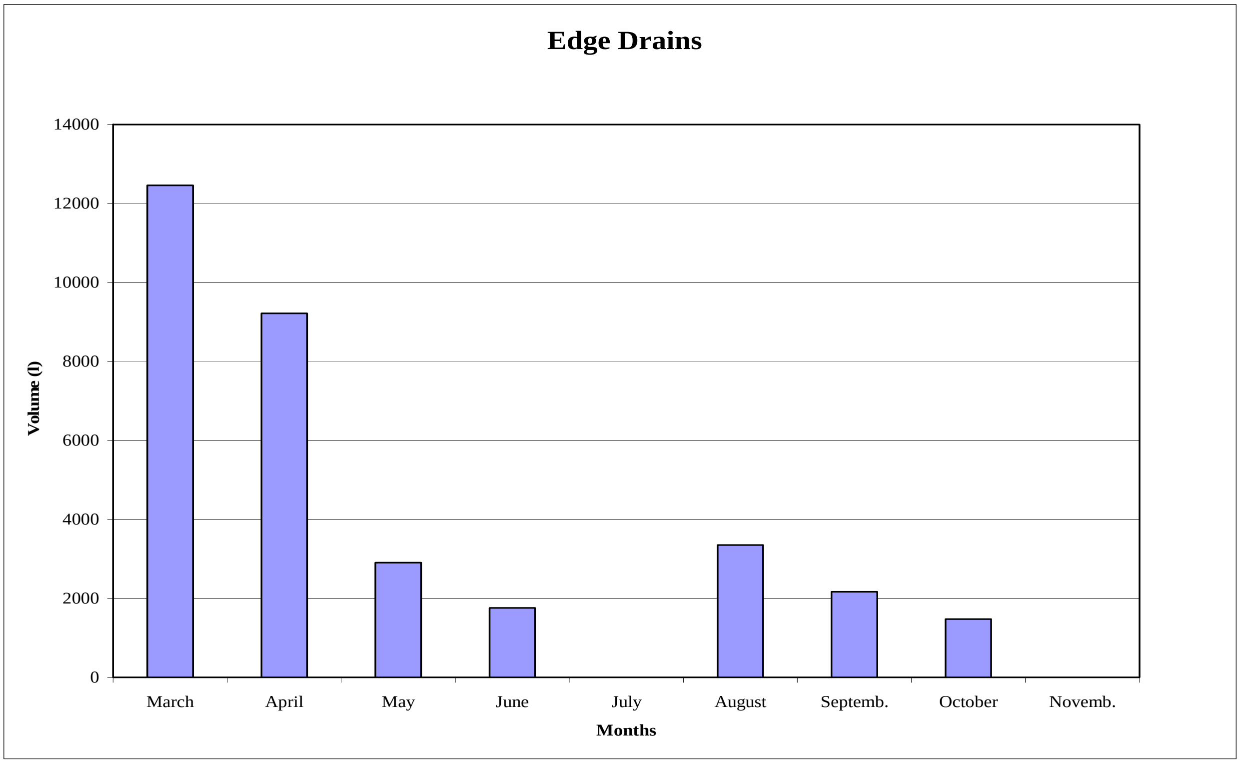

Figure B.7 Average volume drained from edgedrains (l) – 2006-07

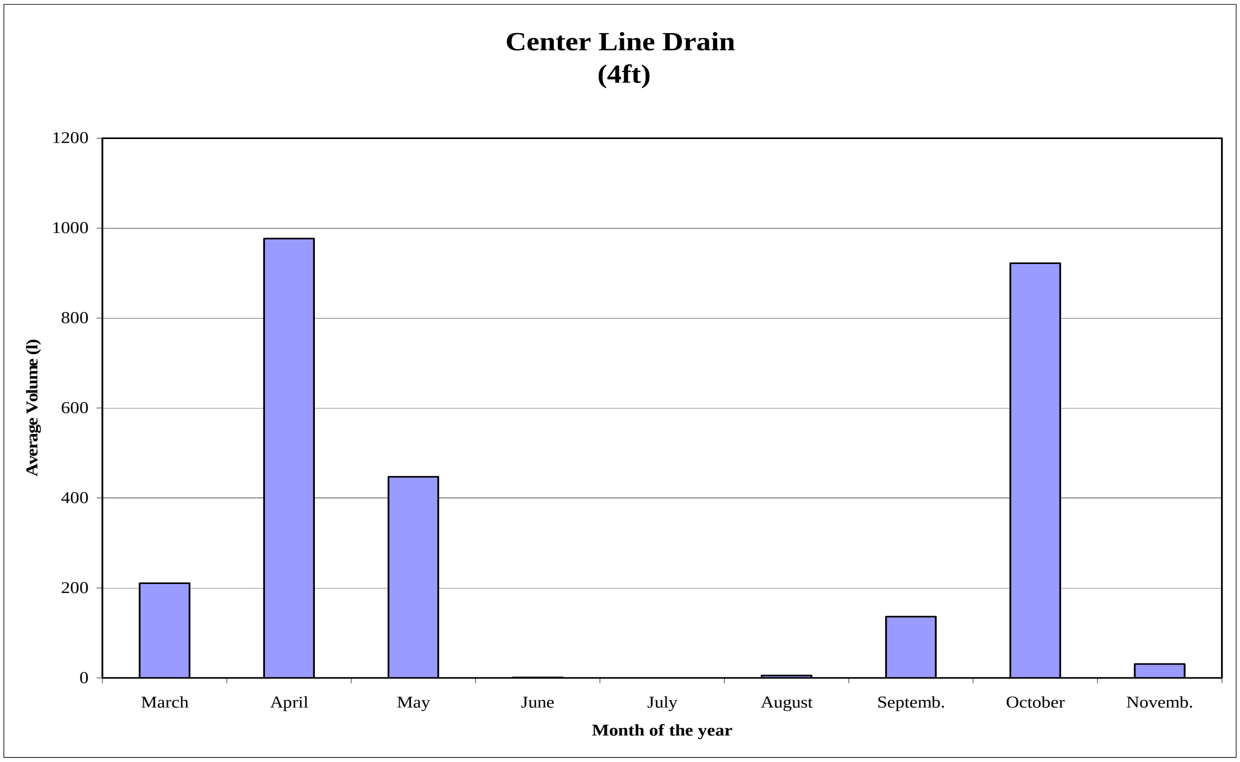

Figure B.8 Average volume drained from 4-ft centerline drains (l) – 2006-07

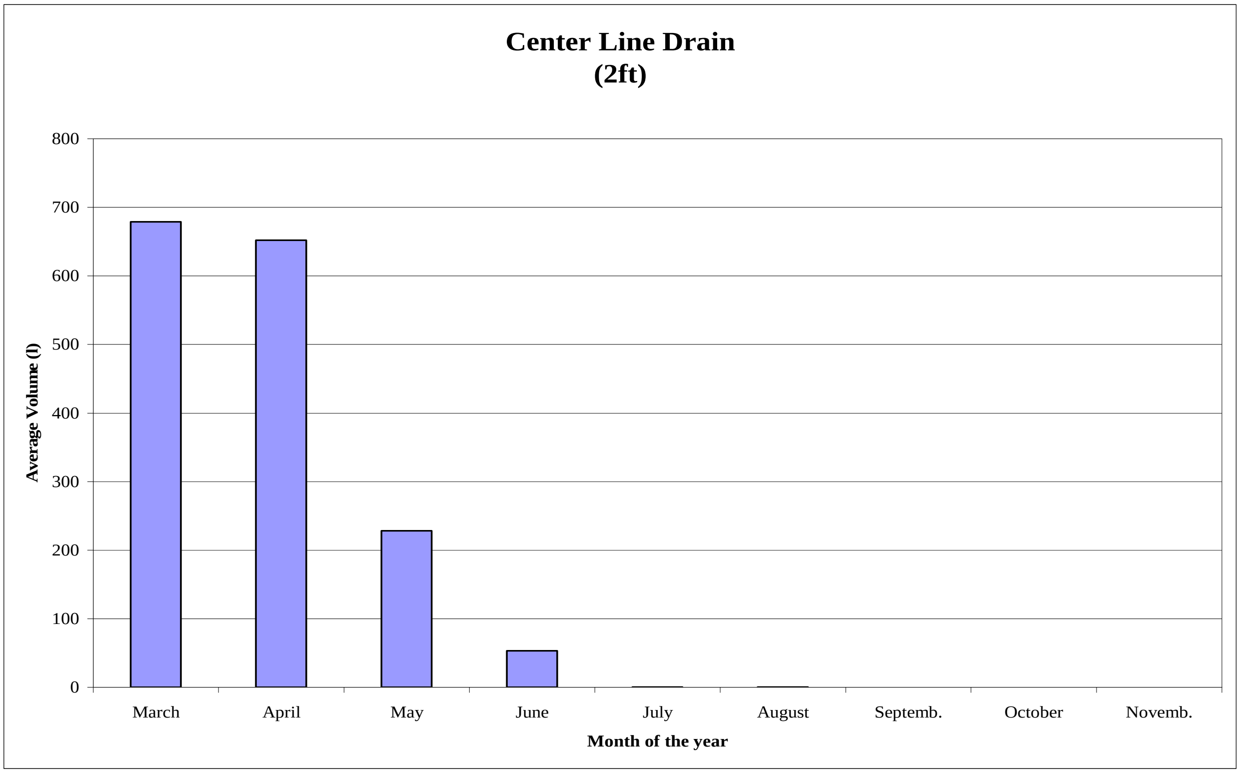

Figure B.9 Average volume drained from 2-ft centerline drains (l) – 2006-07

Appendix C

Additional Information on Electrical Conductivity Measurements

Table C.1 EM38 measurements (mS/m) by drainage treatment, measurement location, and EM38 orientation – July 11, 2006

	EDGE		4-FT CENTERLINE		2-FT CENTERLINE	
	H	**V**	**H**	**V**	**H**	**V**
North of road	51.00	56.00	43.00	51.00	40.00	50.00
	48.00	59.00	45.00	56.00	43.00	53.00
	39.00	46.00	39.00	53.00	43.00	60.00
	40.00	46.00	37.00	48.00	44.00	57.00
	54.00	68.00	38.00	54.00	38.00	47.00
	48.00	66.00	42.00	55.00	39.00	49.00
	36.00	47.00	50.00	51.00	41.00	57.00
	35.00	47.00	42.00	47.00	40.00	52.00
North shoulder	35.00	48.00	36.00	50.00	39.00	52.00
	35.00	46.00	38.00	52.00	42.00	53.00
	35.00	46.00	37.00	52.00	47.00	62.00
	35.00	46.00	35.00	46.00	35.00	59.00
	47.00	63.00	37.00	50.00	36.00	48.00
	46.00	63.00	38.00	49.00	36.00	48.00
	34.00	45.00	39.00	50.00	46.00	55.00
	35.00	46.00	39.00	49.00	37.00	51.00
Center	39.00	58.00	34.00	51.00	38.00	53.00
	39.00	56.00	38.00	53.00	41.00	57.00
	36.00	49.00	40.00	57.00	43.00	61.00
	36.00	49.00	36.00	51.00	40.00	55.00
	49.00	68.00	32.00	44.00	37.00	47.00
	48.00	67.00	34.00	47.00	34.00	46.00
	33.00	44.00	35.00	50.00	38.00	49.00
	33.00	44.00	37.00	50.00	36.00	45.00
South shoulder	41.00	61.00	38.00	50.00	41.00	53.00
	40.00	62.00	38.00	50.00	40.00	40.00
	37.00	51.00	40.00	59.00	58.00	63.00
	39.00	52.00	36.00	49.00	48.00	61.00
	46.00	59.00	33.00	43.00	41.00	53.00
	46.00	61.00	33.00	43.00	41.00	61.00
	33.00	41.00	42.00	51.00	41.00	58.00
	32.00	41.00	38.00	48.00	39.00	53.00
South of road	51.00	61.00	39.00	47.00	44.00	54.00
	48.00	63.00	42.00	47.00	39.00	50.00
	37.00	52.00	45.00	68.00	50.00	58.00
	42.00	54.00	39.00	52.00	51.00	57.00
	47.00	60.00	37.00	44.00	41.00	49.00
	45.00	58.00	35.00	44.00	41.00	48.00
	36.00	41.00	42.00	50.00	46.00	57.00
	35.00	44.00	43.00	29.00	43.00	51.00

Table C.2 EM38 measurements (mS/m) by drainage treatment, measurement location, and EM38 orientation – August 8, 2006

	EDGE		4-FT CENTERLINE		2-FT CENTERLINE	
	H	**V**	**H**	**V**	**H**	**V**
North of road	49.00	61.00	48.00	56.00	43.00	53.00
	58.00	71.00	42.00	54.00	53.00	65.00
	39.00	50.00	48.00	51.00	42.00	50.00
	53.00	62.00	48.00	55.00	46.00	58.00
	55.00	73.00	47.00	56.00	46.00	54.00
	40.00	51.00	39.00	49.00	47.00	58.00
	49.00	61.33	42.00	50.00	39.00	50.00
	49.00	61.33	43.00	49.00	43.00	51.00
North shoulder	35.00	53.00	38.00	51.00	38.00	52.00
	43.00	66.00	36.00	56.00	44.00	64.00
	35.00	47.00	41.00	52.00	36.00	49.00
	36.00	50.00	40.00	56.00	42.00	57.00
	46.00	64.00	37.00	53.00	41.00	55.00
	34.00	46.00	34.00	50.00	46.00	61.00
	38.17	54.33	39.00	52.00	35.00	49.00
	38.17	54.33	38.00	50.00	38.00	53.00
Center	42.00	59.00	35.00	51.00	38.00	54.00
	50.00	70.00	37.00	57.00	44.00	62.00
	33.00	42.00	34.00	43.00	35.00	47.00
	41.00	59.00	34.00	51.00	40.00	51.00
	49.00	68.00	39.00	51.00	42.00	58.00
	34.00	46.00	36.00	52.00	41.00	58.00
	41.50	57.33	36.00	42.00	35.00	44.00
	41.50	57.33	37.00	51.00	37.00	47.00
South shoulder	44.00	64.00	38.00	52.00	42.00	54.00
	46.00	64.00	41.00	61.00	50.00	64.00
	32.00	44.00	38.00	51.00	41.00	54.00
	42.00	65.00	39.00	53.00	42.00	60.00
	46.00	61.00	39.00	52.00	41.00	54.00
	32.00	43.00	37.00	52.00	49.00	65.00
	40.33	56.83	37.00	50.00	40.00	55.00
	40.33	56.83	37.00	51.00	41.00	57.00
South of road	58.00	64.00	40.00	51.00	44.00	56.00
	48.00	63.00	52.00	70.00	53.00	61.00
	48.00	49.00	39.00	48.00	44.00	50.00
	62.00	65.00	47.00	53.00	47.00	59.00
	47.00	61.00	44.00	50.00	43.00	51.00
	43.00	46.00	40.00	54.00	52.00	59.00
	51.00	58.00	39.00	47.00	53.00	51.00
	51.00	58.00	45.00	52.00	46.00	56.00

Table C.3 EM38 measurements (mS/m) by drainage treatment, measurement location, and EM38 orientation – April 21, 2007

	EDGE		4-FT CENTERLINE		2-FT CENTERLINE	
	H	**V**	**H**	**V**	**H**	**V**
North of road	32.00	43.00	43.00	44.00	37.00	43.00
	41.00	58.00	33.00	38.00	32.00	35.00
	28.00	39.00	35.00	42.00	33.00	43.00
	31.00	40.00	35.00	42.00	34.00	43.00
	38.00	56.00	31.00	37.00	30.00	37.00
	28.00	39.00	35.00	46.00	35.00	41.00
North shoulder	32.00	45.00	41.00	49.00	31.00	43.00
	36.00	51.00	30.00	37.00	28.00	36.00
	26.00	36.00	30.00	41.00	32.00	43.00
	32.00	44.00	34.00	48.00	31.00	41.00
	36.00	51.00	29.00	37.00	28.00	36.00
	25.00	36.00	29.00	41.00	31.00	40.00
Center	29.00	41.00	28.00	40.00	30.00	41.00
	38.00	55.00	27.00	32.00	28.00	35.00
	25.00	33.00	27.00	35.00	31.00	41.00
	31.00	42.00	23.00	36.00	31.00	40.00
	37.00	54.00	27.00	32.00	28.00	35.00
	25.00	35.00	30.00	35.00	30.00	37.00
South shoulder	32.00	47.00	30.00	41.00	33.00	44.00
	36.00	49.00	29.00	38.00	32.00	40.00
	25.00	34.00	29.00	38.00	32.00	45.00
	32.00	45.00	30.00	41.00	33.00	43.00
	35.00	48.00	29.00	37.00	32.00	40.00
	26.00	34.00	29.00	37.00	31.00	45.00
South of road	42.00	48.00	33.00	40.00	33.00	47.00
	41.00	51.00	31.00	38.00	32.00	41.00
	30.00	39.00	32.00	42.00	36.00	45.00
	43.00	45.00	33.00	40.00	31.00	44.00
	39.00	49.00	30.00	37.00	34.00	40.00
	33.00	39.00	33.00	43.00	35.00	45.00

Table C.4 EM38 measurements (mS/m) by drainage treatment, measurement location, and EM38 orientation – May 14, 2007

	EDGE		4-FT CENTERLINE		2-FT CENTERLINE	
	H	**V**	**H**	**V**	**H**	**V**
North of road	38.00	46.00	54.00	52.00	46.00	50.00
	45.00	60.00	37.00	46.00	40.00	54.00
	30.00	42.00	36.00	48.00	39.00	50.00
	39.00	46.00	41.00	51.00	40.00	48.00
	43.00	62.00	34.00	47.00	39.00	50.00
	31.00	42.00	44.00	48.00	40.00	46.00
North shoulder	31.00	43.00	46.00	57.00	36.00	49.00
	42.00	58.00	33.00	47.00	40.00	54.00
	31.00	41.00	34.00	46.00	36.00	50.00
	28.00	40.00	42.00	58.00	36.00	49.00
	42.00	59.00	33.00	46.00	40.00	51.00
	30.00	40.00	34.00	48.00	35.00	46.00
Center	32.00	45.00	31.00	48.00	34.00	47.00
	46.00	62.00	30.00	42.00	36.00	52.00
	33.00	27.00	32.00	38.00	35.00	46.00
	31.00	44.00	32.00	43.00	35.00	47.00
	45.00	62.00	31.00	41.00	36.00	50.00
	30.00	40.00	36.00	39.00	34.00	43.00
South shoulder	35.00	51.00	35.00	48.00	39.00	51.00
	40.00	55.00	34.00	48.00	44.00	55.00
	29.00	38.00	35.00	46.00	37.00	52.00
	34.00	51.00	34.00	48.00	39.00	51.00
	42.00	54.00	35.00	48.00	43.00	54.00
	30.00	38.00	36.00	49.00	37.00	50.00
South of road	51.00	49.00	39.00	47.00	38.00	50.00
	41.00	56.00	38.00	48.00	48.00	54.00
	35.00	39.00	40.00	52.00	41.00	53.00
	50.00	50.00	36.00	47.00	38.00	52.00
	40.00	55.00	37.00	49.00	48.00	55.00
	33.00	40.00	36.00	48.00	43.00	52.00