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Use of Nondestructive Evaluation to Detect Moisture in Flexible Pavements

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Use of Nondestructive Evaluation to Detect Moisture in Flexible Pavements

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Supplementary Notes

Abstract

The purpose of this study was to identify the currently available nondestructive evaluation technology that holds the greatest potential to detect moisture in flexible pavements and then apply the technology in multiple locations throughout Virginia. Ground-penetrating radar (GPR) was chosen for use in a field investigation because of its ability to measure large areal extents and reports of successful implementation by other researchers. This technology was used to determine the moisture content of the subgrade beneath five flexible pavement sections in Virginia.

The GPR survey was conducted at normal driving speeds, and data were collected at a sampling rate of 1 scan per foot. For each site, three scans were collected in the travel lane (in the right wheel path, the center of the lane, and in the left wheel path). Existing passing lanes were also scanned. Initial data processing subdivided each pavement section into a three-layer system composed of the hot-mix asphalt layers, the aggregate base layers, and the subgrade. The processing also included calculating the dielectric constant of each layer. These raw data were used to conduct further analyses considering data from only the subgrade. The data were normalized to highlight those areas with the highest dielectric constants since it is known that moisture will have the greatest influence on the dielectric properties of the material.

This study showed that GPR can identify areas of varying dielectric constant attributed to variations in the moisture content of the subgrade of various pavement sections. The use of the GPR offered a safe and rapid means for nondestructively surveying large areas of pavement as the survey was conducted at normal driving speeds. In addition, the use of a statistically based data normalization procedure allowed GPR to be used to assess qualitatively the moisture condition of the subgrade of flexible pavements.

Two advantages of GPR testing are that it can be used to provide a continuous reading of subgrade moisture conditions (rather than a point location) and can be performed at highway speeds with no traffic control. A typical network-level study involving one subgrade bore per mile would cost $1,200 per location. The cost for the current study averaged $0.04 per data point. Assuming one data point every foot and three scans per lane, the resultant cost was approximately $680 per mile. VDOT maintains approximately 225 lane-miles of flexible pavement with subsurface drainage layers and does not routinely inspect the condition of the outlet pipes. In approximately 1 workday, a two-person crew could use a push camera to inspect approximately 5 lane-miles worth of outlet pipes for subsurface drainage layers or the GPR system could scan approximately 330 lane-miles (assuming operation at 55 mph for 6 hours). Thus, the entire system of flexible pavement with subsurface drainage could be inspected in approximately 2% of the time.

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(A partnership of the Virginia Department of Transportation
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DISCLAIMER

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ABSTRACT

The purpose of this study was to identify the currently available nondestructive evaluation technology that holds the greatest potential to detect moisture in flexible pavements and then apply the technology in multiple locations throughout Virginia. Ground-penetrating radar (GPR) was chosen for use in a field investigation because of its ability to measure large areal extents and reports of successful implementation by other researchers. This technology was used to determine the moisture content of the subgrade beneath five flexible pavement sections in Virginia.

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INTRODUCTION

As of 2004, the Virginia Department of Transportation (VDOT) was responsible for maintaining approximately 124,000 lane-miles of pavement on the interstate, primary, and secondary systems (VDOT, 2004). Approximately 6,000 and 19,000 lane-miles of this total are on the interstate and primary networks, respectively. More than 90% of this total consists of either full-depth or one or more flexible layers placed over an existing rigid pavement. With such an extensive roadway network, VDOT incurs a significant annual expense in the maintenance of flexible pavements.

One of the major contributors to deterioration and premature failure of flexible pavements is the presence of excessive moisture within the pavement structure. Water from many sources enters a pavement structure. The largest source of free water in pavement is surface infiltration (Cedergren et al., 1973). This infiltration occurs through cracks and joints in the pavement as well as through the pavement materials themselves. Other sources include rising groundwater, seepage, capillary action, and vapor movement. Common approaches to minimizing the amount of moisture within the pavement include maintaining a longitudinal or a transverse slope, incorporating a permeable drainage layer (with associated longitudinal underdrains) during construction, or retrofitting longitudinal edgedrains after construction.

VDOT uses a uniform cross slope and a longitudinal slope to maintain positive drainage where practicable. In some areas, subsurface drainage features consisting of permeable drainage layers with longitudinal underdrains (placed during the construction process) and retrofitted edgedrains (added after construction) are also used. Published research indicates that if subsurface drainage features are not maintained, their use can be more detrimental to the pavement structure than if subsurface drainage features were not used (Bejarno and Harvey, 2004; National Cooperative Highway Research Program [NCHRP], 2002; Mallela et al., 2000; Hassan et al., 1996; Fleckenstein and Allen, 1996), many state departments of transportation, including VDOT, do not routinely inspect these features on a scheduled basis after acceptance following construction. In addition, VDOT maintains no database to document the physical location of the outlets for these drainage features. At best, roadside markers are placed at the outlet locations. However, these are often damaged or missing because of shoulder maintenance activities or errant vehicular traffic. Thus it is essential that a rapid means for determining the moisture content in the subgrade be investigated. Once identified, this method should also be used to determine if subsurface drainage features, if present, are effective in removing the excess water. In addition, this method could be used to determine where retrofitted edgedrains could best serve in removing excessive moisture from an existing pavement structure.

PURPOSE AND SCOPE

The purpose of this study was to identify the currently available nondestructive (NDE) technology that holds the greatest potential to detect moisture in flexible pavements and then apply that method to multiple locations throughout Virginia.

METHODOLOGY

This study was conducted in two phases: (1) a literature review and (2) selection of an NDE technology and a field investigation.

Literature Review

A literature review was conducted to identify recent studies in moisture damage within flexible pavements and NDE technologies that could be used to detect moisture in flexible pavements. The literature search was conducted by searching relevant electronic databases.

Selection of NDE Technology and Field Investigation

Roadways for NDE testing were identified, and a methodology for evaluating the moisture content of the pavement subgrade was developed. Ground-penetrating radar (GPR) was chosen for use in the field investigation because of its ability to measure large areal extents and reports of successful implementation by other researchers (Maser and Scullion, 1992; Maser, 2002; Al-Qadi et al., 2005).

A GPR survey was performed at highway speeds at five flexible pavement sections in Virginia as shown in Figure 1 and Table 1. The locations tested were the collector/distributor (C/D) lanes on VA Route 288 at US Route 60 in Chesterfield County (near Midlothian), US Route 460 in Prince Edward County (Farmville Bypass), US Route 29 in Pittsylvania County (Chatham Bypass), the C/D lanes on I-81 at US Route 460 in Montgomery County (near Christiansburg), and US Route 460 in Montgomery County (Christiansburg Bypass). These pavements ranged in age from 4 years to greater than 40 years. Two sections (Eastbound Route 460 in Prince Edward County and Southbound Route 29 in Pittsylvania County) were anecdotally known to suffer moisture-related deterioration.

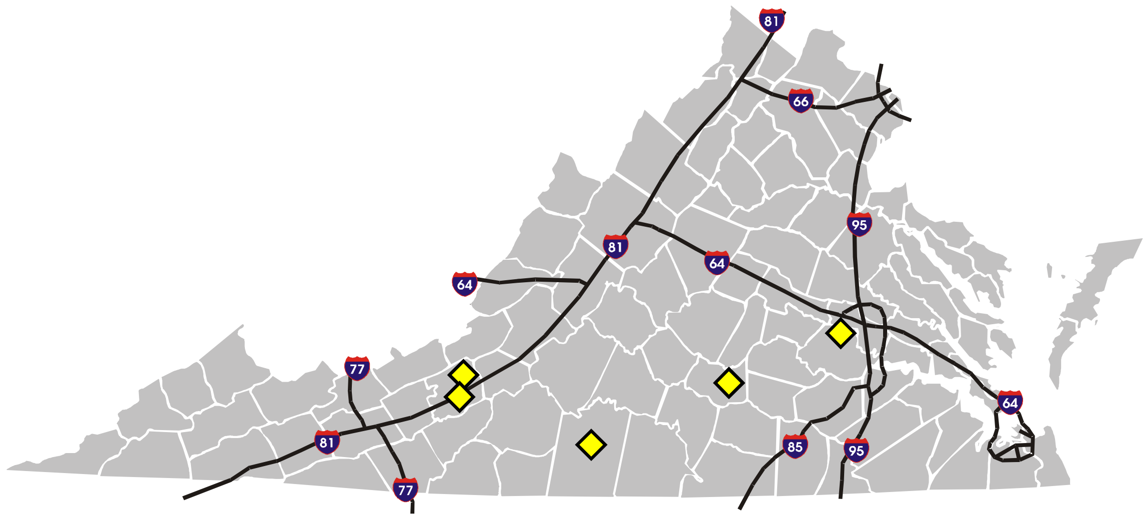

Figure 1. Location of Flexible Pavement Sections

Table 1. Locations for GPR Field Survey

Route	County	Direction	State Relative Mileposts	County Relative Mileposts	Approximate Distance Surveyed, ft
VA 288 C/D lanes at US 60	Chesterfield	Northbound	93+43-109+34 (metric)		6,300
		Southbound	93+24 - 108+56 (metric)		5,520
US 460	Prince Edward	Westbound		8.08-11.91	27,000
		Eastbound		17.04-19.85	15,550
US 29	Pittsylvania	Southbound		23.44-27.13	17,500
I-81 C/D lanes at US 460	Montgomery	Northbound	12.12-14.23		11,765
		Southbound	11.93-13.97		12,000
US 460	Montgomery	Eastbound		9.55-14.37	16,780
		Westbound		9.55-14.37	18,000

C/D = collector/distributor.

As described in greater detail later, the GPR survey was conducted at normal driving speeds, and data were collected at a sampling rate of 1 scan per foot. For each site, three scans were collected in the travel lane (in the right wheel path, the center of the lane, and in the left wheel path). Existing passing lanes were also scanned. Initial data processing subdivided each pavement section into a three-layer system composed of the hot-mix asphalt layers, the aggregate base layers, and the subgrade. The processing also included calculating the dielectric constant of each layer. These raw data were used to conduct further analyses considering data from only the subgrade. The data were normalized to highlight those areas with the highest dielectric constants since it is known that moisture will have the greatest influence on the dielectric properties of the material.

RESULTS AND DISCUSSION

Literature Review

Pavement Moisture Damage

Moisture in a flexible pavement can cause damage in a variety of ways. Moisture in the pavement can interact with the asphalt binder and cause a reduction in the cohesion of the mixture, thus reducing the stiffness and strength of the mixture (NCHRP, 1991). The loss of adhesion between the asphalt binder film and aggregate is caused by water that separates the binder film and the aggregate and breaks the adhesive bond; this phenomenon is commonly called *stripping*. Although stripping is probably one of the most common types of moisture-related damage in pavements, other visually observable distresses include raveling, rutting, shoving, cracking, staining, excess binder, and potholes (Khosla et al., 1999).

Most of the moisture-induced damage in pavements occurs because of loss of adhesion and cohesion of the asphalt mixture. The four main theories of loss of adhesion are chemical reaction theory, mechanical adhesion theory, surface energy theory, and molecular orientation theory (Khosla et al., 1999). As aggregate can be either acidic or basic in nature; when asphalt binder film comes in contact with the aggregate surface, a more basic aggregate surface enhances the bond with the acidic asphalt film. An enhanced bond thus reduces the probability of moisture-induced deterioration. Acidic-type aggregates have also been found to create a sufficient bond with asphalt film; however, the bond with a basic-type aggregate appears to be superior. Mechanical adhesion is dependent on the physical properties of the aggregate. These properties include surface texture, surface area, particle size, and porosity. A rougher surface texture and increased surface area can help enhance the bond of asphalt film to the aggregate. A more porous aggregate can absorb the asphalt and also promote a better bond. The particle size and shape can also enhance the cohesiveness of the mixture through mechanical interlock. Surface energy is associated with the “wettability” of the aggregate. Water is a better wetting agent than asphalt binder because of its lower viscosity and lower surface tension. Thus, the bond between the asphalt binder film and the aggregate may be compromised by excess water on the aggregate surface. The asphalt molecules align with the surface charges on aggregate. This molecular orientation can enhance the bond between the film and the aggregate. Because water is a dipolar molecule, there is a preference for water molecules over asphalt binder molecules at the aggregate surface (Khosla et al., 1999).

Excessive moisture that is allowed to remain under the paved surface can substantially decrease the service life of a pavement structure. Early full-scale pavement tests in the United States, including the Maryland Road Test (Highway Research Board, 1952), the WASHO Road Test (Highway Research Board, 1955), and the AASHO Road Test (Highway Research Board, 1962), indicated that rates of pavement damage attributable to traffic were significantly higher when the pavement structure was saturated. Cedergren (1974) predicted a 50% reduction in pavement service life if a pavement base was saturated as little as 10% of the time.

The most suitable NDE methods to measure moisture in pavements measure the dielectric constant. The dielectric constant is a ratio between the permittivity of a material and the permittivity of a vacuum (free space). The dielectric constant of a porous material, such as a typical pavement, will vary greatly depending on the moisture content within the material (Jaselskis et al., 2003). Thus, variations in the dielectric constant can be correlated to variations in moisture content. However, variations in other materials properties such as air void content and conductivity will also exert some influence (albeit a lesser influence) over the dielectric constant of the in-situ HMA material.

Time Domain Reflectometry

Originally used to measure faults in electrical transmission lines and telecommunication cables, time domain reflectometry (TDR) has been used to monitor the movement of water within soils and determine the moisture content of pavement subbase layers and subgrade materials (Topp et al., 1980; Rada et al., 1994). TDR operates on the principle of measuring the one-way travel time of an electromagnetic wave along a set of metallic waveguides or conductors. The travel time is measured from the wave source to a discontinuity caused by a difference in the impedance of two electrically different materials. For a typical TDR probe, this occurs at two locations: the transition of the cable into the probe and the open end of the probe. If the probe length and the travel time are known, the dielectric constant along the probe can be calculated. The measured dielectric constant will be a function of the electrical properties of the material surrounding the TDR probe.

Although TDR techniques have been used in several projects to study subbase and subgrade moisture within pavements, they are inappropriate for rapidly scanning large areas across many pavement sections. This is because it is not practical to install the probes at one location and then remove them to be used in another location and the measurement area is relatively small when compared to the lateral size of a typical pavement. In addition, research has shown that calibration of the probes for individual materials is necessary for accurate moisture determination (Diefenderfer et al., 2000).

Nuclear and Non-Nuclear Density Gauge

Two devices typically used for pavement density measurements include the nuclear density gauge and the Pavement Quality Indicator (PQI), a non-nuclear technology. The primary purpose of these devices is density measurement; however, each offers a moisture indication. The nuclear density gauge employs a radioactive source that allows a determination of the hydrogen content of the flexible pavement. The hydrogen content is able to be used to determine not only the density of the pavement (since HMA is a hydrocarbon-based product) but also the moisture content. The PQI device displays a value listed as the *H20 Value* and may be used as a way to indicate areas where higher moisture is likely to exist. Although the H20 Value is not the moisture content, it may offer the means for a qualitative view of the moisture beneath the gauge while density measurements are collected. These devices were not considered to be practical for this study since they offer only a point measurement of the moisture content and their primary function is not to measure moisture. These devices may be suitable for measuring moisture within the upper 2 to 3 in of the pavement, but they could not offer the depth of penetration to determine the moisture in the pavement base or subgrade.

Handheld Microwave Device

A device produced by Mesa Systems, Co., and that operates at 2.45 GHz was identified as a potential product that could be used to detect pavement moisture. Based on the manufacturer's claims, the MOIST 200 Handheld Microwave Moisture Sensing System has the ability to measure moisture rapidly within flexible pavements. Moisture detection using this device would be similar to corrosion potential mapping. A combination of the manufacturer's location (Germany) and the lack of retail outlets in the United States did not allow for assessment of this device in this study.

Ground-Penetrating Radar

GPR has been used for evaluating the thickness of new and existing pavements (Maser and Scullion, 1992; Maser, 2002; Al-Qadi et al., 2005) and determining areas of potential deterioration by detecting areas of high-moisture content (Rmeili and Scullion, 1997; Lahouar et al., 2003; Berthelot et al., 2005; Maser and Weigand, 2006). This technology operates by transmitting electromagnetic energy into a pavement structure and receiving the reflection from the various layer interfaces. Since paving materials are insulating (non-conducting), they are able to store energy on a molecular level by polarization when in the presence of an electric field. The degree to which these materials can become polarized is indicated by their dielectric constant.

As an example, water is a highly polar molecule and thus can store more energy than typical paving materials on a molecular level through polarization. The dielectric constant of water is 81 and that of air is 1.0 (Balanis, 1989), whereas values for asphalt and dry granular materials typically range from 4 through 8. Thus, it can be seen that moisture in a paving mixture can greatly influence the dielectric constant of the mixture. The moisture content will have the greatest effect on varying the dielectric constant of a pavement; however, some influence will also be exerted by the materials' conductivity (especially when the subgrade is considered) and air void content.

The dielectric constant of a material can be measured by transmitting electromagnetic energy into the material and recording the reflected signal. For layered material, such as a typical pavement, reflections occur at the interface between two materials having different dielectric properties. By measuring the travel time of the electromagnetic wave, the dielectric constant (ε_r) of the material can be calculated using the following:

$$\varepsilon_r = \left(\frac{c \times \Delta t}{2h}\right)^2 \qquad \text{(Eq. 1)}$$

where

c = speed of light = 3×10^8 m/sec
Δt = two-way travel time, sec
h = thickness of the material, m.

By knowing the dielectric constant of one material at an interface (ε_{r1}), a relationship defining the reflection coefficient (Γ) at an interface between two dissimilar materials allows the calculation of the dielectric constant of the other material (ε_{r2}) at the interface using the following:

$$\Gamma_{1-2} = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \quad \text{(Eq. 2)}$$

Maser and Scullion (1992) used GPR and collected cored samples to measure the thickness of paving layers in addition to the moisture content of the base layer for multiple pavement sections. They stated that the moisture content of the base layer is determined by calculating the dielectric constant following the complex refractive index model (a mixture law) according to the following:

$$\sqrt{\varepsilon_m} = \sum V_i \sqrt{\varepsilon_i} \quad \text{(Eq. 3)}$$

where

ε_m = dielectric constant of the mixture
V_i = the volume fraction of the i^{th} component
ε_i = the dielectric constant of the i^{th} component.

Since the dielectric constant of the subgrade constituents; air, solids, and water have a dielectric constant of 1, 4-8, and 81, respectively, additional moisture has a great influence over the dielectric constant of the entire mixture.

GPR Field Survey

Infrasense, Inc., of Arlington, MA, was contracted to perform a survey of the roadways listed in Table 1 using a GPR system. The testing was conducted between June 15 and June 19, 2005. The testing was performed during a dry period in the summer; there was no recorded precipitation 1 week prior to the testing at any of the sites. The GPR system employed was manufactured by Geophysical Survey Systems, Inc. (GSSI), and consisted of a 1.0 GHz air-coupled horn antenna controlled by a SIR-20 system that collected and recorded the data. The antenna was mounted off the rear of a survey vehicle that was equipped with an electronic distance-measuring instrument (DMI) attached to the rear wheel. A photograph of the vehicle is shown in Figure 2. The GPR survey was conducted at normal driving speeds for the respective routes and used the DMI to pulse the system controller to achieve a sampling rate of 1 scan per foot. For each site, three scans were collected in the travel lane (within the right wheel path, the center of the lane, and within the left wheel path). Passing lanes were also scanned for those sites that possessed them. The GPR survey was conducted in three intervals from the right edge of each lane; thus the data are presented as an offset of 3, 6, or 9 ft for the travel lane only or 3, 6, 9, 15, 18, and 21 ft for the travel and passing lanes.

Figure 2. Ground-Penetrating Radar Survey Vehicle

Testing at Each Location

The following describes the pavement cross section and the testing performed at each location. The pavement cross section information was obtained from VDOT's Highway Traffic Record Information System (HTRIS) database, except for the information for US 29 in Pittsylvania County, which was taken directly from the GPR data.

VA 288 C/D Lanes at US 60, Chesterfield County

The C/D lanes of VA 288 at US 60 in Chesterfield County were constructed in 2004 and consist of approximately 11 in of HMA, placed over 2 in of a permeable aggregate drainage layer, over 8 in of cement-stabilized subgrade. Longitudinal underdrains with outlet pipes were installed during construction. These pavements were surveyed using the GPR device in the northbound (NB) and southbound (SB) directions. The distance scanned in each direction was approximately 1.2 and 1.0 mi for the NB and SB direction, respectively.

US 460, Prince Edward County

The pavement cross section of US 460 in Prince Edward County in the westbound (WB) direction consists of approximately 10 in of HMA placed over 6 in of aggregate base material. The pavement cross section in the eastbound (EB) direction consists of approximately 8.5 in of HMA, 4 in of permeable aggregate drainage layer, 4 in of cement-treated aggregate subbase, and 6 in of cement treated subgrade. A majority of the EB direction was reconstructed in 1995. The pavement was surveyed between county mileposts 8.1 to 11.9 in the WB direction and between county mileposts 17.0 to 19.8 in the EB direction. The EB portion of this route contains longitudinal underdrains with outlet pipes that were placed during reconstruction of this portion of roadway. Anecdotally, the EB direction has a history of moisture-related deterioration. Two lanes were scanned in both the EB and WB directions, *US 29, Pittsylvania County*

VDOT did not have any information in its database as to the composition of the pavement cross section of US 29 in Pittsylvania County. From the GPR testing, this section appears to consist of approximately 11 in of HMA placed over an 8-in layer of aggregate base material. The HMA thickness was verified by coring at two locations. Two lanes were surveyed between county mileposts 23.4 and 27.1. This section of pavement also has an anecdotal history of deterioration related to excessive moisture.

I-81 C/D Lanes at US 460, Montgomery County

The C/D lanes of I-81 at US 460 in Montgomery County were constructed in 2001 and consist of approximately 10.5 in of HMA placed over 3 in of a permeable aggregate drainage layer. This was placed on an 8-in layer of cement treated aggregate. Testing was performed in the NB and SB directions. The distance scanned was approximately 2.2 and 2.3 mi for the NB and SB direction, respectively. One lane was scanned in each direction.

US 460, Montgomery County

US 460 in Montgomery County was constructed as part of a new bypass in 2002; the cross section consists of approximately 9.5 in of HMA, 3 in of a permeable aggregate layer, and 8 in of cement-treated aggregate. The section was surveyed between county mileposts 9.6 and 14.4 in the EB and WB directions. Two lanes were scanned in each direction.

Data Analysis

Initial data processing was performed by Infrasense, Inc., to subdivide each pavement section into a three-layer system composed of the HMA layers, the aggregate base layers, and the subgrade. The processing also included calculating the dielectric constant of each layer. The researchers then used these raw data to conduct further analysis by considering only data from the subgrade. To mitigate the various influences that may affect the dielectric constant of the subgrade (such as density and conductivity), the data were normalized to highlight those areas with the highest dielectric constants since it is known that moisture will have the greatest influence on the dielectric properties of the material.

The normalization procedure was used to return the highest 10% and 1% of the data range through consideration of the mean and standard deviation of the entire data set for each project as shown in Table 2. Thus, a unique normalization was performed at each of the nine pavement sections surveyed. These data ranges were used to determine a low, medium, and high probability of moisture.

An example of the resultant normalized data is shown in Figure 3 for a 60-ft portion of US 460 EB in Montgomery County (Christiansburg Bypass). It is interesting to note that a longitudinal underdrain outlet was located at approximately 8,033 ft. As seen in Figure 3, a concentration of moisture exists within the subgrade between approximately 8,010 and 8,030 ft nearly centered within the right wheel path. Additional figures showing the normalized

Table 2. Statistical Data Analysis

Route	County	Direction	Dielectric Constant		Statistical Limits	
			Average	Standard Deviation	90%	99%
VA 288 collector/distributor lanes at US 60	Chesterfield	Northbound	7.1	1.3	8.8	10.2
		Southbound	6.9	1.1	8.4	9.5
US 460	Prince Edward	Westbound	7.8	1.3	9.5	10.8
		Eastbound	6.1	0.9	7.3	8.3
US 29	Pittsylvania	Southbound	5.7	0.7	6.6	7.4
I-81 collector/distributor lanes at US 460	Montgomery	Northbound	7.3	1.0	8.6	9.7
		Southbound	6.5	0.8	7.6	8.5
US 460	Montgomery	Eastbound	7.8	1.0	9.0	10.1
		Westbound	8.0	1.0	9.4	10.5

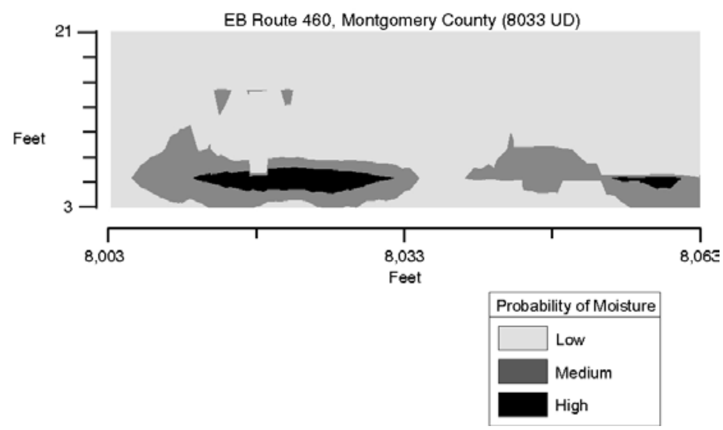

Figure 3. Example of Normalized Dielectric Constant: Portion of Eastbound US 460 in Montgomery County

dielectric constant for the nine locations are provided in the Appendix. Because of space limitations, only 3,000 ft from each location is presented in this report. Figures showing more detailed information for the VA 288 NB and SB C/D lanes at US 60, US 460 EB in Prince Edward County, and US 460 EB in Montgomery County are also provided in the Appendix. These three sections were highlighted since they included subsurface underdrain outlets that were readily located and could be compared with the collected normalized dielectric constant data.

Summary of GPR Field Survey

The Appendix presents the figures showing the normalized dielectric constant for each of the nine sections surveyed using the GPR. These figures show a variation in the normalized dielectric constant throughout the pavement sections. This variation depicts the changes in moisture content within the pavement subgrade. Because of the ability of this technology to detect areas of potentially higher moisture contents, it may have the potential to be used as a tool for preventive maintenance by indicating areas with the potential for moisture-induced damage before it occurs. The ability of the technology to detect moisture before the pavement actually deteriorates will help to reduce maintenance and rehabilitation costs over the life of the pavement. In addition, Figures A-6 and A-8 show areas of high potential for moisture where no subsurface drainage exists.

CONCLUSIONS

- *GPR can identify areas of varying dielectric constant attributed to variations in the moisture content within the subgrade of various pavement sections.*
- *GPR offers a safe and rapid means for nondestructively surveying large areas of pavement as the survey can be conducted at posted speeds.*
- *Use of a statistically based data normalization procedure allows GPR to be used to assess qualitatively the moisture condition of the subgrade of flexible pavements.*

RECOMMENDATIONS

1. *VDOT's Materials Division and VTRC should consider using GPR to periodically monitor variations in the subgrade moisture to identify areas with the potential for moisture-induced deterioration for those projects that encounter a high-moisture content in the subgrade during construction.*
2. *VTRC should revisit the sites tested in this study after a precipitation event to determine the change in subgrade moisture condition and quality of pavement drainage in accordance with the 1993 AASHTO Guide for the Design of Pavement Structures (AASHTO, 1993).*
3. *VTRC should investigate whether the statistical methodology for evaluating the GPR results could be correlated to quantitative subgrade moisture content across a variety of subgrade and pavement conditions through the use of soil borings in a future study.*
4. *As part of the design process for placement of retrofitted longitudinal edgedrains for future rehabilitation, VDOT's Materials Division should consider conducting a study using GPR to determine where the areas of highest moisture content exist such that the edgedrains are used in areas where they are most effective and most needed.*
5. *VTRC should monitor pavements with retrofitted edgedrains using GPR before and after installation to determine the effectiveness of using retrofitted edgedrains.*
6. *VTRC should study the potential for correlating the condition of subsurface drainage outlets with qualitative moisture content as measured using GPR.*

BENEFITS AND COSTS ASSESSMENT

This study showed that GPR has the potential to survey large areas of pavement rapidly. Currently, VDOT does not conduct routine inspections of its flexible pavement inventory to assess the potential for moisture-induced damage. If VDOT were to investigate the probability of moisture within the subgrade, the only currently available technique would be subgrade boring.

Two advantages of GPR testing are that it can be used to provide a continuous reading of subgrade moisture conditions (rather than a point location) and can be performed at highway speeds with no traffic control. A typical network-level study involving one subgrade bore per mile would cost $1,200 per location. The cost for the current study averaged $0.04 per data point. Assuming one data point every foot and three scans per lane, the resultant cost was approximately $680 per mile. VDOT maintains approximately 225 lane-miles of flexible pavement with subsurface drainage layers and does not routinely inspect the condition of the outlet pipes. In approximately 1 workday, a two-person crew could use a push camera to inspect approximately 5 lane-miles worth of outlet pipes for subsurface drainage layers or the GPR system could scan approximately 330 lane-miles (assuming operation at 55 mph for 6 hours). Thus, the entire system of flexible pavement with subsurface drainage could be inspected in approximately 2% of the time.

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APPENDIX
RESULTS OF GPR FIELD SURVEY SHOWING PROBABILITY OF MOISTURE

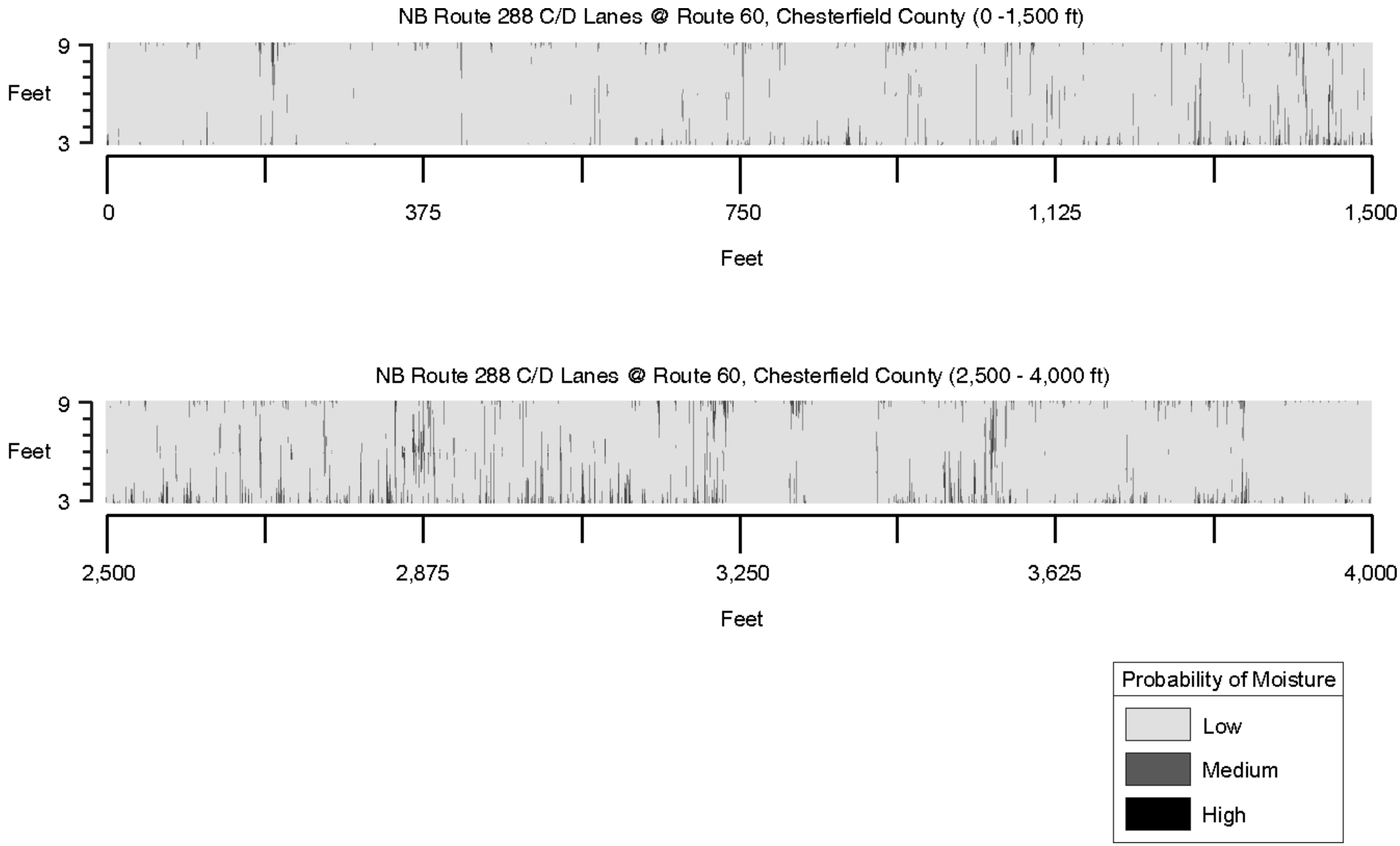

Figure A-1. Normalized dielectric constant showing probability of moisture for portions of northbound Route 288 collector/distributor lanes at Route 60 in Chesterfield County

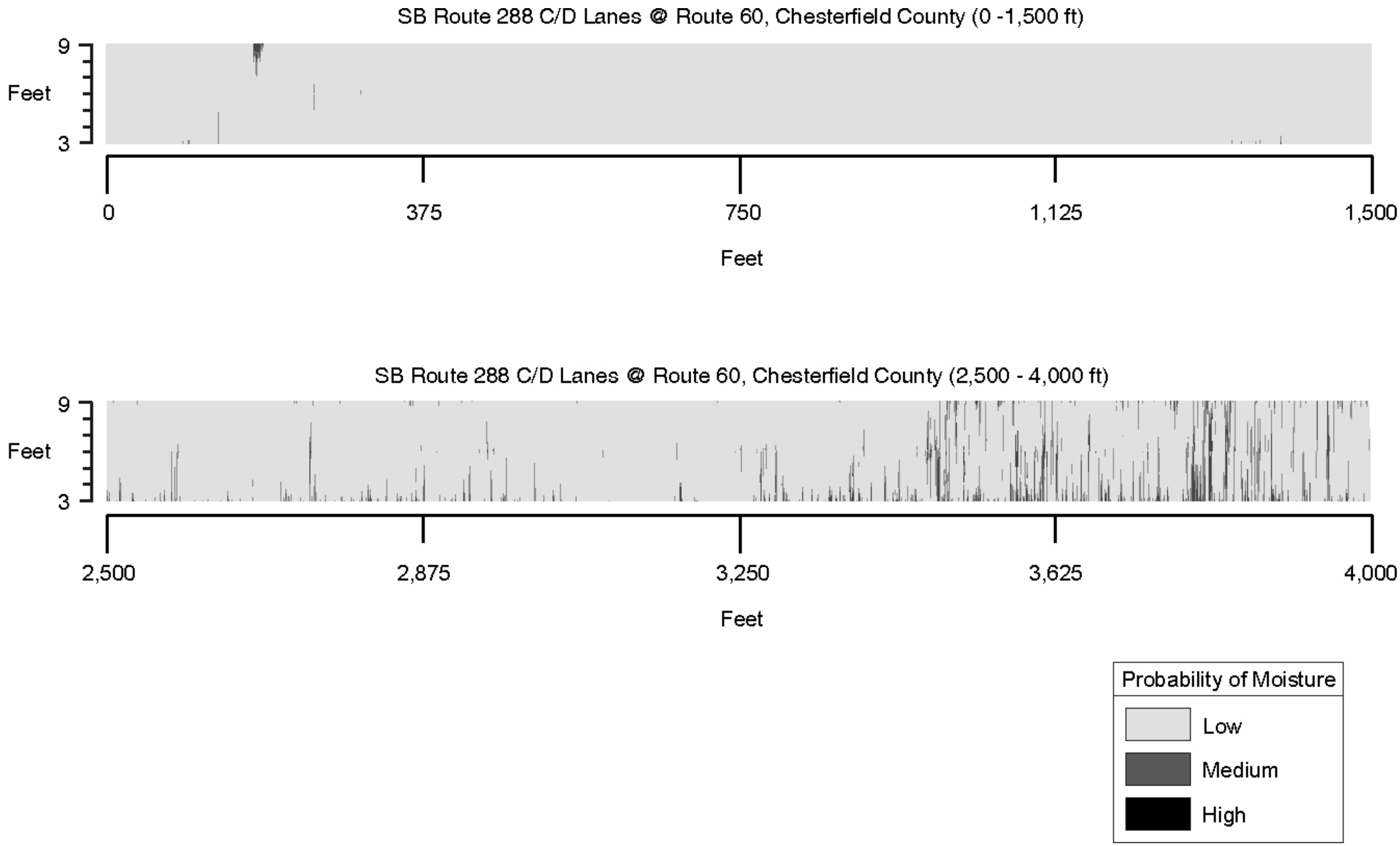

Figure A-2. Normalized dielectric constant showing probability of moisture for portions of southbound Route 288 collector/distributor lanes at Route 60 in Chesterfield County

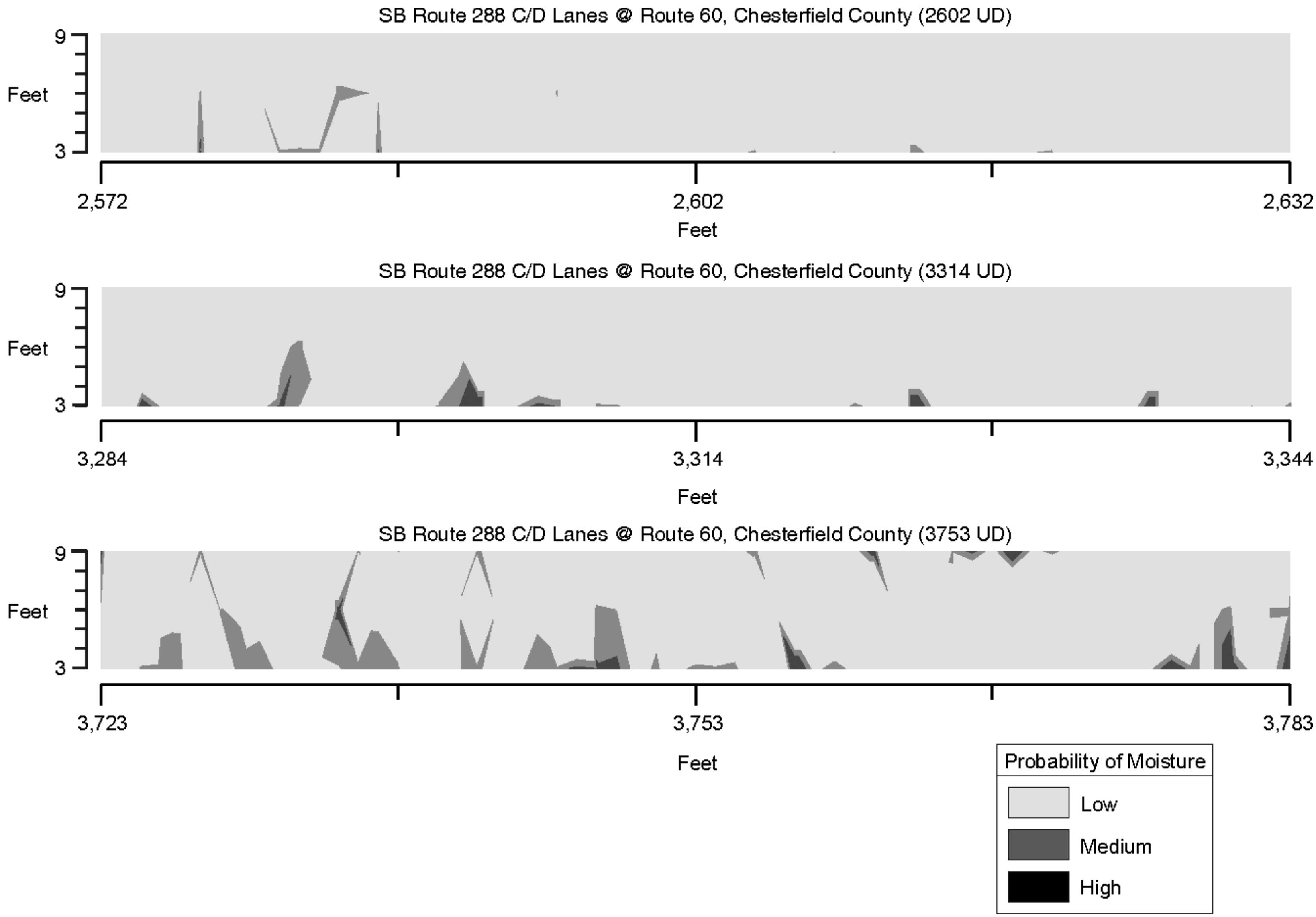

Figure A-3. Detailed view of normalized dielectric constant showing probability of moisture for portions of southbound Route 288 collector/distributor lanes at Route 60 in Chesterfield County at locations of underdrain outlets

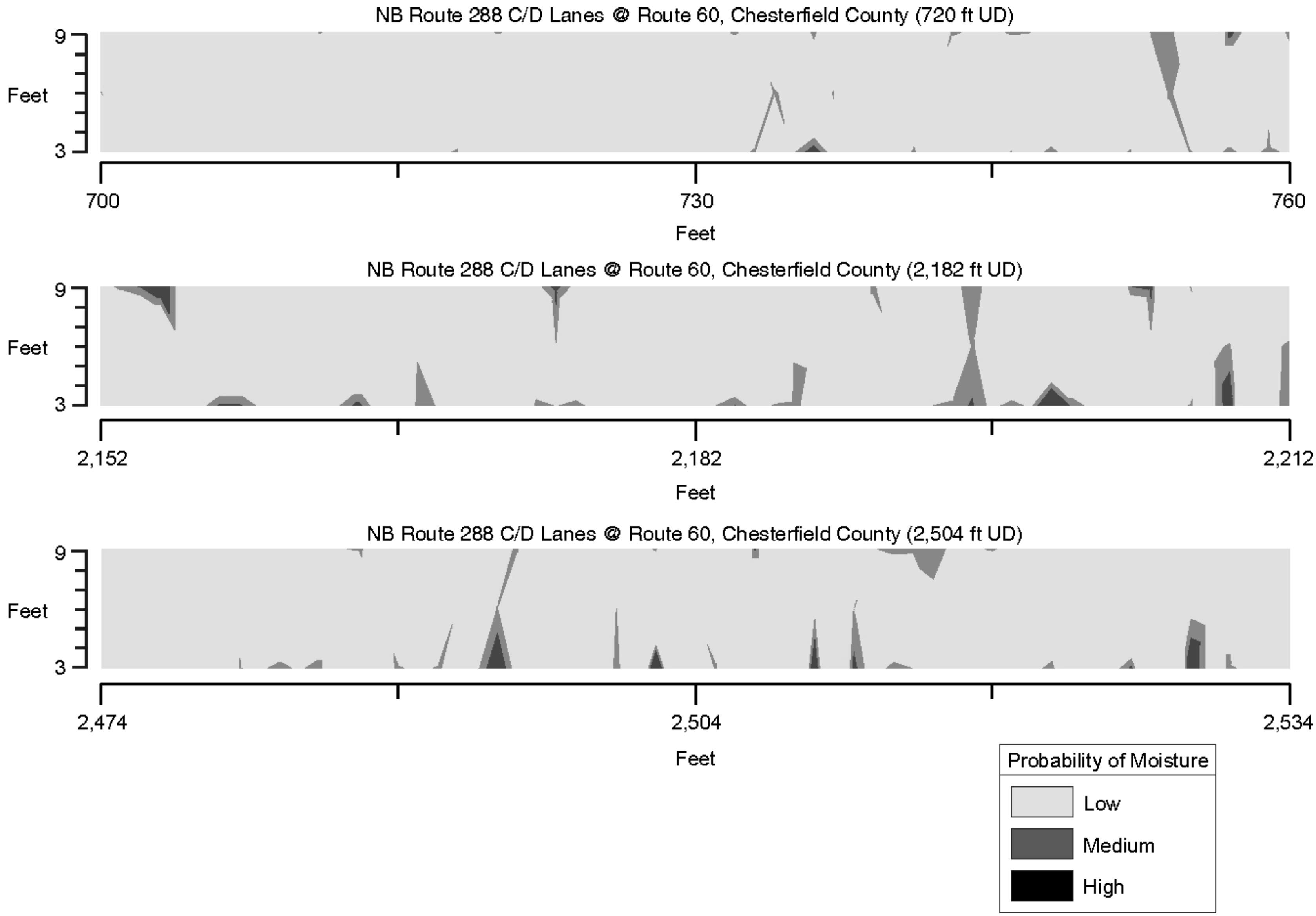

Figure A-4. Detailed view of normalized dielectric constant showing probability of moisture for portions of northbound Route 288 collector/distributor lanes at Route 60 in Chesterfield County at locations of underdrain outlets

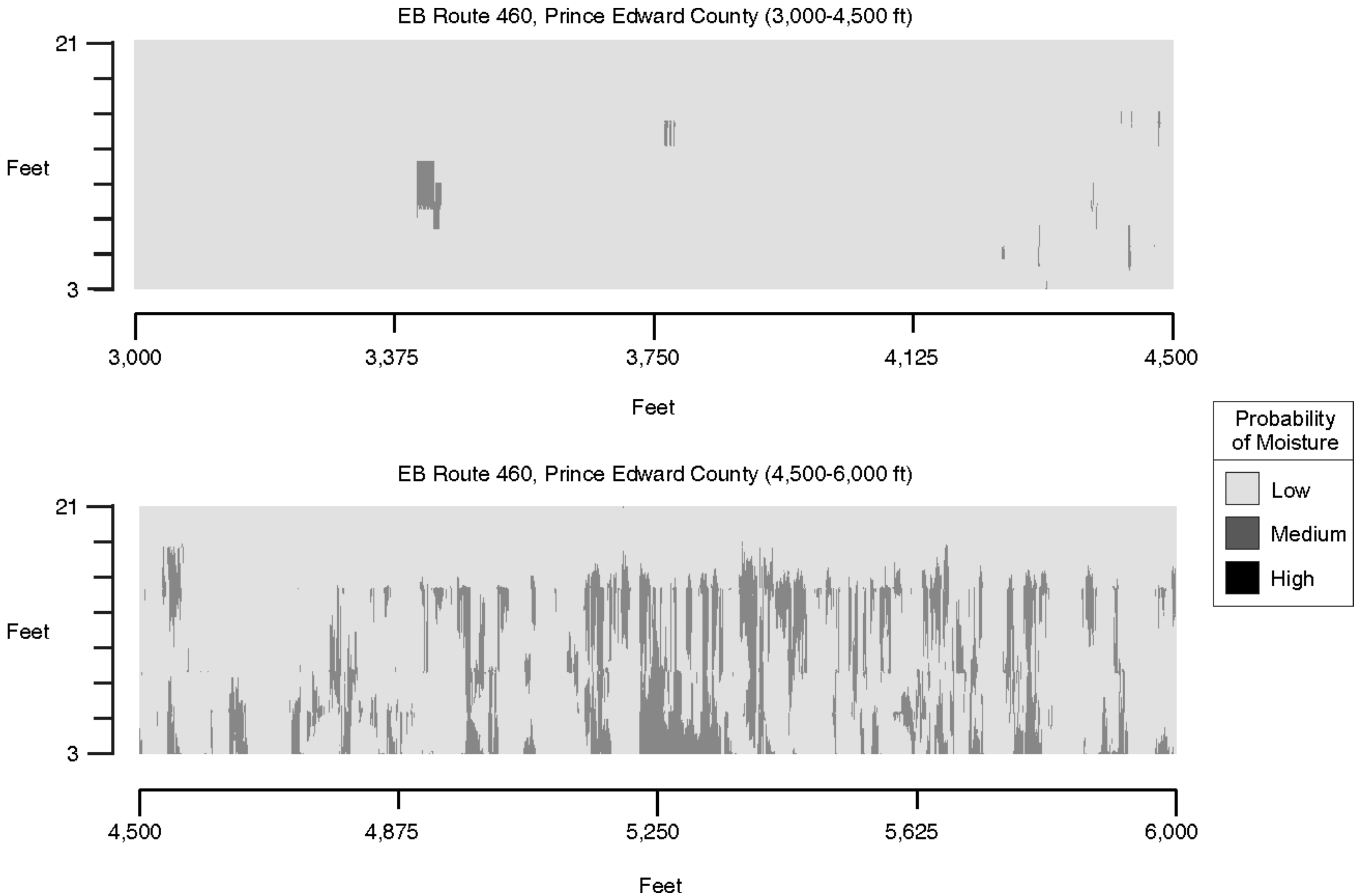

Figure A-5. Normalized dielectric constant showing probability of moisture for portions of eastbound Route 460 in Prince Edward County

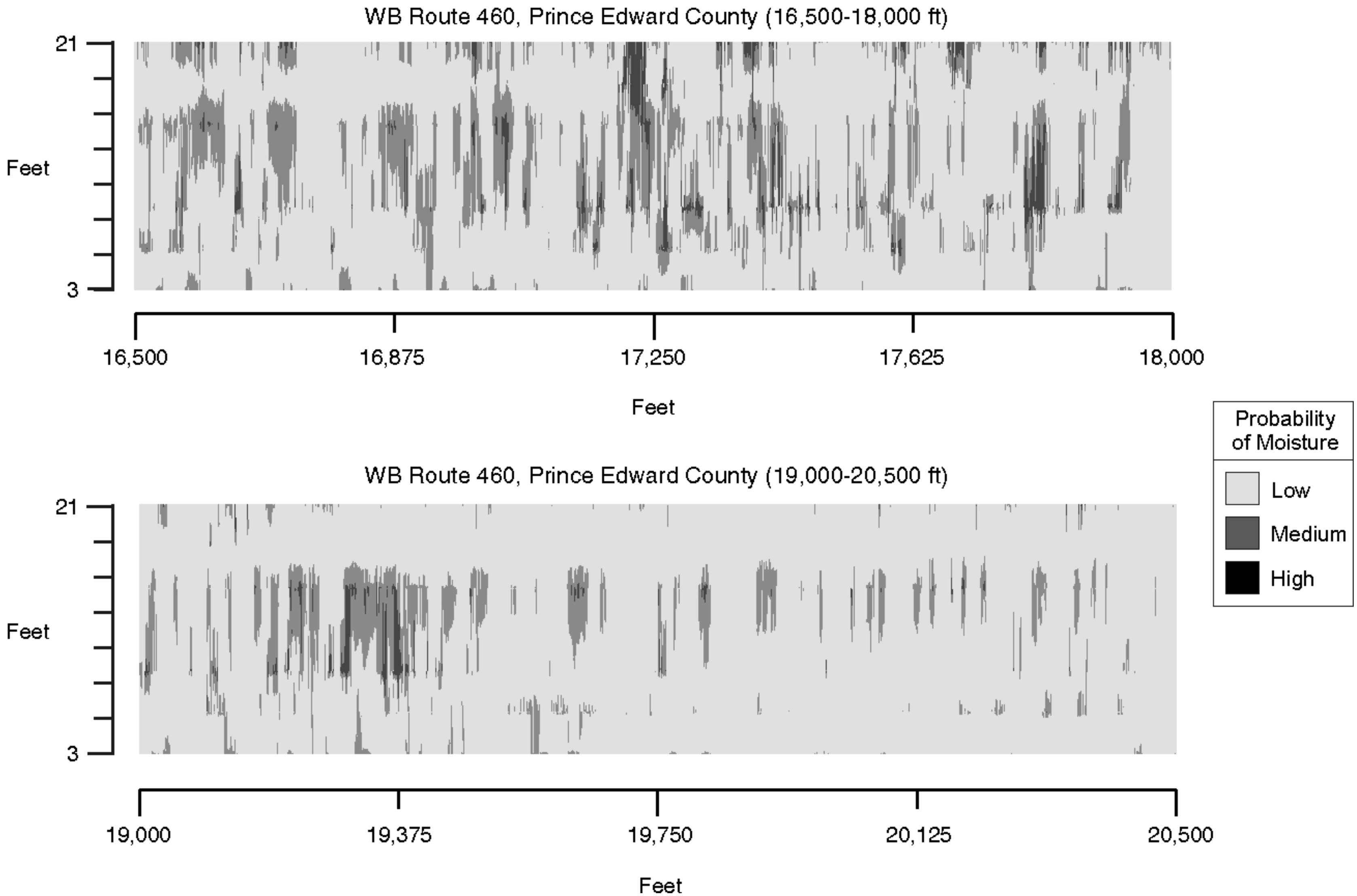

Figure A-6. Normalized dielectric constant showing probability of moisture for portions of westbound Route 460 in Prince Edward County

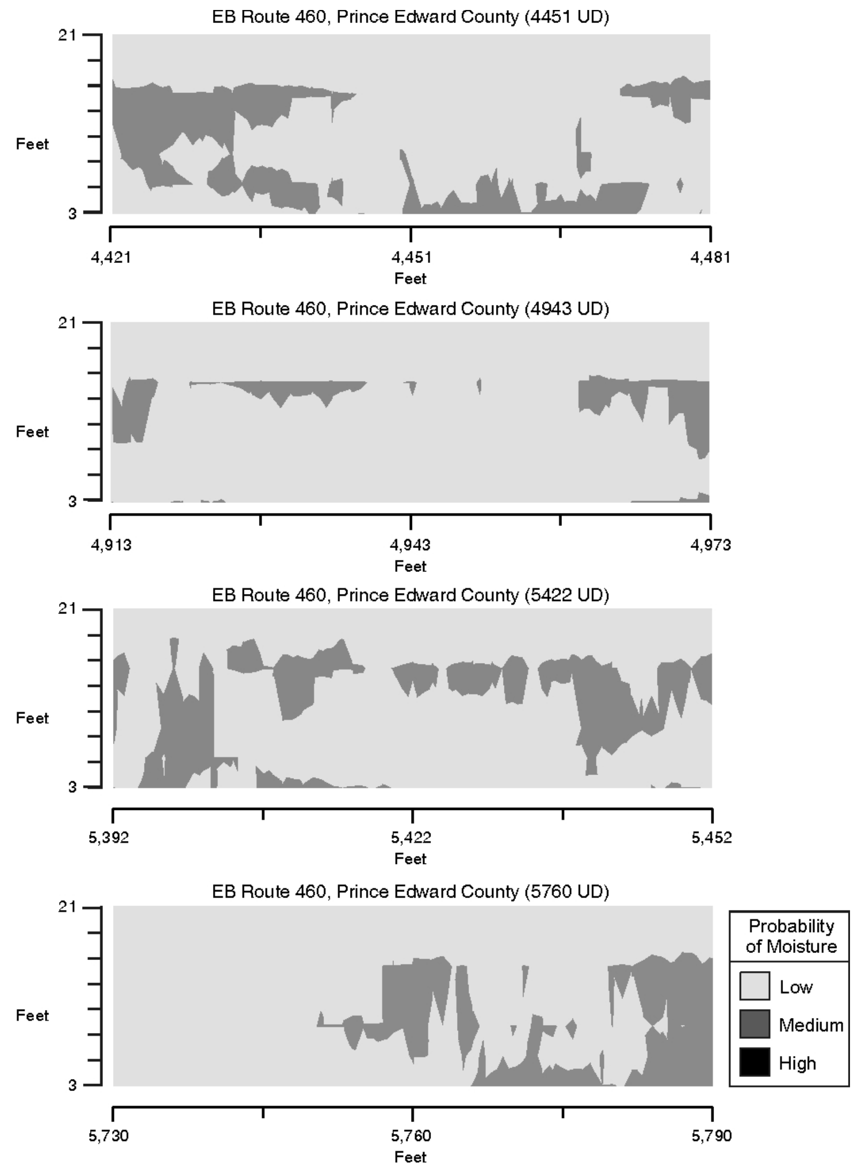

Figure A-7. Detailed view of normalized dielectric constant showing probability of moisture for portions of eastbound Route 460 in Prince Edward County at locations of underdrain outlets.

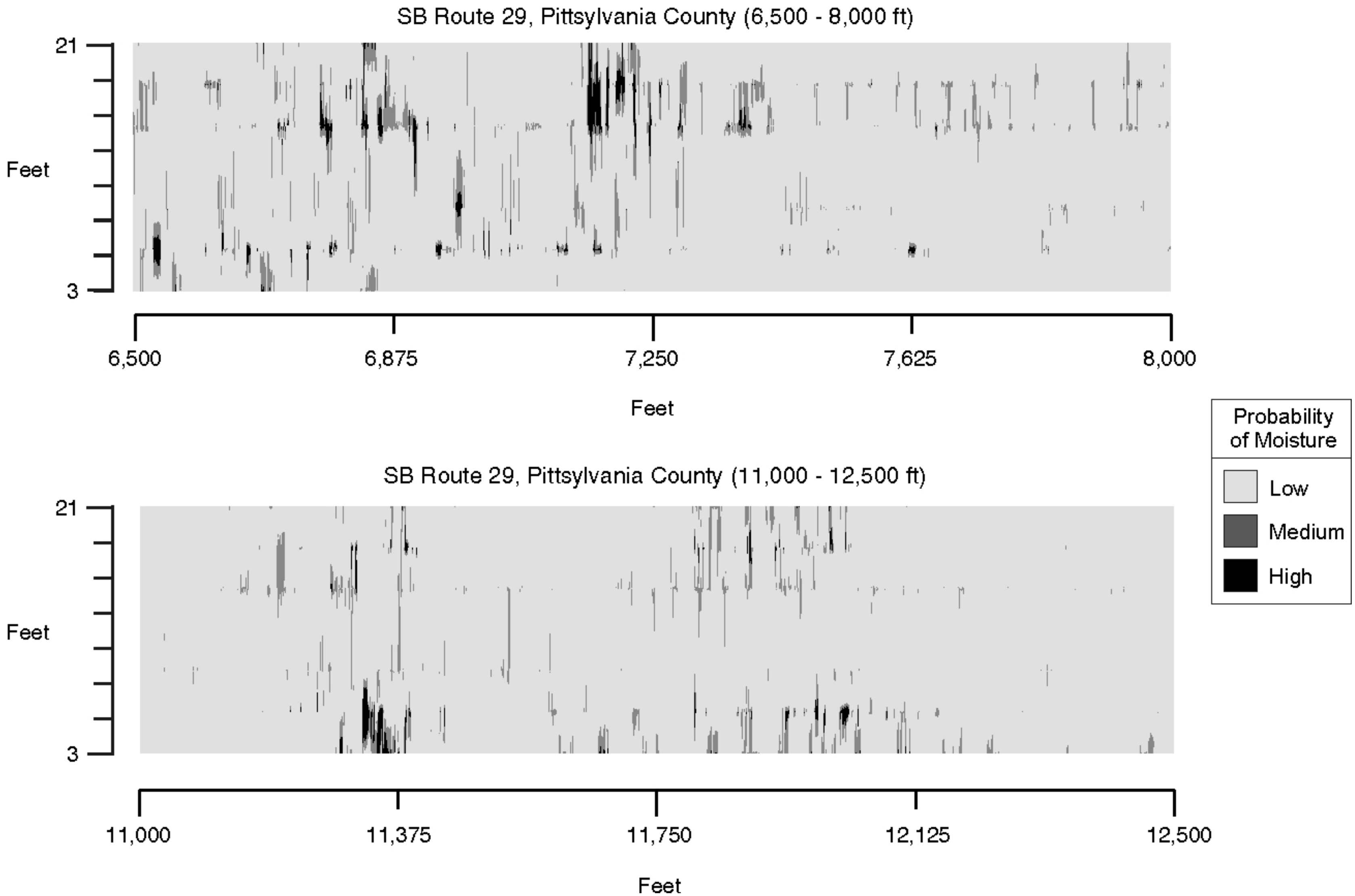

Figure A-8. Normalized dielectric constant showing probability of moisture for portions of southbound Route 29 in Pittsylvania County

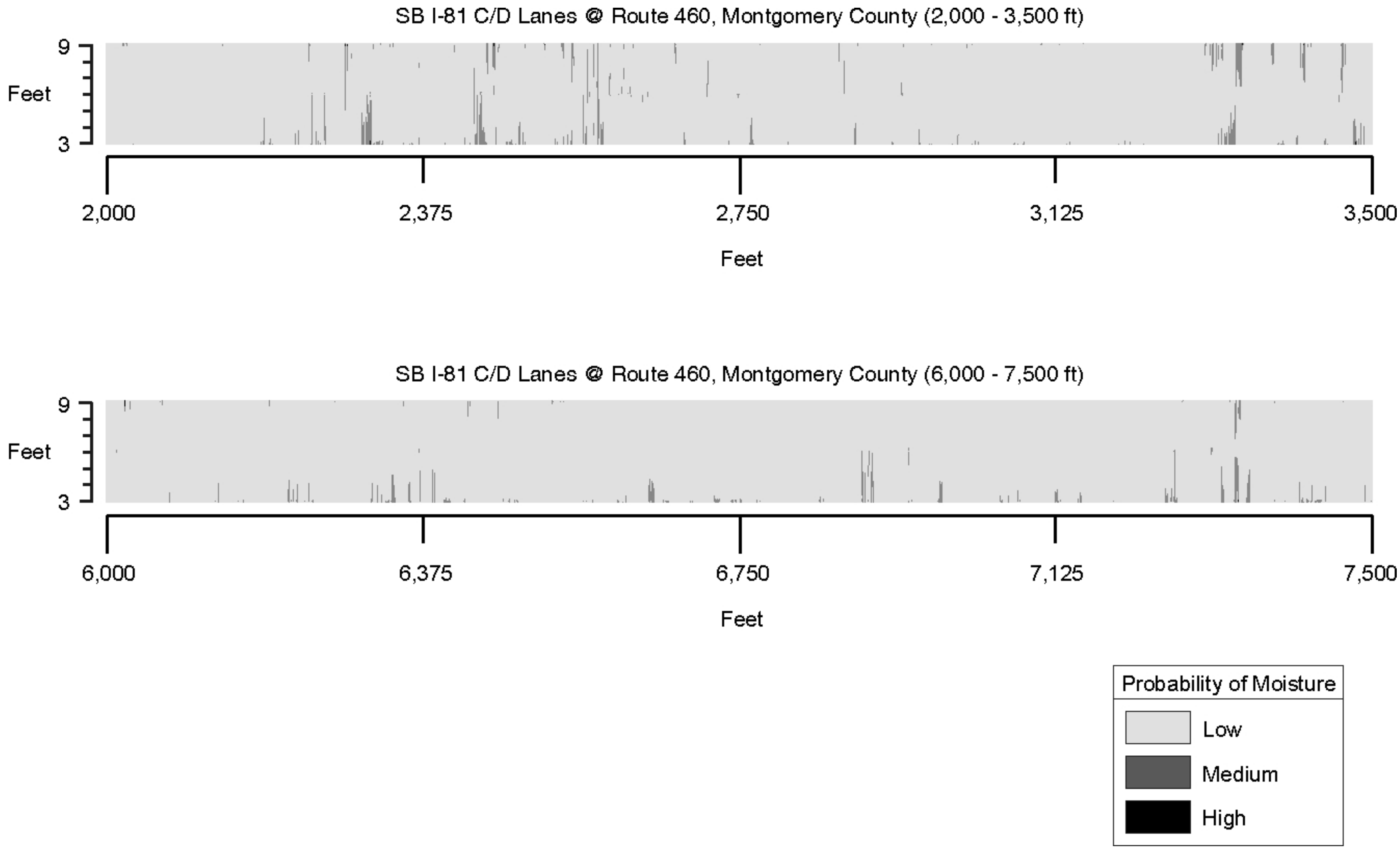

Figure A-9. Normalized dielectric constant showing probability of moisture for portions of southbound I-81 collector/distributor lanes at Route 460 in Montgomery County

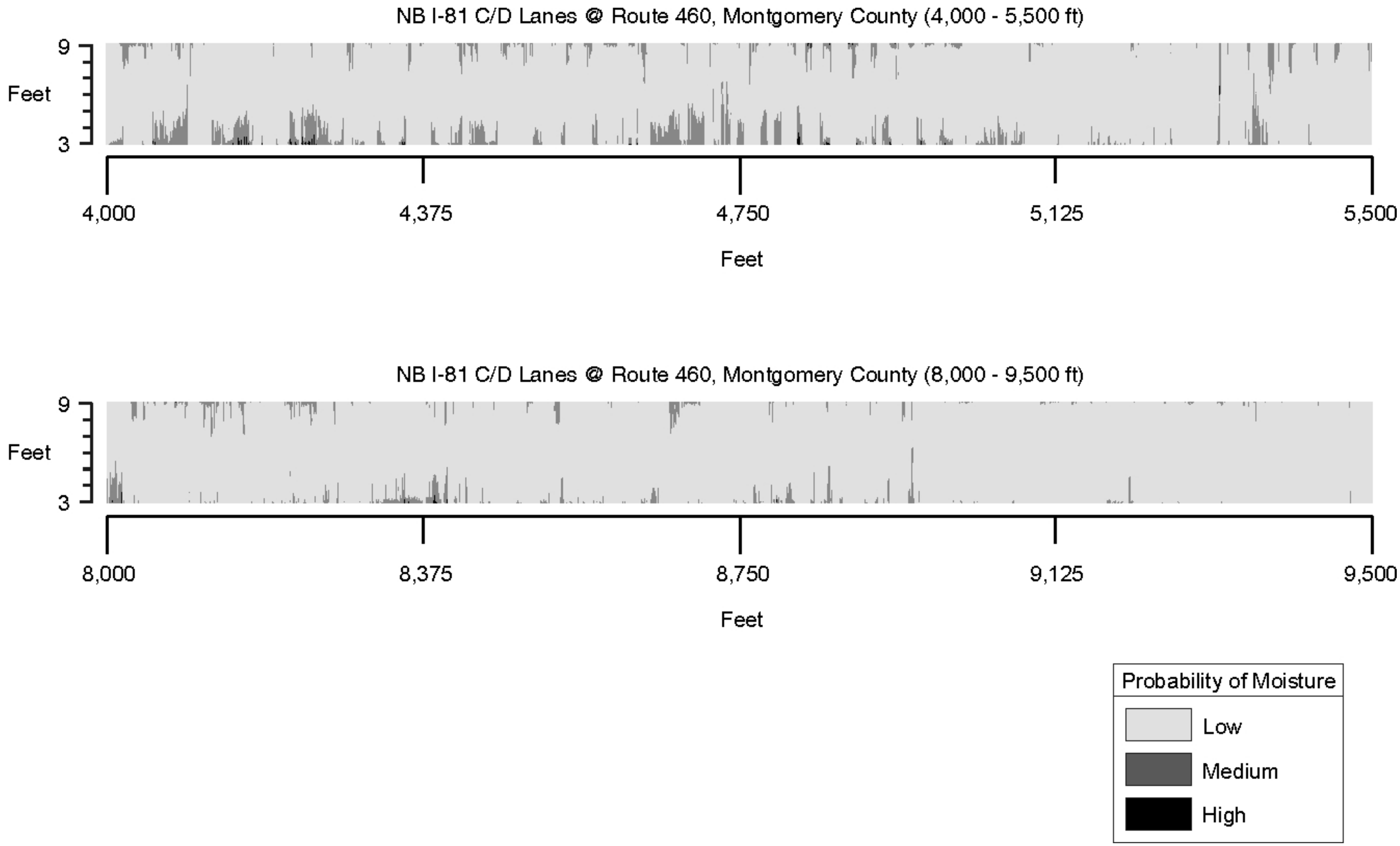

Figure A-10. Normalized dielectric constant showing probability of moisture for portions of northbound I-81 collector/distributor lanes at Route 460 in Montgomery County

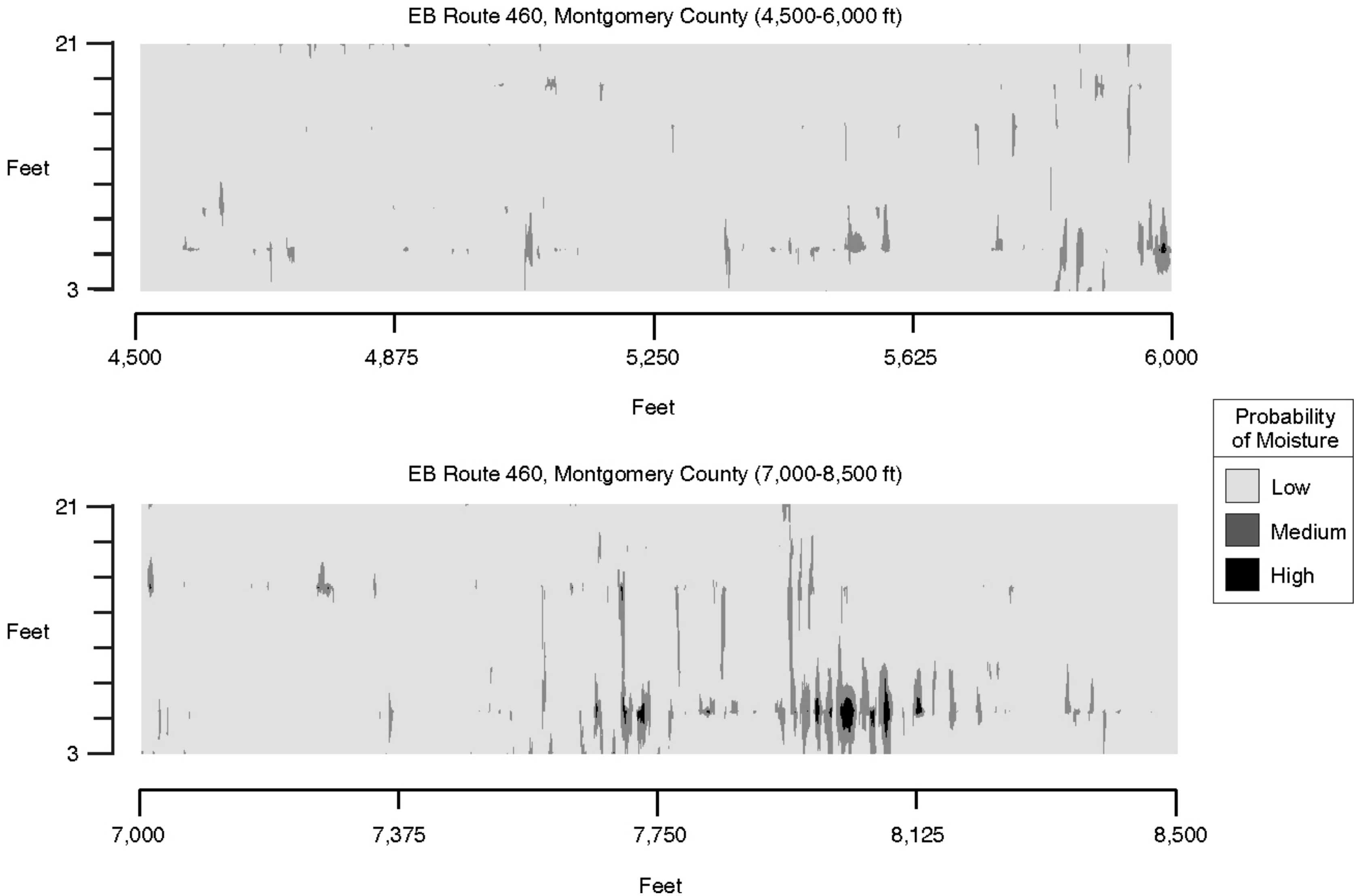

Figure A-11. Normalized dielectric constant showing probability of moisture for portions of eastbound Route 460 in Montgomery County

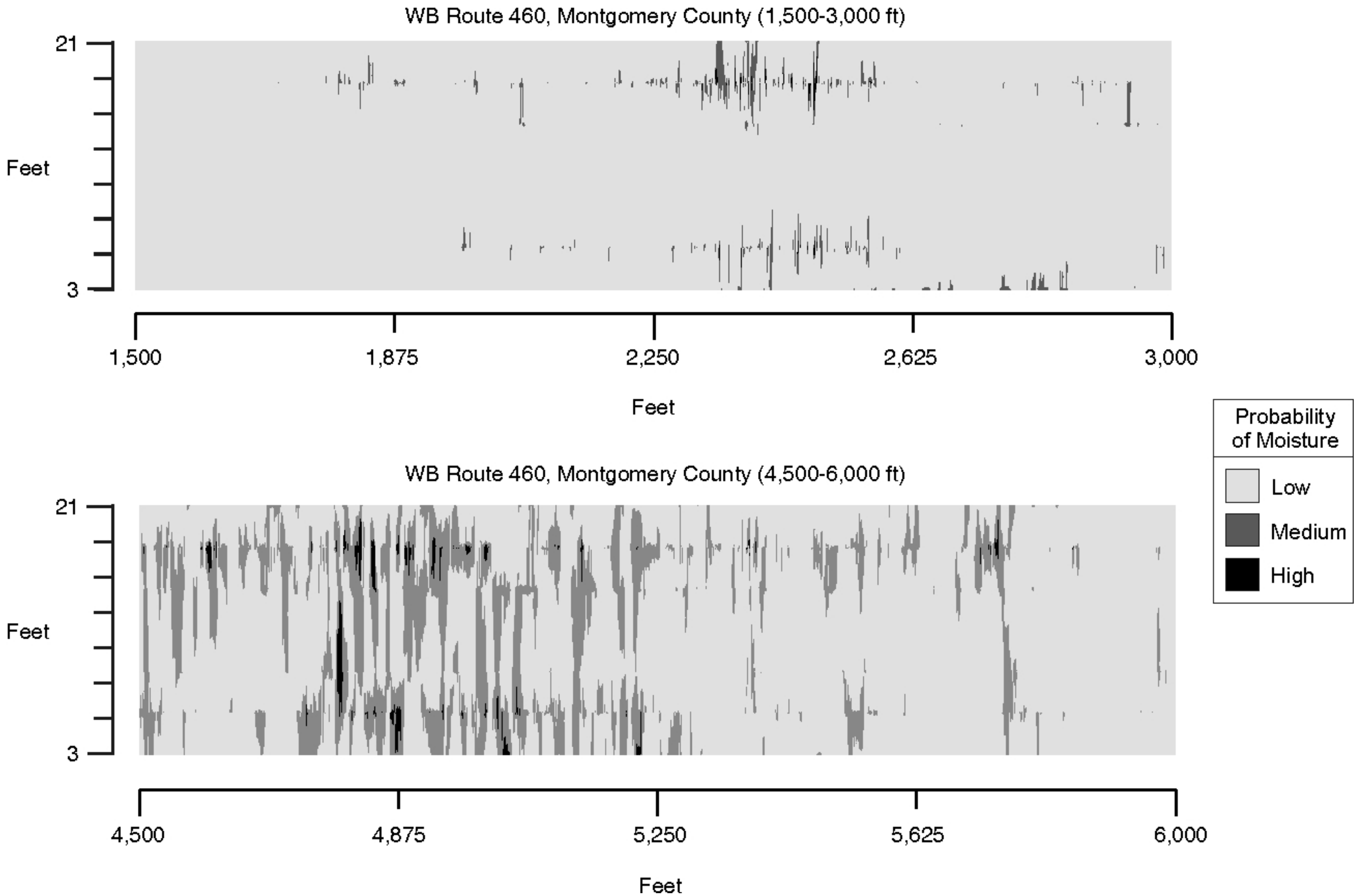

Figure A-12. Normalized dielectric constant showing probability of moisture for portions of westbound Route 460 in Montgomery County

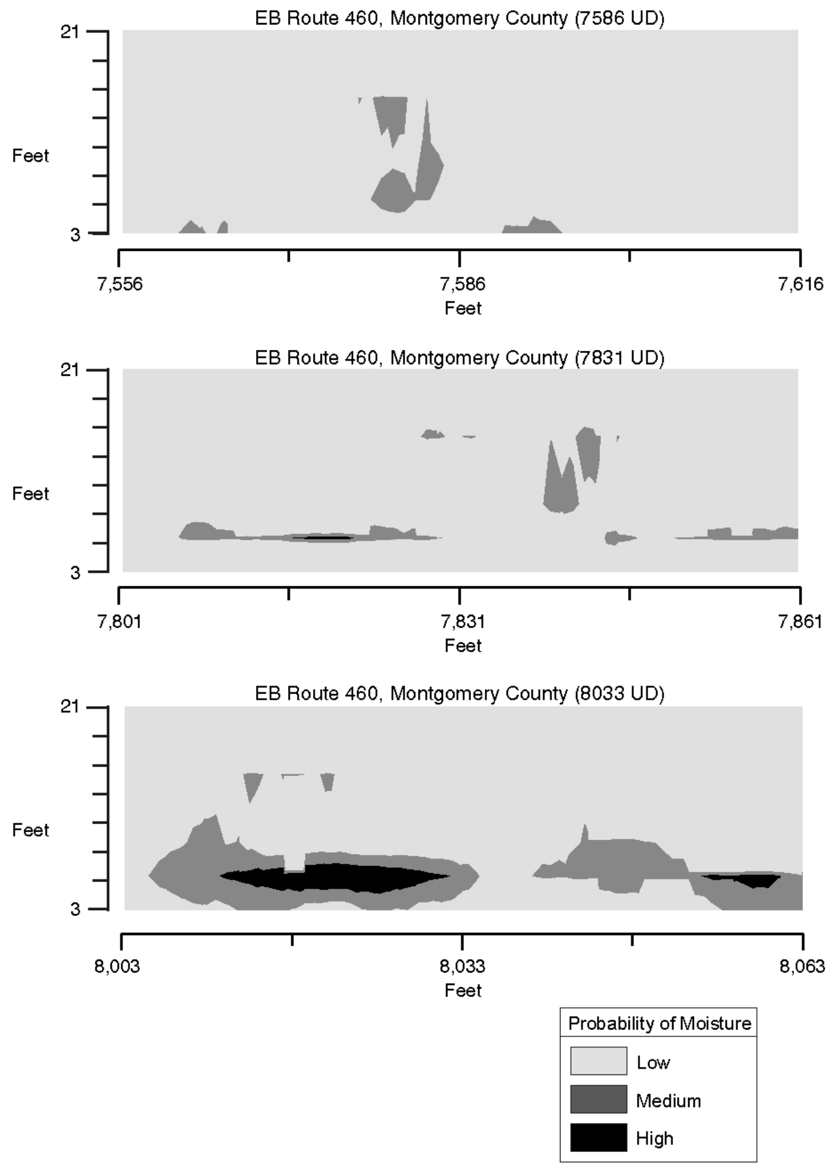

Figure A-13. Detailed view of normalized dielectric constant showing probability of moisture for portions of eastbound Route 460 in Montgomery County at locations of underdrain outlets