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Demonstration and Inter-Comparison of Seasonal Weight Restriction Models – Phase II

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Aurora Project 2014-01

Final Report
December 2020

About Aurora

The Aurora program is a partnership of highway agencies that collaborate on research, development, and deployment of road weather information to improve the efficiency, safety, and reliability of surface transportation. The program is administered by the Center for Weather Impacts on Mobility and Safety (CWIMS), which is housed under the Institute for Transportation at Iowa State University. The mission of Aurora and its members is to seek to implement advanced road weather information systems (RWIS) that fully integrate state-of-the-art roadway and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures.

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16. Abstract

The major tasks of Phase II were to implement the models recommended from Phase I at demonstration sites and to calibrate those models, if required. The models included both degree-day threshold and frost-thaw depth prediction models. Output from the models was then compared with validation data provided by the departments of transportation (DOTs) involved in this study. These validation data consisted of subsurface temperature data (which were reduced by the research team to compute frost and thaw depths) and, in some cases, deflection and/or stiffness data from lightweight deflectometer (LWD) and falling weight deflectometer (FWD) tests.

With the results of these implementation and validation efforts, recommendations based on accuracy, simplicity of use, and cost were developed to aid road management agencies in selecting which model or protocol is most appropriate for their intended purposes, personnel, and specific conditions.

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DEMONSTRATION AND INTER-COMPARISON OF SEASONAL WEIGHT RESTRICTION MODELS – PHASE II

Final Report
December 2020

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1. INTRODUCTION

1.1 Problem Statement

Many miles of roads are in seasonal frost areas that are highly susceptible to damage during the spring thaw period. As freezing occurs from the surface downward, moisture is drawn toward the freezing front, ice lenses are formed, and the roadways become stronger. When the ice lenses (above still-frozen underlying layers) melt, the structure is left in an undrained, unconsolidated condition that is highly susceptible to damage under traffic.

In seasonal frost areas, some state departments of transportation (DOTs) take advantage of the period of higher strength in mid-winter by applying winter weight premiums (WWPs), increasing the allowable weight that trucks can haul. On the other hand, to reduce damage during the spring thaw, many road management agencies apply spring load restrictions (SLRs), which restrict the allowable load on the road during the critical time interval when the pavement is most vulnerable to damage.

These spring load restrictions can pose an economic hardship to trucking and other industries responsible for the movement of goods and services. Restrictions on movement may cause trucks to take detours that are costly in fuel and driving time. Restrictions may also cause trucks to haul with lighter loads resulting in more trips, additional fuel consumption, and increased driving time.

Of greatest impact, perhaps, is the common scenario of the placement of a 6-ton load limit, which completely prohibits trucking, often without the provision of an alternate route. This is typically the case for access to timber, and it completely halts hauling operations.

Clearly, SLRs pose sustainability as well as financial concerns for many regions of our nation, and the challenge is to create a rational balance between infrastructure protection and roadway usage during high-stress periods such as freeze-thaw cycles.

1.2 Background

Historically, many transportation agencies have imposed WWPs and SLRs based on set dates and/or visual inspection procedures. The problem with using fixed dates is that subsurface freezing and thawing patterns vary from year to year; thus, appropriate dates/durations for one year may not be appropriate for other years. In the inspection/observational approach, field personnel observe changes in the roadways in the early spring, such as rutting, cracking, water seepage from cracks, and/or other indicators of pavement distress, to determine whether to impose WWPs or SLRs. One problem with inspection/observation methods is that, by the time pavement failures are observed, the agency has essentially committed to allowing some level of damage because legislation normally requires three to five days' notice prior to applying SLRs. Additionally, these methods tend to be highly subjective.

More recently, many transportation agencies have become interested in determining SLR application and duration according to science-based decisions rather than merely using hard physical dates or individual judgment. Some agencies are using quantitative approaches to monitor spring thaw processes, such as measuring pavement deflections with a falling weight deflectometer (FWD) and backcalculating layer moduli, or determining other indices.

Some agencies have installed sensors beneath roadways to monitor subsurface temperature and/or moisture profiles during the spring thaw period. Studies where subsurface temperature and/or moisture profiles were monitored and correlated with FWD and/or other in situ test results are reported by Van Deusen et al. (1998), Ovik et al. (2000), Kestler et al. (2007), Miller et al. (2007), Tighe et al. (2007), Marquis (2008), Eaton et al. (2009), Bradley et al. (2012), and Miller et al. (2013). These studies indicate a strong correlation between the onset of thaw and a decrease in the strength and stiffness of the overall pavement system. The studies also suggest that strength and stiffness recover gradually as thawing progresses and excess moisture in the base and subgrade layers dissipates.

Although quantitative approaches provide a rational basis for making SLR decisions, FWD testing and associated analyses are time consuming and expensive. Expenses associated with installing instrumentation to measure subsurface temperature and/or moisture profiles and obtaining data from those instruments in real time can be prohibitive. Because atmospheric weather data are more readily available and much less expensive to obtain than FWD data and/or subsurface temperature data, many transportation agencies are now considering the use of SLR thresholds linked to weather-based indices and/or frost-thaw depth prediction models that can be coupled with atmospheric forecasts to provide advance warning of estimated dates when WWPs or SLRs should be placed and lifted. Table 1 presents a summary of the approaches used by transportation agencies for applying WWPs and SLRs.

Table 1. Methods for applying winter weight premiums and spring load restrictions

Method		Comments
1	Fixed dates based on long-term experience	Because of year-to-year variations in freezing and thawing, damage could still occur, or hauling may be restricted because of a given date when conditions are fine for hauling without damage.
2	Inspection/observational approaches where field personnel observe changes in the roadways, such as water seepage from cracks, other indicators of pavement distress, or a worst-case scenario of major rutting, cracking, or breaking up of asphalt	Too late; damage has already occurred.
3	Monitoring changes in pavement load bearing capacity as indicated by deflections measured using FWD tests	State DOTs typically own one FWD, possibly two, and can test only a sample of roadway segments statewide; most other road management agencies or municipalities, such as cities and counties, do not own FWDs.
4	Monitoring subsurface temperature and/or moisture profiles beneath roadways	Excellent for conducting studies, but required at each site to monitor for SLR and WWP placement and removal.
5	Degree-day thresholds/protocols based on air temperature data	Can be very simple to use, but do not provide any information regarding when to remove SLRs.
6	Predictive models based on atmospheric weather data to predict subsoil temperature profiles	Can range from somewhat simple to very complex; more complex models can be very expensive and require input data that are not always available.

1.3 Objectives and Scope of Work

The objective of this research was to provide an understanding of the reliability, benefits, cost, and risks of alternative approaches to scheduling SLRs. Specifically, the approaches listed in Table 1, items 5 and 6, were evaluated via a field demonstration in which several protocols and/or model predictions were validated against observed subsurface temperature profiles and measurements of pavement deflection at instrumented sites in five of the pooled-fund highway jurisdictions (Alaska, Michigan, North Dakota, Wisconsin, and Ontario, Canada).

This understanding will improve the management of road usage during high-stress periods such as thaw cycles, which will ultimately improve roadway lifetime and usability, benefitting both state DOTs and roadway users (the trucking industry, etc.). The research was divided into two phases, as follows.

1.3.1 Phase I

The major task under Phase I was to conduct a review of available models for WWP and SLR application, including technical aspects, intellectual property, and implementation issues. A subset of all reviewed models was recommended for the Phase II study. In addition, the research team identified demonstration site requirements for Phase II and reviewed available data and instrumentation at proposed validation sites. Finally, the research team developed a plan for the Phase II demonstration and evaluation work.

1.3.2 Phase II

The major task under Phase II was to implement the recommended models from Phase I at demonstration sites and calibrate those models, if required. Output from the models was then compared with validation data. Validation data, provided by the DOTs, consisted of subsurface temperature data (which was reduced by the research team to compute frost and thaw depths) and, in some cases, data from FWD tests. The following SLR protocols and models were originally planned for implementation during the 2014–2015 and 2015–2016 winter/spring seasons:

- **Degree-Day Threshold Models**
    - *Minnesota DOT (MnDOT)* – Five sites both years
    - *Lakehead University* – Run for two years at Ontario site since already calibrated; for other sites, used year 1 data for calibration and then run in predictive mode for year 2

- **Frost and Thaw Depth Prediction Models (Freeze-Thaw Index)**
    - *Freeze-Thaw Index Model: Linear Regression* (Miller et al. 2012) – Five sites using year 1 data for calibration; run in predictive mode for year 2
    - *Freeze-Thaw Index Model: Polynomial Regression* (Chapin et al. 2013, Pernia et al. 2014) – Run for two years at Ontario site, since already calibrated; for other sites, used year 1 data for calibration and then run in predictive mode for year 2
    - *Modified Model 158* (Orr and Irwin 2006, Miller et al. 2015) – Five sites for two years

- **Frost and Thaw Depth Prediction: Enhanced Integrated Climatic Model (EICM)**
    - *Meridian/Iteris, Clarus SLR Tool/Leon Osborne* – Run for five sites for one year

The original Phase II contract agreement between the Iowa DOT and the U.S. Department of Agriculture (USDA) Forest Service began on January 25, 2016 and ended on September 30, 2018. (We will hereafter refer to this as the Phase IIa contract and scope of work.) During the Phase IIa contract, all of the models stipulated under the scope of work were run, with the exception of the EICM. A subcontract for the EICM work with Leon Osborne was executed; however, he became ill before that work could be conducted and passed away prior to the original Phase II contract end date.

In the fall of 2019, a contract between the Iowa DOT and Frost Associates was negotiated so that the EICM could be evaluated for this project, and conclusions and recommendations were then incorporated into this final project report. We will hereafter refer to this as the Phase IIb contract and scope of work. Frost Associates received a notice to proceed on this contract on December 10, 2019, with a contract end date of March 31, 2021.

Since the proprietary (Clarus) version of the EICM was not available after the unfortunate passing of Leon Osborne, Frost Associates formulated a plan to complete the EICM evaluation using a phased approach, initially using an alternate version of the EICM (available in the AASHTOWare Pavement ME Design software). That software was used to evaluate the EICM at the five original project sites for both the 2014–2015 and 2015–2016 winter/spring seasons. Then, given that the AASHTOWare software was primarily developed for pavement structural design and does not provide a user-friendly interface for SLR timing decisions, Frost Associates also proposed evaluating a demonstration version of the vRWIS software interface at the current project sites (Alaska, Michigan, and Wisconsin) for the 2020 spring thaw season. The Ontario site was not used in this Phase IIb analysis because that Canadian province withdrew from the project after Phase IIa. The vRWIS software tool was developed by Applied Research Associates (ARA), the same firm that developed the AASHTOWare software. The vRWIS software tool automatically gathers existing atmospheric weather data (as well as forecast data) from numerous weather stations in real time, runs the EICM in the background, and presents the results of the EICM predictions of frost and thaw depths in a user-friendly graphical interface.

Additionally, since the MnDOT degree-day threshold protocol had risen to the top as a highly recommended SLR tool during the Phase IIa model evaluations, Frost Associates also evaluated a demonstration version of a graphical user interface (GUI) constructed for applying the MnDOT protocol across North Dakota for the 2020 spring thaw season.

Finally, in late May/early June 2020, the Aurora project champion indicated that the North Dakota DOT (NDDOT) would like an additional model (FrezTrax) compared and some additional analysis completed. FrezTrax is essentially another degree-day threshold model. The thaw index (TI) calculation, which is included in the FrezTrax model, was developed by Mahoney et al. (1986) and was reviewed in the Phase I work on this Aurora project. The FrezTrax model further builds on the Mahoney et al. (1986) protocol by including regionally calibrated moisture effects in defining the critical thawing index benchmark values.

Frost Associates agreed that, if funds could simply be moved from the travel and software lines to the salary line, that work could be accomplished within the existing budget and could be completed within the current period of performance. An amendment to capture this change in scope was filed on June 12, 2020, and all signatures were obtained on June 15, 2020. The additional work agreed upon under this amendment included the following analyses:

1. For the original two project study years (2014–2015 and 2015–2016), run the freeze and thaw index calculations using air temperature data from sensors at the study sites and August–November precipitation data obtained from the Federal Highway Administration (FHWA) Long-Term Pavement Performance (LTPP) program database and/or a similar one.

a. Evaluate the FrezTrax TI benchmark values listed for SLR application and removal for the Bowman, North Dakota, study site.

b. Evaluate the FrezTrax TI benchmark values listed for SLR application at the other Aurora study sites in Alaska, Michigan, and Wisconsin. Unfortunately, since the other DOTs were not able to provide FWD data for either of the study years at their sites, validation of the FrezTrax TI benchmark values listed for SLR removal was impossible at those study sites.

2. Using FWD data from 2020 at several additional sites in North Dakota, conduct a more robust analysis of the FrezTrax SLR removal criteria.

3. Compare the output provided by NDDOT from the proprietary FrezTrax software tool with the validation data (subsurface temperature and FWD data). The purpose of this was to determine whether obtaining input data from different sources causes the model output to differ substantially.

2. DEMONSTRATION SITES AND VALIDATION DATA

2.1 Demonstration Sites

At the start of Phase I, a project technical advisory committee (TAC) was established by the Aurora program. The research team convened with the majority of the TAC via a conference call to provide an overview of the project and outline demonstration site requirements. Subsequently, numerous individual contacts via phone and email took place between individual research team members and individual TAC members. Ultimately, the sites listed in Table 2 were selected for this project.

Table 2. Demonstration site details

Highway Jurisdiction	Site Identification	Latitude	Longitude	Elevation (ft)
Alaska	Whittier Access Road @ Tunnel MP 6.5	60.7900	-148.8127	116
Michigan	Republic M-95	46.25009	-88.01069	1,504
North Dakota	Bowman US 85 @ MP 12.2	46.1169	-103.4107	2,911
Wisconsin	STH 70 @ Johnson Road	45.7729	-92.7169	911
Ontario	HWY 527	49.3598	-89.3775	1,470

2.2 Available Instrumentation and Pavement Structure Data

A road weather information system (RWIS) station providing atmospheric weather data was located at all of the sites listed, and all sites (except for Wisconsin) already had a thermistor string installed to measure subsurface temperatures down to a depth of about 6 feet. In general, individual temperature sensors were located in the asphalt surface and just below the asphalt layer, at 3-inch intervals from the bottom of the asphalt down to a depth of 12 inches, and then at 6-inch intervals down to a depth of 72 inches. The Wisconsin DOT (WisDOT) installed a similar thermistor string at its demonstration site during Phase II of this study.

At most sites, information regarding pavement layer thicknesses and material types was available from construction records and/or from soil samples obtained from boreholes at the sites. The pavement structure data listed in Table 3 was obtained from individual TAC members and/or other personnel at their respective DOTs.

Table 3. Pavement layer thicknesses and material types at demonstration sites

Alaska	**Thickness (in.)**	**Material Type**
Asphalt	2.5	asphalt
Layer 2	3	crushed aggregate base
Layer 3	60	shot rock fill
Subgrade	NA	bedrock
Michigan	**Thickness (in.)**	**Material Type**
Asphalt	3.5	asphalt
Layer 2	11	processed aggregate
Layer 3	58	med. sand & gravel
Subgrade	NA	fine-medium sand
North Dakota	**Thickness (in.)**	**Material Type**
Asphalt	6	asphalt
Layer 2	16	RAP and virgin aggregate base
Subgrade	NA	clay to clayey loam
Wisconsin	**Thickness (in.)**	**Material Type**
Asphalt	3.5	asphalt
Layer 2	8	gravel
Subgrade	NA	fine sand
Ontario	**Thickness (mm)**	**Material Type**
Asphalt	40	asphalt
Subgrade	NA	sand

NDDOT personnel also provided extensive laboratory data from samples obtained at the North Dakota demonstration site. Those data are presented in Tables 4a and 4b.

Table 4a. Laboratory test data from samples at North Dakota demonstration site: laboratory soil tests and classification (bulk/bagged samples)

Depth below top of pavement, (ft)	**Soil Classification (AASHTO M-145)**	**Texture Classification**	**LL**	**PI**	**PL**	**Frost Class**	**Avg. Moisture from jar samples (%)**
2.1–3.1	A-7-6 (16)	CLY	49	30	19	F3	26.8
3.1–5.1	A-7-6 (11)	CLY LM	47	29	18	F3	24.6
5.1–7.1	A-7-6 (15)	CLY	49	30	19	F3	28.5
7.1–9.1	A-7-6 (7)	CLY LM	34	18	17	F3	15.4
9.1–11.1	A-7-6 (14)	CLY	43	28	15	F3	17.1

Table 4b. Laboratory test data from samples at North Dakota demonstration site: moisture determined from field can samples

Depth below top of pavement (ft)	Field Sample Moisture Content (%)
1.1	6.4
2.1	23.3
3.1	9.1
4.1	23.5
5.1	28.9
6.1	26.1
7.1	25.9
8.1	18.7
9.1	21.9
10.1	18.2
11.1	14.1

2.3 Validation Data

Each of the highway jurisdictions participating in the study designated one demonstration site, as listed in Table 2. Throughout the monitoring seasons, subsurface temperature data at each site were collected from thermistor strings, and air temperature data were obtained from nearby RWIS stations. Those data were provided to the research team, and the team then computed frost and thaw depths using linear interpolation between thermistors and 32°F as the freezing point.

In the original validation proposal for Phase II, each agency planned to run FWD or lightweight deflectometer (LWD) tests on a grid around the subsurface temperature sensors. Ideally, FWD or LWD testing would be conducted prior to the start of winter, once a week for the first three weeks of winter, and two times per week during the spring thaw and strength recovery period. An extensive set of FWD data was provided for this project by NDDOT. Unfortunately, it was not possible for the other participating DOTs to provide adequate FWD or LWD data during either of the study years at the remaining demonstration sites.

3. IMPLEMENTATION OF MODELS

3.1 General

Several models and protocols have been reported in the literature for determining when to place and remove WWPs and SLRs. Initial efforts were undertaken by Mahoney et al. (1986) to apply scientific methods to determine when to place and remove SLRs. Their method has been revised, and several variations of it have been used since that initial effort.

The most notable revision is the procedure used by Van Deusen et al. (1998) and currently the Minnesota DOT (MnDOT 2009, 2014). This procedure and several other methods are based on the accumulation of degree-days computed from average daily air temperatures. Air temperatures used in the models are ideally obtained from a weather station at the site but may also be obtained from a nearby National Oceanic and Atmospheric Administration (NOAA) or National Weather Service (NWS) weather station, a state-owned RWIS or similar station, or a combination of sources. The models are relatively simple to apply and can be accomplished using spreadsheets. The methods typically use some threshold value(s) for cumulative freezing or thawing degree-days to determine when to place WWPs and SLRs, respectively. These methods frequently use a reference temperature other than 32°F, the freezing point of pure bulk water, to consider differences between the air and pavement surface temperatures and increases in incoming shortwave radiation during the spring and early summer.

Another approach for WWP and SLR timing is to use models that estimate frost and thaw depths; the WWP would then be applied when the predicted frost depth reaches some threshold value, and the SLR would be applied when the predicted thaw depth reaches some other threshold value. For example, Mahoney et. al. (1986) recommend that the SLR “should” be applied when the upper thaw front reaches the bottom of the base layer and “must” be applied by the time the thaw depth reaches 4 inches below the bottom of the base. Some of these models require only air temperature data as input (to compute cumulative degree-days) but require site-specific calibration to determine coefficients for computation of frost and thaw depths. Other models, such as the U.S. Army Corps of Engineers Model 158, do not require site-specific calibration but require knowledge about the thermal properties and thickness of the pavement layers (in addition to air temperature data). The most sophisticated class of models uses finite element or finite difference methods to compute frost and thaw depths on a daily basis. These models typically require the following climatic inputs: air temperature, precipitation, wind speed, percent sunshine, relative humidity, and groundwater table depth. The thermal properties and thickness of the pavement layers are also usually required inputs for these numerical models. Thermal properties can be estimated based upon methods outlined in references such as Kersten (1949), Cortez et al. (2000), or Andersland and Ladanyi (2004).

Sections 3.2 and 3.3 of this report describe the details of the protocols and models that were evaluated at the demonstration sites during Phase II of this project. Chapter 4 summarizes conclusions and recommendations that resulted from analysis of those model results.

3.2 Posting Methods Based on Degree-Day Thresholds

3.2.1 Minnesota Department of Transportation (MnDOT 2009)

3.2.1a Description of Protocol and Phase IIa Analysis

MnDOT provides guidance for when WWPs and SLRs should be applied based upon threshold values for the cumulative freezing index (CFI) and cumulative thawing index (CTI), respectively. MnDOT (2009, 2014) recommends that the WWP can be allowed when the three-day weather forecast indicates that the CFI will exceed 280°F-days and extended forecasts predict continued freezing temperatures. The cumulative freezing index for a given day, CFI_n, is computed using the following Equation:

$$CFI_n = \sum_{i=1}^{n} 32°\text{F} - \frac{T_{max} + T_{min}}{2} \quad (1)$$

where,

T_{max} = Maximum daily air temperature (°F)
T_{min} = Minimum daily air temperature (°F)

The end date of the WWP period is determined when forecast air temperatures predict daily thawing, as indicated by the cumulative thawing index, and the impending placement of spring load restrictions, as described subsequently.

MnDOT recommends that the SLR should be applied when the "three-day weather forecast indicates that the cumulative thawing index for a zone will exceed 25°F-days and longer-range forecasts predict continued warmth." The agency recommends computing the cumulative thawing index for a given day, CTI_n, using the following equations:

$$CTI_n = \sum_{i=1}^{n}(Daily\ Thawing\ Index - 0.5 \times Daily\ Freezing\ Index) \quad (2)$$

a. $When\ \left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\} < 0°\text{F}$
And $CTI_{n-1} \leq 0.5 \times \left(32°\text{F} - \frac{T_{max} + T_{min}}{2}\right)$, (Significant thawing has not yet occurred)
Daily Thawing Index = 0°F-day and
Daily Freezing Index = 0°F-day

b. $When\ \left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\} > 0°\text{F}$ (The pavement structure is thawing)
Daily Thawing Index = $\left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\}$ and
Daily Freezing Index = 0°F-day

c. $When \left\{\frac{T_{max} + T_{min}}{2} - T_{ref}\right\} < 0°F$
And $CTI_{n-1} > 0.5 \times \left(32°F - \frac{T_{max} + T_{min}}{2}\right)$, (The pavement structure is refreezing)
Daily Thawing Index = 0°F-day and
$$\text{Daily Freezing Index} = \left\{32°F - \frac{T_{max} + T_{min}}{2}\right\}$$

where,
CTI_{n-1} = Cumulative thawing index for the previous day
T_{max} = Maximum daily air Temperature (°F)
T_{min} = Minimum daily air Temperature (°F)
T_{ref} = Reference air temperature (°F)

Note that the CTI resets to zero on January 1 and on any day when $CTI_n < 0$.

The use of a reference temperature in Equation 2 was recommended by MnDOT to compensate for the temperature differential between the air temperature and asphalt temperature. In Minnesota, it was found that the air temperature required for pavement thawing to begin actually decreases during the early spring, probably due to the increase in the elevation angle of the sun (Van Deusen et al. 1998). Therefore, MnDOT implemented the use of a floating reference temperature to account for increased solar gain. MnDOT recommends using a reference temperature of 32°F between January 1 and January 31. The solar gain is then reflected using a depression of 2.7°F during the first seven days of February and thereafter using a further depression of 0.9°F per week (MnDOT 2009, 2014).

In Minnesota, the SLR end date for various frost zones is determined using measured frost and thaw depths, forecast daily air temperatures, and other key indicators at several locations within each frost zone; therefore, the duration of the spring load restrictions varies from year to year. However, the MnDOT policy states that "the spring load restrictions will last no more than eight weeks unless extraordinary conditions exist that require additional time or route-specific signage" (MnDOT 2009, 2014).

An example of implementation of the MnDOT protocol at the demonstration site in North Dakota is shown in Figures 1 through 3. For WWP application, the CFI threshold of 280°F-days is exceeded on December 26, 2015 (Figure 1).

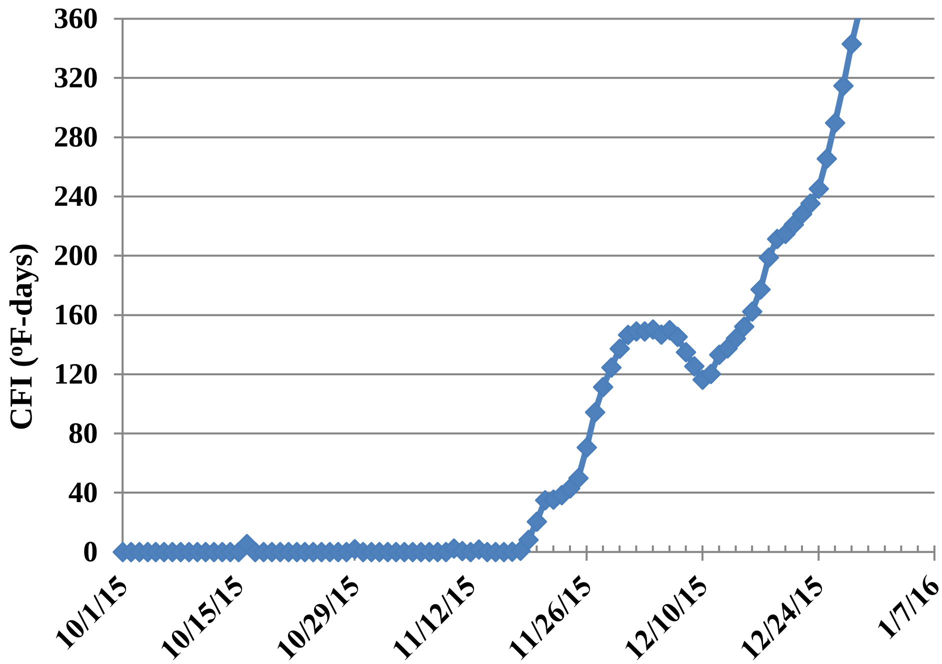


Figure 1. CFI at North Dakota site during 2015–2016

For SLR application, the CTI threshold of 25°F-days is reached briefly on February 10, 2016; however, longer-range weather forecasts predicted on or before that date would likely have suggested a subsequent colder period (as opposed to "continued warmth"). Therefore, applying the SLR would not be recommended on February 10, 2016 according to MnDOT policy. The 25°F-day threshold was again exceeded on February 15, 2016, with continued warming (Figure 2).

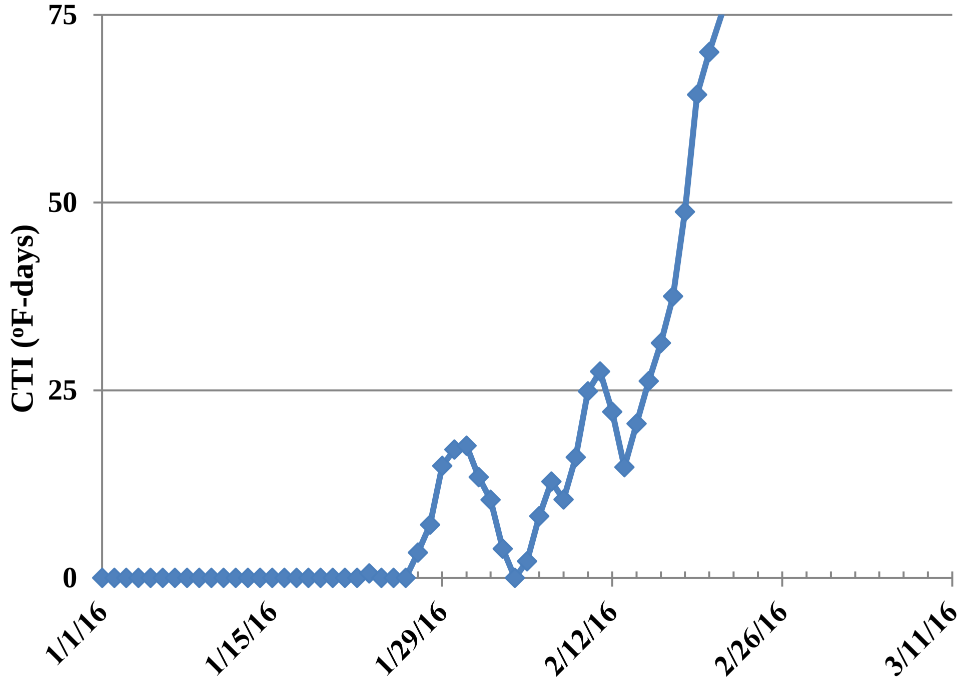


Figure 2. CTI at North Dakota site during 2015–2016

As such, February 15, 2016 would be recommended as the SLR start date according to the MnDOT protocol. These two threshold dates are superimposed on a plot of measured frost and thaw depths in Figure 3.

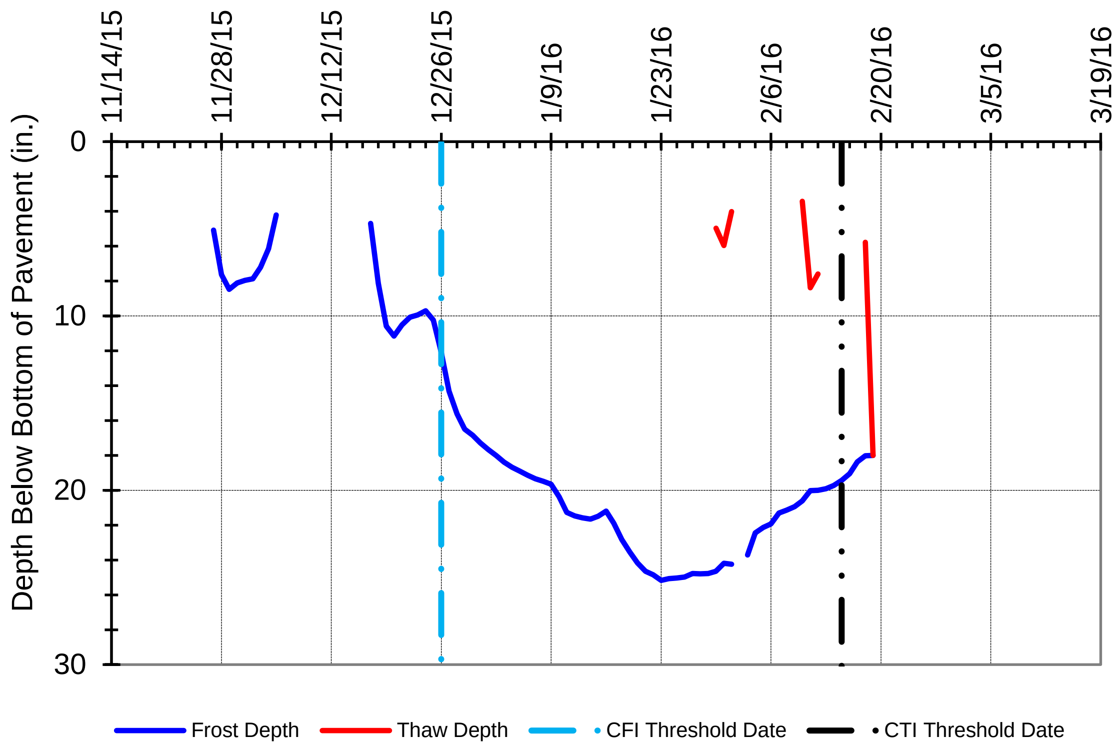


Figure 3. Interpolated frost and thaw depths and MnDOT WWP (CFI) and SLR (CTI) threshold dates at North Dakota site during 2015–2016

It can be seen that there was some minor freezing (down to about 8 inches) around the end of November 2015, followed by thawing. This trend is apparent in the CFI plot (Figure 1). When the WWP threshold was reached (CFI of 280°F-days), frost had only penetrated about 14 inches deep.

In terms of the CTI and thaw depths, minor thawing followed by refreezing was observed around the end of January and then again just before and after February 10, 2016 (when the CTI threshold of 25°F-days was briefly exceeded). The 25°F-day threshold was again exceeded on February 15, 2016, and final thawing at the North Dakota site then occurred very rapidly between February 18 and 19, 2016. So, in this example, the CTI threshold recommended by MnDOT worked very well as an indicator of impending roadway thawing.

For all demonstration sites, plots of interpolated frost and thaw depths for the Phase IIa study years (2014–2015 and 2015–2016), along with WWP and SLR threshold dates according to the MnDOT protocol, are included in Appendix A. For WWP timing, with the exception of the Alaska and Wisconsin sites in 2015, frost penetration was generally between about 10 and 30 inches when the MnDOT WWP threshold was reached. For SLR timing, the MnDOT protocol generally did an excellent job of conservatively predicting the SLR start date just prior to (1 to 6 days before) the onset of thawing. For Ontario and Alaska in the spring of 2015, the MnDOT protocol was excessively conservative.

Frost and thaw patterns at the demonstration site in Whittier, Alaska, were very unusual during both 2014–2015 and 2015–2016, exhibiting multiple complete frost and thaw cycles during a single season. For example, during the first study year, the MnDOT thawing threshold was triggered on January 10, during an early frost and thaw cycle, even though the freezing threshold was not triggered until February 6 during a subsequent frost and thaw cycle. Normally, the CFI threshold would be hit before the CTI threshold was reached. During the second study year, there were two complete frost and thaw cycles during November and December 2015, followed by only brief and minor freezing events (less than 10 inches deep) during January 2016. Since the MnDOT protocol specifies starting the CTI computation with a value of zero on January first, the protocol could not be applied for that frost and thaw season.

It was not surprising that the MnDOT protocol did not perform as well at the test sites in Canada and Alaska, since the latitude of those sites was much higher than that of Minnesota, where the MnDOT reference temperatures were calibrated. This finding from the Aurora study has been further supported by research conducted under a separate contract sponsored by the National Aeronautics and Space Administration (NASA) (Eftekhari et al. 2018). In that study, investigators applied the MnDOT protocol over a wide range of sites throughout the state of Alaska over the course of several years (40 freeze-thaw season and site combinations were used in their analysis). For each site, and for every frost-thaw season where a complete set of data was available, the investigators tabulated the dates that the MnDOT CTI threshold values were reached, the date at the onset of thaw, and the date when the thaw depth exceeded 12 inches. They then checked to see whether the recommended CTI threshold dates fell early (before the onset of thaw), within the window, or late (after the 12-inch thaw depth had been surpassed). The MnDOT method predicted SLR start dates before the onset of thaw for 98% of the freeze-thaw season and site combinations in Alaska and only captured 2% of the events within the window. The early predictions ranged from about one to four weeks before the onset of thawing, with a mean of about two weeks. This early prediction bias was expected, since the MnDOT reference temperatures were calibrated in Minnesota, where solar gain increases are observed much earlier in the springtime compared to Alaska.

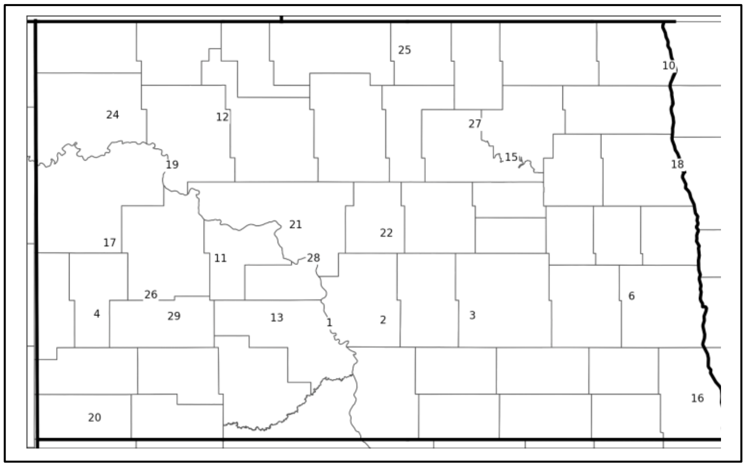
In summary, the findings from Phase IIa of this Aurora study, as well as the study reported by Eftekhari et al. (2018), suggest that the MnDOT protocol performs well, albeit slightly conservatively, in regions of the contiguous United States (CONUS) where the latitude is similar to that of Minnesota. In regions of higher latitude, such as Canada and Alaska, the MnDOT protocol is likely to produce excessively conservative results, with SLR application dates that fall significantly earlier than the actual start of thawing.

3.2.1b Phase IIb Analysis

During Phase IIb of this project, Frost Associates evaluated a demonstration version of a GUI constructed for applying the MnDOT protocol across the state of North Dakota for the 2020 spring thaw season. The Northeast Regional Climate Center (NRCC) at Cornell University constructed the demonstration GUI (see http://www.nrcc.cornell.edu/industry/roads-nd/).

Data for this analysis were obtained from a total of 22 sites in North Dakota. All 22 sites had a temperature depth probe (TDP) sensor at 12 inches below the bottom of the asphalt layer, and several of those sites had additional TDP sensors at 6 inches and/or 9 inches below the bottom of the asphalt layer.

All of the 22 sites in North Dakota had air temperature values based on gridded data (provided by NOAA/NRCC); 19 of the 22 sites in North Dakota also had air temperatures measured by sensors located at the sites. A base map of North Dakota showing the location of the sites used in this analysis is presented in Figure 4.



Site ID	Location	Site ID	Location
1	Bismarck	17	Grassy Butte
2	Sterling	18	Grand Forks
3	Medina	19	New Town
4	Fryburg	20	Bowman
6	Buffalo	21	Coleharbor
10	Bowesmont	22	Denhoff
11	Golden Valley	24	Ray
12	Blaisdell	25	Dunseith
13	New Salem	26	Manning
15	Devils Lake	28	Washburn
16	Mooreton	29	Gladstone

Figure 4. Base map of North Dakota showing the locations of sites used in the NRCC GUI

Table 5 summarizes the dates when the recommended 25 degree-day threshold was exceeded, as well as the dates when thaw progressed past the TDPs at 6, 9, and 12 inches below the bottom of the asphalt layer at each site.

Table 5. Results from Phase IIb (2020) MnDOT protocol evaluation

		Date Thaw Depth Exceeds			Date CTI > 25	
Site ID	Location	6 in. TDP	9 in. TDP	12 in. TDP	NOAA/Gridded Air Temp Data	Air Temp Measured at Site
20	Bowman	2/21/2020	x	2/21/2020	2/29/2020	2/29/2020
29	Gladstone	2/22/2020	x	2/23/2020	2/29/2020	2/28/2020
17	Grassy Butte	x	x	3/1/2020	2/29/2020	2/29/2020
26	Manning	3/5/2020	3/6/2020	3/7/2020	2/29/2020	2/28/2020
4	Fryburg	3/7/2020	3/6/2020	3/8/2020	2/29/2020	2/28/2020
11	Golden Valley	3/7/2020	3/8/2020	3/8/2020	2/29/2020	2/29/2020
28	Washburn	2/24/2020	x	2/29/2020	3/1/2020	2/29/2020
1	Bismarck	x	2/23/2020	2/29/2020	3/1/2020	x
13	New Salem	3/1/2020	3/1/2020	3/1/2020	3/1/2020	2/29/2020
19	New Town	3/1/2020	3/3/2020	3/6/2020	3/1/2020	2/28/2020
21	Coleharbor	3/8/2020	3/24/2020	3/25/2020	3/1/2020	2/29/2020
24	Ray	3/5/2020	3/6/2020	3/7/2020	3/3/2020	3/2/2020
12	Blaisdell	13/1/2020	3/27/2020	3/28/2020	3/3/2020	x
2	Sterling	3/7/2020	3/7/2020	3/7/2020	3/4/2020	3/4/2020
22	Denhoff	3/12/2020	3/26/2020	3/27/2020	3/4/2020	3/5/2020
16	Mooreton	3/7/2020	3/8/2020	3/17/2020	3/8/2020	3/7/2020
6	Buffalo	3/8/2020	3/8/2020	3/8/2020	3/25/2020	3/7/2020
15	Devils Lake	x	x	3/24/2020	3/25/2020	3/25/2020
25	Dunseith	x	x	3/24/2020	3/25/2020	3/25/2020
3	Medina	3/27/2020	3/27/2020	3/28/2020	3/25/2020	3/7/2020
10	Bowesmont	x	x	3/28/2020	3/27/2020	x
18	Grand Forks	3/28/2020	3/29/2020	3/29/2020	3/28/2020	3/24/2020

TDP depths are measured below the bottom of the asphalt layer.

Time series plots of CTI values and subsurface temperatures from the TDPs are included in Appendix B. CTI values were computed according to the equations recommended by MnDOT (2009, 2014), as summarized in Section 3.2.1a of this report. For the GUI constructed by the NRCC, gridded air temperature data provided by NOAA was utilized as input for the CTI computations. For the majority of sites where air temperature sensors were available on site, those air temperatures were also utilized as input for alternate CTI computations.

In Table 5, if a given TDP sensor only briefly exceeded 32°F and then dropped back down below freezing, that event was neglected. However, when temperatures at a given depth went into an isothermal state (fluctuating just slightly above and below freezing for some time), the start of that isothermal period was conservatively taken as the thaw date for that TDP sensor.

Based on those assumptions, several trends are suggested from the data in Table 5, which are further illustrated by the computer images from the NRCC GUI shown in Figures 5 and 6.

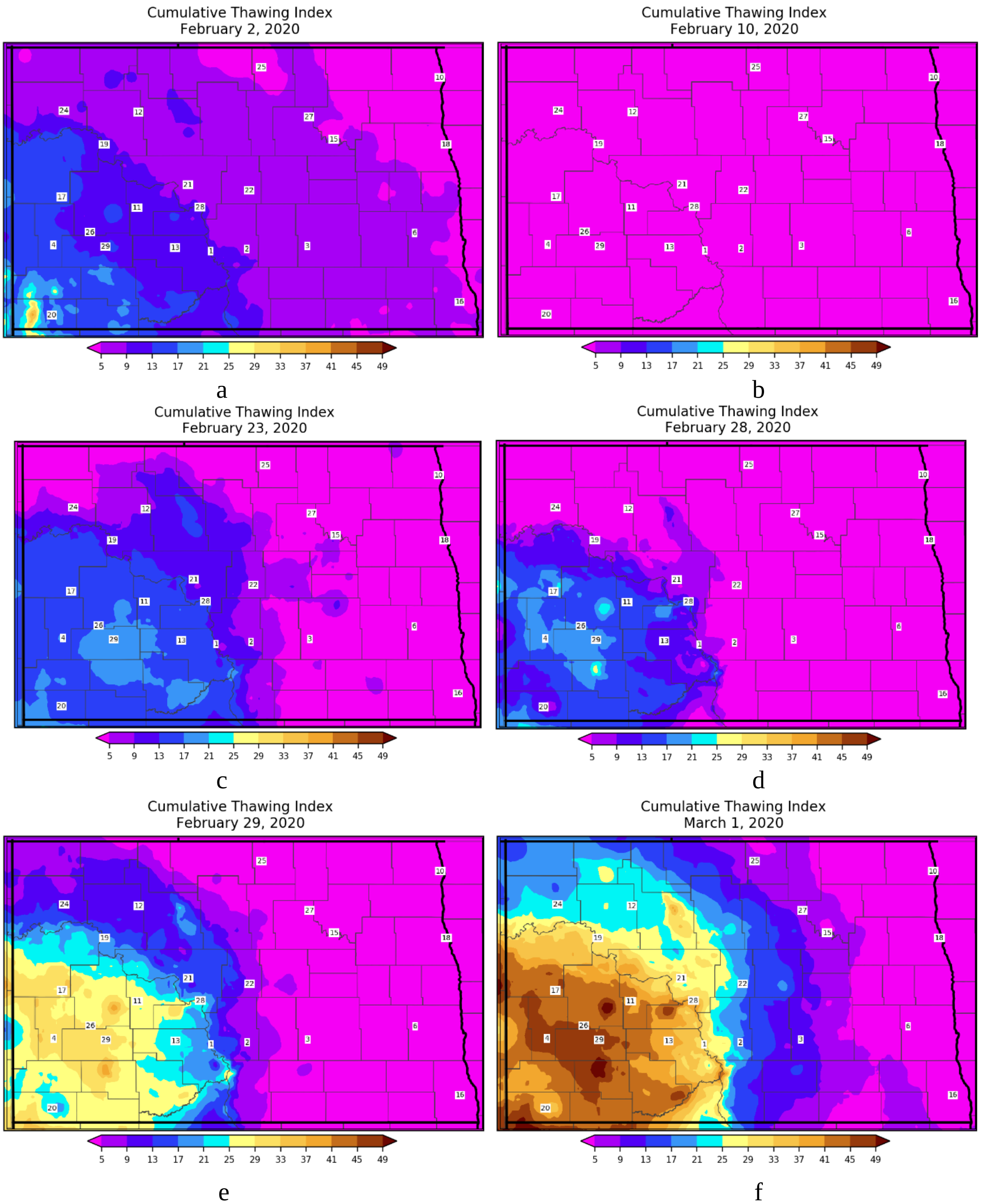


Figure 5. North Dakota CTI trends (February 2–March 1, 2020)

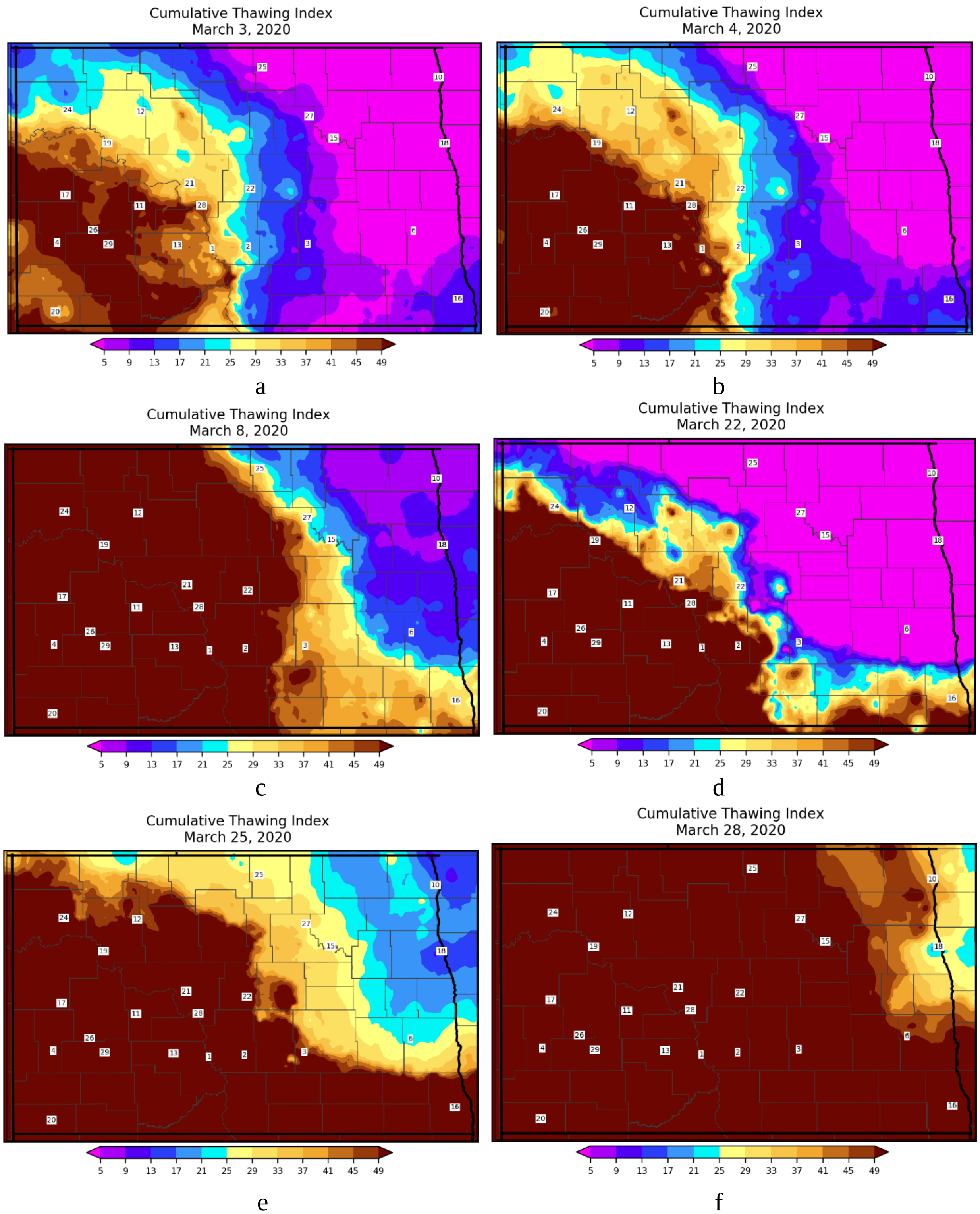


Figure 6. North Dakota CTI trends (March 3–March 28, 2020)

In late January, air temperatures warmed, causing CTI values in the southwest corner of the state to spike above the 25 degree-day threshold briefly in early February (see Figure 5a). Although the Bowman site (Site 20) was just outside of the warmest spot, thawing at that site progressed past both the 6- and 12-inch TDP sensors on January 29, 2020. Temperatures then decreased and CTI values remained at zero throughout the entire state of North Dakota during the middle of February (see Figure 5b). During the last week in February, warming again progressed northward and eastward from the southwest corner of the state (see Figures 5 c and d). Between January 29, 2020 and February 21, 2020, the 6- and 12-inch TDP sensors at Bowman fluctuated above and below freezing; then, fairly rapid and complete thawing of the base and subgrade occurred on February 23, 2020.

Figure 5e shows that as warming progressed, CTI values exceeded the 25 degree-day threshold at five additional sites on February 29, 2020 (Sites 4, 17, 26, 29, and 11). Thaw depths at four of those sites exceeded the 6- to 12-inch TDP sensors during the first week in March, suggesting that the MnDOT protocol reasonably predicted the onset of thaw and was slightly conservative (predicting thaw a few days in advance of when it was actually observed in the subsurface temperature sensors). At the Gladstone site (Site 29), thawing was observed in the TDP sensors about a week ahead of when the CTI threshold was exceeded; however, it is noted in Figure 5c that warming started occurring in an area surrounding that site beginning around February 23, 2020.

Figure 5f shows that CTI values exceeded the 25 degree-day threshold at five sites on March 1, 2020 (Sites 28, 1, 13, 19, and 21). At four of those five sites, the MnDOT criteria were in reasonably good agreement with the date that thaw was observed in the TDP sensors. At Site 21 (Coleharbor), the MnDOT protocol was somewhat, although not excessively, conservative. Although thaw was not observed in the 12-inch TDP sensor until March 25, it was observed in the 6-inch TDP sensor at that site on March 8, 2020.

On March 3 and 4 the CTI threshold was exceeded at four more sites (see Figures 6a and b). At Sites 24 (Ray) and 2 (Sterling), thaw progressed to the 12-inch TDP sensor by March 7, in good agreement with the MnDOT protocol. At Site 12 (Blaisdell) and Site 22 (Denhoff), the MnDOT protocol was somewhat conservative. Thaw was observed in the 6-inch TDP sensor at those sites on March 11 and 12, respectively, which is only eight days after the CTI threshold was exceeded. As shown in Figure 6d, a subsequent cold spell brought CTI values at Sites 12 and 22 down below 25 degree-days around March 22 before warming again raised CTI values above the threshold on March 25, 2020 (see Figure 6e). Those air temperature swings likely explain why thawing was observed in the 6-inch TDP earlier in March but was not observed in the 12-inch TDP sensor until March 27 and 28 at the Denhoff and Blaisdell sites, respectively.

At the Mooreton, North Dakota, site (Site 16), the CTI threshold was exceeded on March 8, which was in good agreement with observed thaw depths on March 7 (6-inch sensor) and March 17 (12-inch sensor). At five of the remaining six North Dakota sites (Sites 15, 25, 3, 10, and 18), thawing did not occur until the last week in March, and the CTI threshold dates were in good agreement (within 1 or 2 days +/-) of the dates when thaw was observed in the TDPs.

At the Buffalo site (Site 6), significant warming of the subsurface occurred in early March, and all TDP sensors down to a depth of 54 inches went into an isothermal state around March 8, continuing through around March 26 when temperatures at the 6-, 9-, and 12-inch depths then rose rapidly. The Buffalo site was one of only two sites in North Dakota where there was a significant difference between the air temperatures measured at the site and the gridded values of air temperature provided by NOAA. Interestingly, the CTI computed from the air temperatures measured at the Buffalo site hit the 25 degree-day threshold on March 7, near the start of the isothermal period, and the CTI computed from the gridded values of air temperature provided by NOAA hit the threshold on March 25, near the end of the isothermal period.

In summary, the MnDOT protocol generally performed very well as a tool for predicting when SLRs should be applied at the 22 sites in North Dakota where subsurface temperature data were obtained for the 2020 analysis. The following observations were made:

- The MnDOT protocol was slightly conservative for the majority of the 22 study sites: for 15 of the 23 sites, thawing was observed at the 6-, 9-, and/or 12-inch TDP sensor within zero to nine days after the date that the CTI threshold was exceeded.
- At four sites, the MnDOT protocol was slightly non-conservative. At those sites, thawing was observed in the 12-inch sensor just one day before the CTI threshold was exceeded.
- At two sites (Gladstone and Bowman), thawing was observed about a week before the CTI threshold was exceeded.
- At only 1 of the 22 sites, the MnDOT protocol may have been substantially non-conservative (Buffalo). It was noted that two factors may have contributed to the results at that site:
    - Isothermal conditions were observed at that site during the 2020 thaw season.
    - There was a significant difference between the air temperatures measured at the site and the gridded values of air temperature utilized in the NRCC interface.

For this study, the NRCC constructed a demonstration GUI, whereby the MnDOT protocol could be implemented over a large geographic region (i.e., the entire state of North Dakota). That GUI was very straightforward and easy to use and shows much potential for improving SLR timing decisions compared to doing calculations by hand (or on an Excel spreadsheet) for multiple individual roadway locations. The NRCC GUI utilizes gridded air temperature data provided by NOAA as input for the CTI computations. To check the accuracy of the gridded air temperature data, separate CTI calculations were also performed for 19 of the 22 sites where data were available from air temperature sensors located on site. At 15 of the 19 sites, the dates that the CTI exceeded the recommended 25 degree-day threshold were the same as, or within +/- one day of, each other. At two sites, the CTI computed from the NRCC GUI exceeded the recommended threshold two and four days later than the CTI computed from air temperatures measured at the sites. There were only two sites (Buffalo and Medina) where there was a significant difference (18 days) between the CTI values computed from air temperatures measured at the site and the CTI values computed from the gridded values of air temperature utilized in the NRCC interface. Overall, this study suggests that the gridded air temperature data generally produced satisfactory results for use in the GUI.

3.2.2 Lakehead University and Ministry of Transportation Ontario (MTO)

Researchers at Lakehead University have been working in conjunction with the Ministry of Transportation Ontario (MTO) since 2005 to develop several modelling methodologies to predict frost and thaw trends at seven instrumented sites in Northern Ontario. Similar to the approaches described in Section 3.2.1, the researchers recommend applying WWPs based on CFI thresholds and SLRs based upon CTI thresholds. At the Ontario sites, LWD data were used to confirm WWP and SLR threshold values. LWD data suggest that the pavement structure is sufficiently strong to permit WWP overloads when the frost depth exceeds 100 cm, or about 40 inches, and that the pavement structure weakens to the point of permanent damage when the thaw depth exceeds 30 cm, or about 12 inches (Pernia et al. 2014).

The Lakehead University protocol suggests using variable threshold values for applying WWPs and SLRs, which must be calibrated on a site-specific basis, by determining the CFI and CTI values corresponding to the dates that the frost and thaw depths exceed about 40 and 12 inches (100 cm and 30 cm), respectively. The researchers computed cumulative freezing and thawing indices according to MnDOT (2009), as outlined in Section 3.2.1 of this report. Since the Lakehead University protocol for applying WWPs and SLRs was already calibrated at the Ontario site (Highway 527) based upon several years of measured frost and thaw depth data, we had proposed to run that model at the Ontario site during both the 2014–2015 and 2015–2016 seasons. The site-specific threshold values for WWP and SLR application at the Highway 527 demonstration site are shown in Tables 6 and 7, respectively.

Table 6. Lakehead University WWP-CFI model calibration at Ontario Highway 527 site

Project Site	Region	Data Set	Date FD > 1 m	Corresponding CFI (°C·days)	Site-Specific Threshold Value
Highway 527	NW	2008/2009	10/12/2008	324	347
		2009/2010	15/12/2009	262	
		2010/2011	17/12/2010	395	
		2011/2012	01/01/2012	407	

Source: Pernia et al. 2014

Table 7. Lakehead University SLR-CTI model calibration at Ontario Highway 527 site

Project Site	Region	Data Set	Date TD > 0.3 m	Corresponding CTI (°C·days)	Site-Specific Threshold Value
Highway 527	NW	2008/2009	11/04/2009	72	72
		2009/2010	15/03/2010	82	
		2010/2011	08/04/2011	58	
		2011/2012	17/03/2012	76	
		2009/2010	13/03/2010	51	
		2010/2011	08/04/2011	54	

Source: Pernia et al. 2014

Note that these cumulative indices were originally provided in SI units, so for this demonstration site, plots of CFI and CTI in SI units are presented in Figures 7 and 8, respectively. For WWP application during the 2015–2016 frost and thaw season, the CFI threshold of 347°C-days is exceeded on January 9, 2016 (Figure 7).

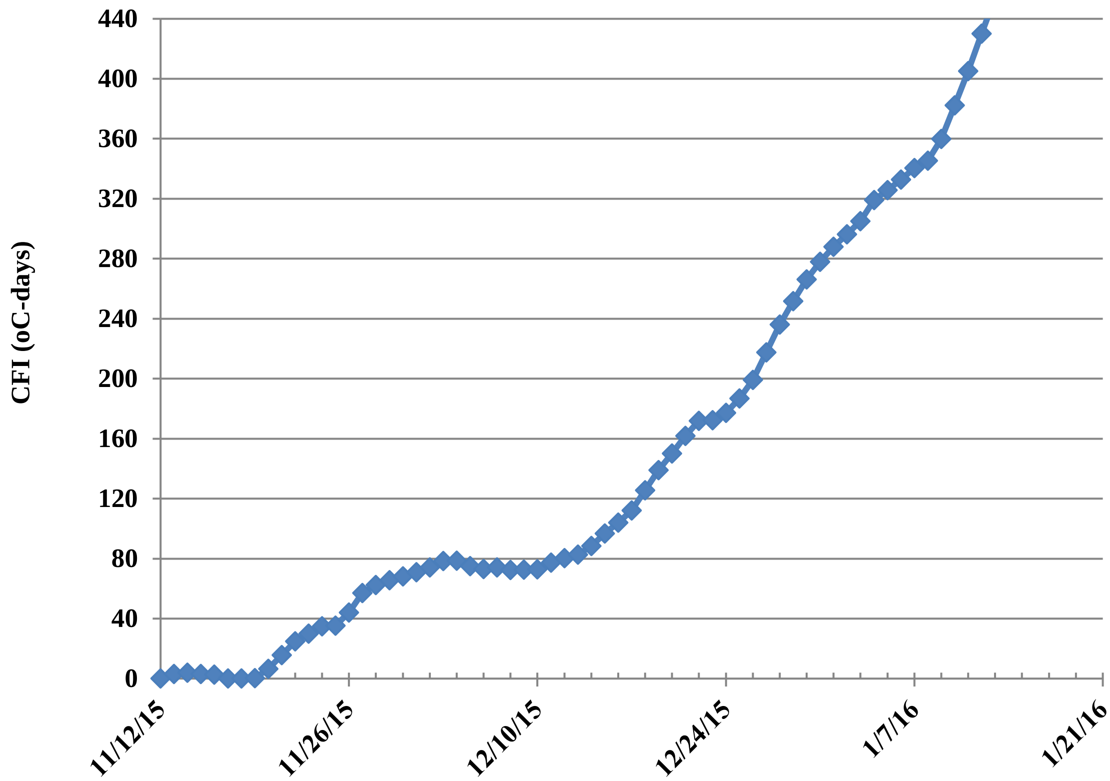


Figure 7. CFI at the Ontario Highway 527 site during 2015–2016

For SLR application, the CTI threshold of 72°C-days is reached on April 16, 2016 (Figure 8).

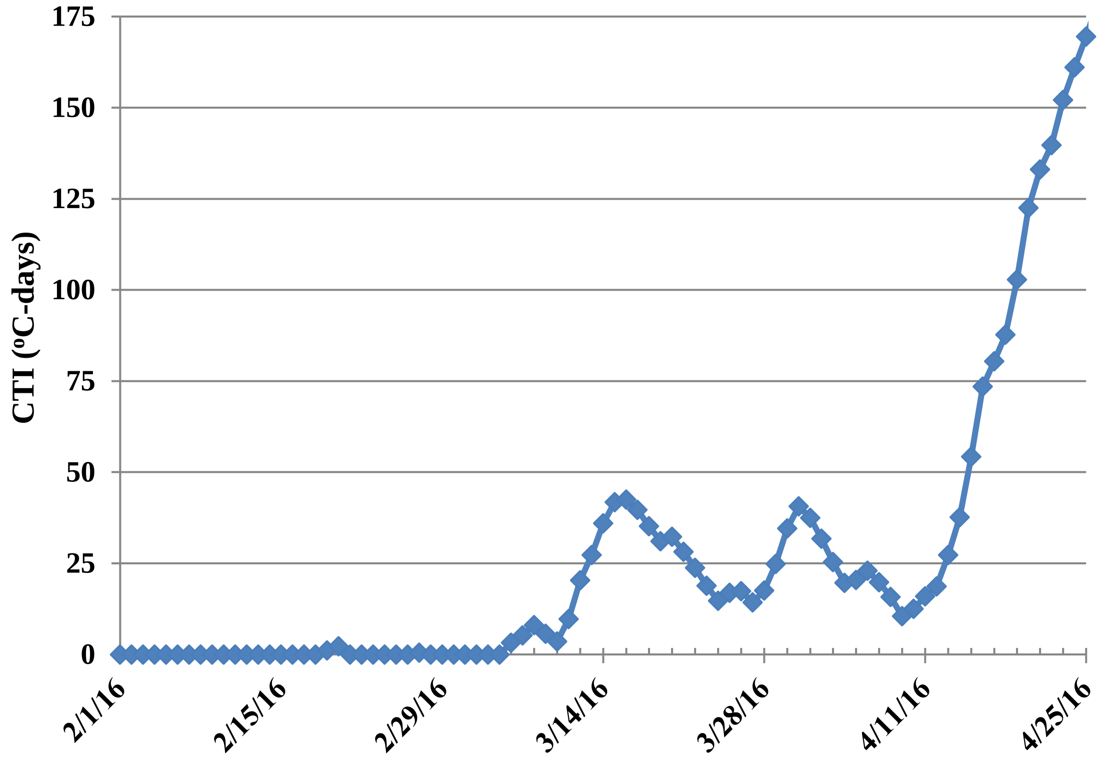


Figure 8. CTI at the Ontario Highway 527 site during 2015–2016

These two threshold dates are superimposed on a plot of measured frost and thaw depths in Figure 9.

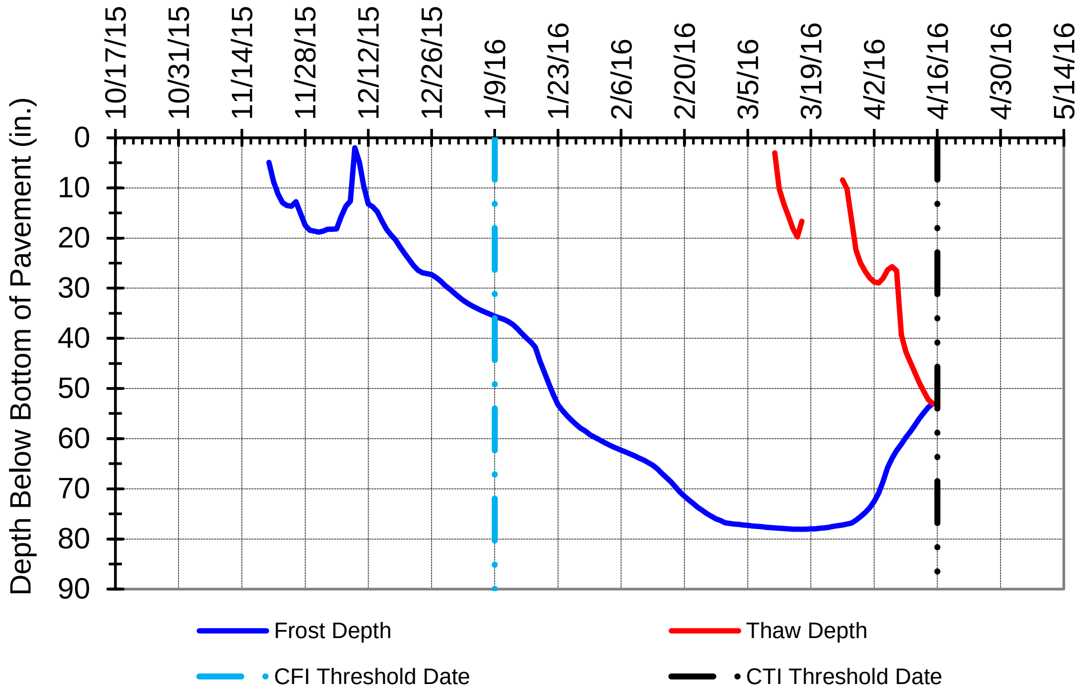


Figure 9. Interpolated frost and thaw depths and Lakehead University WWP (CFI) and SLR (CTI) threshold dates at the Ontario Highway 527 site during 2015–2016

In Figure 9, frost had penetrated to a depth of about 35 inches when the WWP threshold was reached, which is consistent with the 40-inch frost depth criteria suggested by the LWD data in Ontario. On the other hand, the recommended SLR threshold during the 2015–2016 frost and thaw season was not reached until the subsurface was completely thawed, suggesting that this protocol was quite non-conservative in terms of SLR application for the 2015–2016 season.

Figure 10 shows the CFI and CTI threshold dates superimposed on a plot of measured frost and thaw depths for the 2014–2015 season.

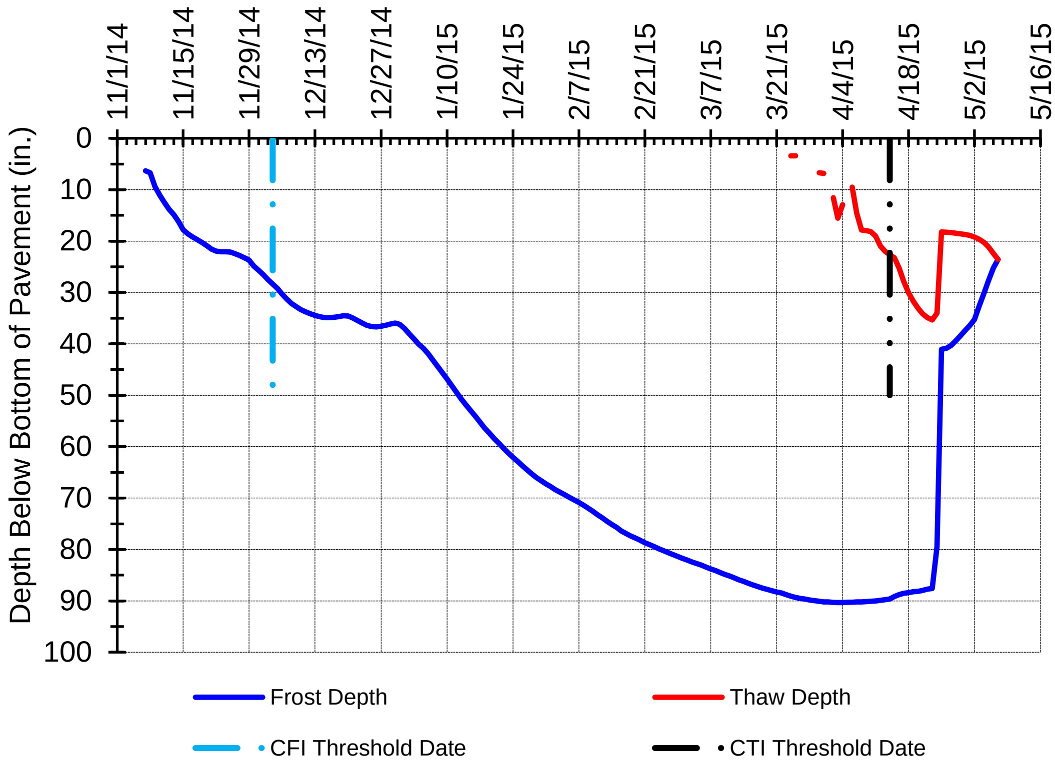


Figure 10. Interpolated frost and thaw depths and Lakehead University WWP (CFI) and SLR (CTI) threshold dates at the Ontario Highway 527 site during 2014–2015

In Figure 10, frost had only penetrated to a depth of about 28 inches when the WWP threshold was reached on December 4, 2014, which was substantially less than the 40-inch frost depth criteria suggested by the LWD data in Ontario. On the other hand, the recommended SLR threshold during the 2014–2015 frost and thaw season was reached on April 14, 2015, when thaw had penetrated 23 inches deep. While this is a bit more conservative than the results from 2015–2016, it may still be a bit late in terms of preventing damage from thaw weakening.

As noted in Section 1.3.2, the Phase II scope of work included running the Lakehead University model for two years at the Ontario site (since it had already been calibrated at that site). For the other four demonstration sites, the authors used year 1 (2014–2015) data for calibration and then ran this model in predictive mode for year 2 (2015–2016). For WWP calibration, the date frost penetrated 40 inches and the corresponding CFI value on that date were tabulated, as shown in Table 8.

Table 8. Lakehead University WWP and SLR model calibration at US demonstration sites (2014–2015)

	WWP (CFI) Calibration		SLR (CTI) Calibration	
Site	**Date Frost Depth > 40 in.**	**CFI (°F-days) on Date Frost Depth > 40 in.**	**Date Thaw Depth > 12 in.**	**CTI (°F-days) on Date Thaw Depth > 12 in.**
AK	01/28/2015	115.70	2/19/2015	80.5
MI	1/4/2015	741.00	3/16/2015	101.1
ND	N/A	N/A	3/10/2015	64.2
WI	1/3/2015	281.10	3/10/2015	49.2

*N/A = frost depth never reached 40-inch depth

Similarly, the date that thaw penetrated 12 inches and the corresponding CTI value on that date were tabulated.

Then, during year 2 of the study, the authors superimposed the dates when the site-specific threshold values for CFI (WWP) and CTI (SLR) were reached on the frost-thaw depth plots for each site. Those plots are included in Figures 11 through 14. When comparing SLR start dates from the MnDOT protocol (Appendix A) with the Lakehead University protocol (Figures 11 through 14), it appears that the Lakehead University protocol is somewhat non-conservative.

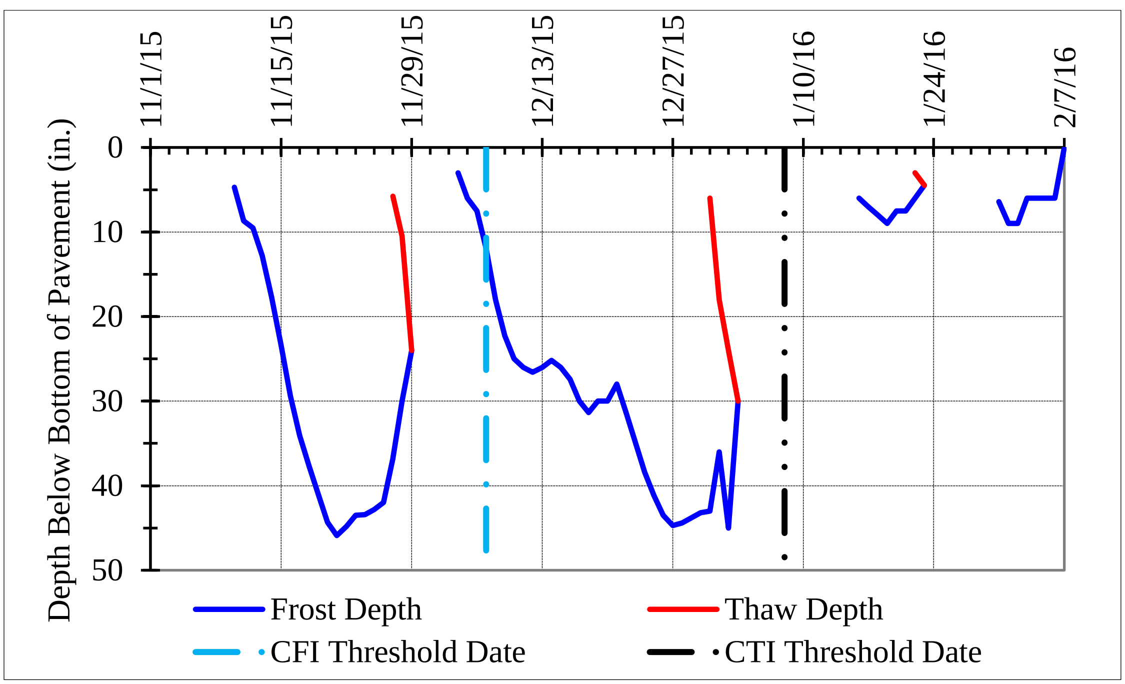


Figure 11. Interpolated frost and thaw depths and Lakehead University WWP (CFI) and SLR (CTI) threshold dates at the Alaska site during 2015–2016

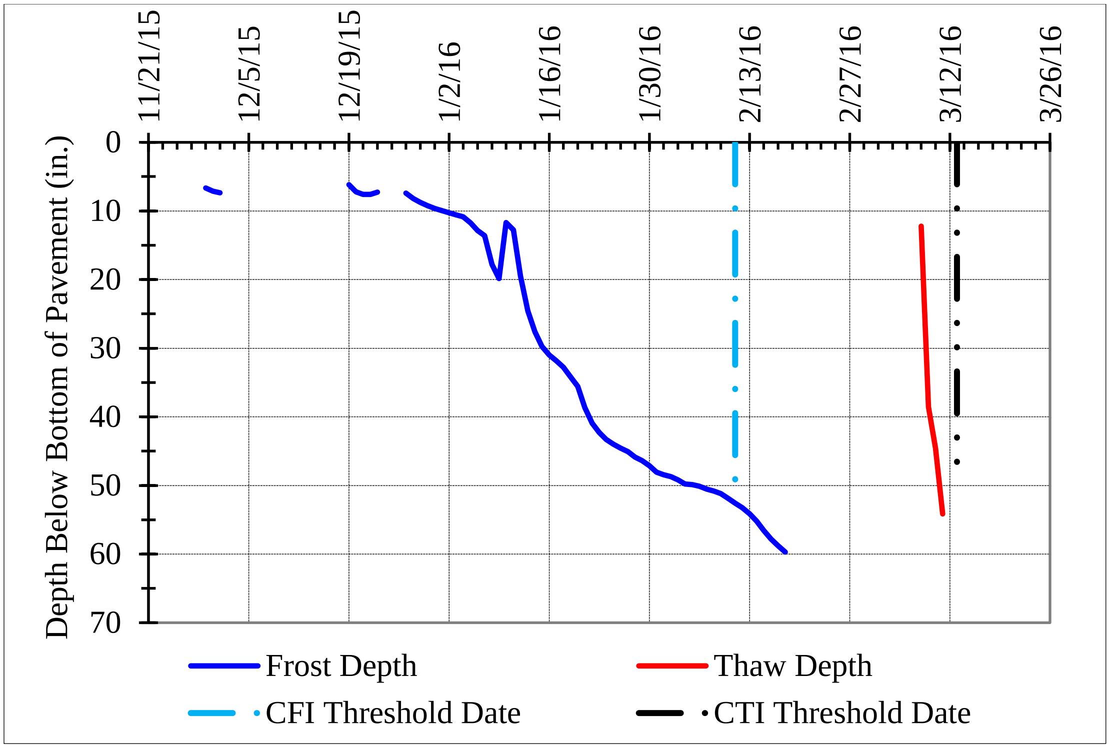


Figure 12. Interpolated frost and thaw depths and Lakehead University WWP (CFI) and SLR (CTI) threshold dates at the Michigan site during 2015–2016

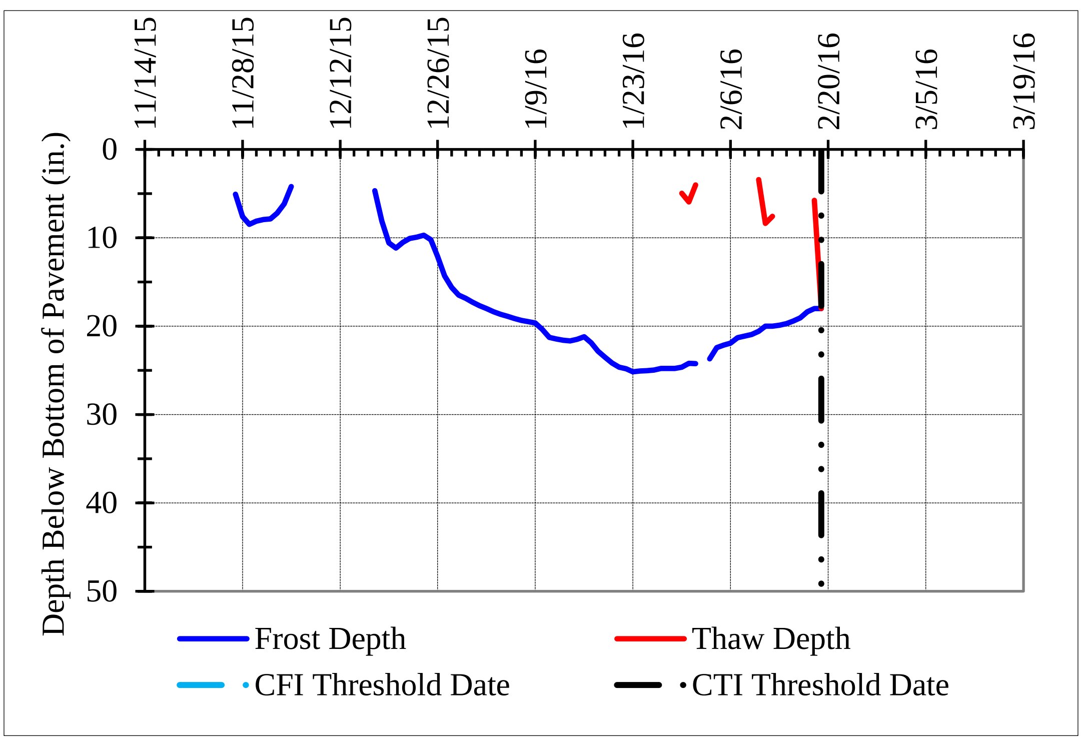


Figure 13. Interpolated frost and thaw depths and Lakehead University WWP (CFI) and SLR (CTI) threshold dates at the North Dakota site during 2015–2016

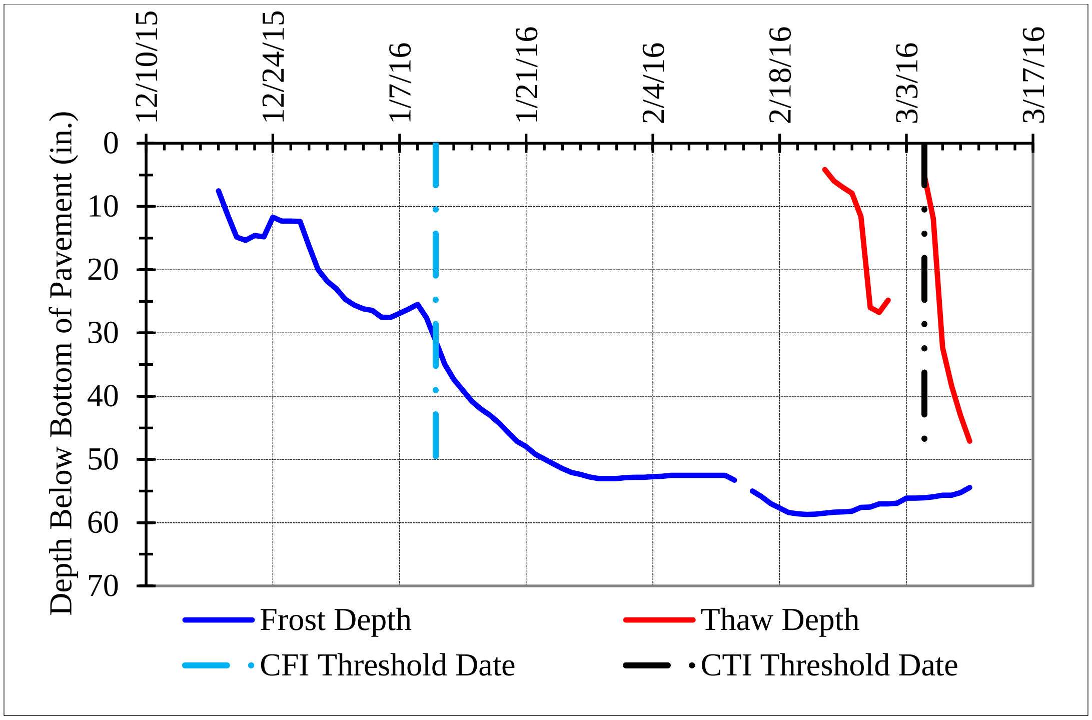


Figure 14. Interpolated frost and thaw depths and Lakehead University WWP (CFI) and SLR (CTI) threshold dates at the Wisconsin site during 2015–2016

While the MnDOT method generally did an excellent job of setting the SLR start date very close to the onset of thawing, the Lakehead University protocol often set the SLR start date after significant thawing (or sometimes complete thawing) had occurred. In terms of WWP start dates, there was more scatter in the data. In general, for both protocols, frost penetration was between about 10 and 30 inches when the WWP threshold was reached, and slightly deeper in a few cases.

3.2.3 Potential Alternative Protocols for Regions at Higher Latitudes

3.2.3a Introduction

Both of the SLR application protocols described in Sections 3.2.1 and 3.2.2 link SLR placement to cumulative thawing indices, which use daily air temperature and a variable reference temperature (as specified by MnDOT 2009) to account for increased solar gain during the late winter and early spring. While several researchers have found that the MnDOT protocol and reference temperatures work well for regions located at about the same latitude as Minnesota, other investigators have suggested that local calibration may be required for sites at different latitudes.

As discussed in Section 3.2.1a, the findings from this Aurora study, as well as a study reported by Eftekhari et al. (2018), which examined an extensive range of sites throughout the state of Alaska, suggest that the MnDOT protocol is likely to produce excessively conservative results in regions of higher latitude, such as northern and central Canada and Alaska. This early prediction bias is not surprising, since the MnDOT reference temperatures were calibrated in Minnesota, where solar gain increases are observed much earlier in the springtime compared to Alaska.

Although not part of the Phase II scope of this Aurora study, the two sections that follow present a brief summary of two alternative degree-day threshold protocols that show more promise for SLR timing in regions at higher latitudes, such as Alaska.

3.2.3b Pavement Surface-Temperature Prediction Model for SLR Application (Rajaei et al. 2017; Eftekhari et al. 2018)

Recently, a relatively new model/approach for SLR application was developed by Rajaei et al. (2017). Building upon earlier research conducted by Diefenderfer et al. (2006), Rajaei et al. (2017) took one year of data from 12 RWIS stations in the Lower Peninsula of Michigan and developed a statistical model for estimating pavement surface temperatures based upon the latitude of the site and measured daily average air temperatures. Rather than incorporating a freeze temperature depression adjustment as per MnDOT (2009), the Rajaei et al. (2017) model directly uses sun angle to compute insolation, although blocking due to vegetation, which is significant close to morning/evening, is not accounted for. Additionally, the radiation calculation doesn’t incorporate reductions due to atmosphere/clouds.

Rajaei et al. (2017) further suggested using pavement surface temperatures estimated from their model to compute daily and cumulative thawing indices for use in SLR application. Because this approach accounts for changes in latitude (and thus changes in solar gain during the early spring), a potential advantage of this approach is that it may eliminate the need for local calibration of CTI threshold values and reference temperatures. Rajaei et al. (2017), however, did not recommend a threshold value to be used for that pavement temperature-based CTI, nor did they correlate thawing index values with thaw depth profiles beneath any of the roadway stations in their study.

Therefore, several investigators working on a contract sponsored by NASA (Grant NNX16AN34G) conducted research to accomplish the following:

1. Validate the Rajaei et al. (2017) model over a wider range of geographic regions using measured air and pavement temperatures at several roadway sites

2. Determine whether a consistent CTI threshold could be determined that would be appropriate for SLR application for all of the roadway sites regardless of location

3. Compare this new SLR application protocol with the more traditional MnDOT protocol

For details regarding the Rajaei et al. (2017) pavement surface temperature prediction model and its extension to SLR timing protocols, the reader is referred to Eftekhari et al. (2018); however, conclusions from both of those studies are summarized herein.

The first goal of a research effort undertaken by Eftekhari et al. (2018) was to evaluate the Rajaei et al. (2017) pavement surface temperature prediction model at sites located in other parts of the country. Furthermore, the research team wanted to correlate CTI values computed using this new approach with measured thaw depths at numerous sites to see whether an appropriate CTI threshold value could be determined for SLR timing that would not be location dependent. Data were obtained from 37 sites located in Maine, New Hampshire, Michigan, North Dakota, Wisconsin, and Alaska. At each site, data were obtained from RWIS or other monitoring systems that included daily average values for air temperature, pavement temperature(s), and subsurface temperatures at various depths. The sites in Michigan, North Dakota, Wisconsin (one site in each state), and Alaska (30 sites) were all part of the RWIS system. The four sites in New Hampshire and Maine were not part of the RWIS system but had instrumentation installed as part of other research projects (Zarrillo et al. 2012, Miller et al. 2017).

The results presented by Eftekhari et al. (2018) suggest that the Rajaei et al. (2017) model yields reasonable estimates for pavement surface temperatures over a wide latitudinal range, although they noted that the Rajaei et al. (2017) model slightly underpredicted pavement surface temperatures. Eftekhari et al. (2018) correlated CTI values computed using pavement surface temperatures from the Rajaei et al. (2017) model with measured thaw depths at the 37 study sites. For the purpose of determining a CTI threshold for SLR application in their study, it was decided to target a window between the onset of thaw and the date when the thaw depth exceeded 12 inches. It should be noted that, for most sites and most thaw seasons included in their study, it was observed that the window/duration of time between the start of thaw and a 12-inch thaw depth was generally quite short (about two to eight days). Based upon their correlations, they suggested that a CTI threshold value of 30°F-days might be appropriate for SLR application.

For each site, and every frost-thaw season where a complete set of data was available, the investigators tabulated the dates that CTI threshold values were reached (using both the new model and the MnDOT protocol). They then checked to see whether the recommended CTI thresholds fell early (before the onset of thaw), within the window, or late (after the 12-inch thaw depth had been surpassed). A summary of these determinations is presented in Table 9.

Table 9. Comparison of MnDOT protocol and new SLR timing model

		% of Determinations Falling		
Method	**Region**	**Early**	**Within Window**	**Late**
MnDOT	CONUS (N=11)	36	64	0
New Model	CONUS (N=11)	18	64	18
MnDOT	Alaska (N=40)	98	2	0
New Model	Alaska (N=40)	32	58	10

N = number of freeze-thaw season and site combinations used in analysis
Source: Eftekhari et al. 2018

Despite the ability to reasonably estimate pavement surface temperatures, when those temperatures were used to compute CTI values for SLR timing, no significant improvement over the MnDOT approach was observed for the sites located in the CONUS. At the CONUS sites, although both approaches yielded SLR application dates that fell within the target window 64% of the time, for the remaining 36% of determinations, there was less variability and the SLR application dates fell closer to the middle of the window using the MnDOT protocol. The MnDOT protocol was more conservative than the new model at the CONUS sites; all of the 36% of determinations falling outside the target window fell early using the MnDOT protocol. Using the new model, half of the determinations falling outside the target window fell early and half fell late. Therefore, the MnDOT approach would be recommended over the new model in the CONUS.

At the sites in Alaska, the new SLR timing model did not perform quite as well as it did at the CONUS sites, capturing only 58% of the events within the window. However, the new model greatly improved SLR timing compared to the MnDOT protocol in Alaska. The MnDOT method predicted SLR start dates before the onset of thaw for 98% of the freeze-thaw season and site combinations in Alaska and only captured 2% of the events within the window.

Overall, the Eftekhari et al. (2018) study supports the suggestion by Rajaei et al. (2017) for using estimated pavement surface temperatures to compute daily and cumulative thawing indices for use in SLR application. The trends in CTI values, computed using these estimated pavement temperatures, can reasonably indicate the initiation of thawing beneath roadways and may improve SLR timing estimates in regions at higher latitudes such as Alaska. However, the reduced performance in Alaska as compared to the CONUS suggests that the Rajaei et al. (2017) regression equation for pavement surface temperature prediction may need to be improved prior to broader application for SLR timing beyond the original study region. Furthermore, it might be prudent to consider using a slightly higher CTI threshold value when using this new approach in regions at higher latitudes, since predicting the SLR start date on the late side can lead to pavement damage.

3.2.3c Berg/FS Method

The Berg/USFS method provides an alternative approach for applying spring load restrictions that also takes into account the influence of pavement surface temperatures. This method assumes that both average daily air temperatures and average daily pavement surface temperatures can be approximated by sinusoidal functions, according to Equation 3.

$$T_t = MAT + Amp * Sin\left(\left(\frac{2\Pi}{P}\right) * \left(t - Lag\right)\right) \tag{3}$$

where

T_t = sinusoidal temperature on Julian day t
P = period of sinusoidal variation (365 days)
MAT = 30-year mean annual temperature
Amp = amplitude of temperature sinusoid

Lag = time lag of the temperature sinusoid (i.e., the amount of time it takes the temperature sinusoid to reach the MAT)

This method requires an initial trial-and-error fit for the air temperature sinusoid based upon 30-year normals of average monthly air temperature data from a weather station located near the candidate site. The National Weather Service, and its successors, define a 30-year normal as the average temperature over a 30-year period. A 30-year normal temperature may be the average daily maximum, the average daily minimum, the average monthly maximum, or the average monthly minimum. The 30-year period changes every decade. For example, the current 30-year normal period is from 1981 through 2010. Thirty-year normal data are available for several weather stations in every state and can be found at the National Climatic Data Center's (NCDC's) website, https://www.ncdc.noaa.gov/.

A trial-and-error procedure for determining the amplitude of the air temperature sinusoid is carried out in an Excel spreadsheet using Equation 3 with a generally recommended value of 110 days for the time lag.

Figure 15 shows the 30-year mean monthly air temperatures (as diamonds) for Whittier, Alaska, along with the computed daily air and pavement surface temperatures (solid lines) computed using the Berg/FS method.

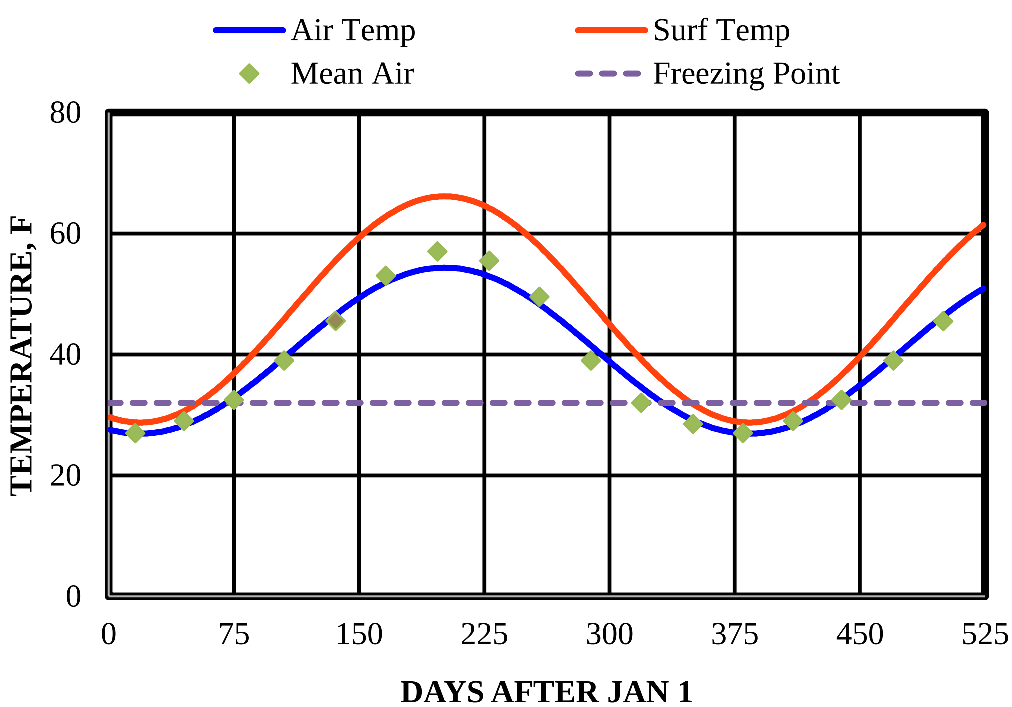


Figure 15. 30-year normal mean monthly air temperatures and computed daily air and surface temperatures, Whittier, Alaska (using lag = 110 days)

Also included in Figure 15 is the freezing point line, 32°F. Areas between the sinusoidal variations and the freezing line represent the thawing index, ATI (above), or freezing index, AFI (below).

After the air temperature sinusoid is computed, the pavement surface temperature sinusoid is also computed using a trial-and-error fitting procedure. To do that, the following empirical correlations are used to relate pavement surface freezing and thawing indices to air freezing and thawing indices:

$$SFI = n_f \left(AFI\right) \tag{4}$$

$$STI = n_t \left(ATI\right) \tag{5}$$

where
SFI = surface freezing index
STI = surface thawing index
n_f = n-factor applied to the air freezing index, *AFI*
n_t = n-factor applied to the air thawing index, *ATI*

Based on studies conducted in the New England area, Berg et al. (2006) recommend using n_f = 0.5 and n_t = 1.7; however, as discussed subsequently, these n-factors had to be modified for Alaska.

After the air and pavement surface temperature sinusoidal functions are established, the difference between the two can be calculated for each Julian day (1 to 365). The difference is then added to the measured average daily air temperature for a specific day to approximate the pavement surface temperature. Daily thawing index (DTI) calculations must start before the onset of thawing, and are computed according to Equation 6:

$$DTI = (Pavement\ Surface\ Temp) - 32^{o}F \tag{6}$$

The DTI is then used to compute a cumulative index (CTI) using Equation 7:

$$CTI = \sum_{i=1}^{N} (DTI_i) \tag{7}$$

This method recommends applying the SLR when the CTI increases to 30°F-days above the minimum CTI value (Berg et. al 2006, Kestler et al. 2007). A protocol for removal of the SLR is not currently provided in this approach.

Although the Berg/FS method was reviewed during the Phase I contract for this Aurora project, it was not originally recommended for the Phase II study because the trial-and-error calibration process is somewhat tedious and because, in the CONUS, previous studies indicated that SLR posting dates derived from this method were quite similar to those obtained using the MnDOT (2009) protocol. However, since the MnDOT protocol has now been found to produce excessively conservative results in regions of higher latitude, such as central and northern Canada and Alaska, we decided to conduct a small study to determine whether the Berg/FS method might show more promise at higher latitudes such as the Aurora test site in Alaska.

Examination of Equations 3, 4, and 5 indicate that, in addition to the mean monthly air temperatures, three other factors also impact the amplitudes and timing of air and surface sinusoidal temperature variations computed from the Berg/FS method:

- Time lag of the sine wave (which impacts both the air and surface sine waves)
- Freezing n-factor
- Thawing n-factor (n_f and n_t impact only the surface temperature sine wave)

Because all of the sites where we have previously applied the Berg/FS method have been in the contiguous 48 states, we conducted a small study to determine whether n-factors would be different in this part of Alaska. We analyzed data (shown in Table 10) obtained for the four years prior to the Aurora project study years.

Table 10. Measured air and surface freezing and thawing indices from Whittier, Alaska, site

	Thawing Index, ATI			Freezing Index, AFI		
Season/Year	**Air**	**Surface**	**N-Value**	**Air**	**Surface**	**N-Value**
2010–2011	3,194	5,283	1.7	1,706	1,812	1.1
2011–2012	3,257	5,293	1.6	1,733	1,541	0.9
2012–2013	2,923	4,918	1.7	1,639	1,494	0.9
2013–2014	3,410	5,694	1.7	803	962	1.2
Average	3,196	5,297	1.7	1,470	1,452	1.0

The average n-factor for the thawing seasons, n_t, is 1.7, and the average n-factor for the freezing seasons, n_f, is 1.0. The n_t is the same as that used in the contiguous 48 states, but the n_f is 1.0, compared to 0.5, which is typically used in the contiguous 48 states. Thus, at this site in Alaska, the air and pavement surface temperatures are very similar (almost equal, on average) over the entire winter, whereas in the contiguous 48 states, pavement surface temperatures are generally higher than air temperatures during the winter months. This is primarily due to less solar radiation reaching the pavement surface at higher latitudes in the winter.

We used these n-factors in the Berg/FS spreadsheet to determine if the time lag, or phase shift, in mathematical terminology, is different at the Whittier, Alaska, site compared to sites in the contiguous 48 states. We did not know what to expect because we had never attempted to apply the methodology to locations in Alaska, or in a maritime environment. Using the same n-factors, we changed the time lag from 110 days to 105 days and then 100 days. The shift in the sine wave was slight, but using a time lag of 105 days did slightly improve the sinusoidal “fit” between computed air temperatures and measured monthly mean temperatures. Therefore, “add-to-air temperatures” determined using the time lag of 105 days, along with the previously discussed n-factors (n_t, = 1.7 and n_f, = 1.0) were used in a spreadsheet to calculate the SLR application date at the Whittier, Alaska, site according to the Berg/FS method. Part of that spreadsheet is included in Table 11.

Table 11. Berg/FS method applied to Whittier, Alaska, site for 2019–2020

Date	Julian Day	Air Temp °F	Add to Air °F	Surf. Temp. °F	Freeze Temp. °F	Daily Index °F-days	Cum. Index °F-days	Comments
2/14	45	0.6	2.5	3.1	32.0	-28.9	-28.9	
2/15	46	8.9	2.6	11.5	32.0	-20.5	-49.4	
2/16	47	3.7	2.6	6.3	32.0	-25.7	-75.0	End Freeze
2/17	48	34.4	2.7	37.1	32.0	5.1	-69.9	
2/18	49	38.3	2.7	41.0	32.0	9.0	-60.9	
2/19	50	34.1	2.8	36.9	32.0	4.9	-56.0	
2/20	51	33.4	2.8	36.2	32.0	4.2	-51.8	
2/21	52	30.2	2.9	33.1	32.0	1.1	-50.7	
2/22	53	23.2	2.9	26.1	32.0	-5.9	-56.6	Start Refreeze
2/23	54	18.6	3.0	21.6	32.0	-10.4	-67.0	
2/24	55	6.1	3.0	9.1	32.0	-22.9	-89.8	
2/25	56	1.4	3.1	4.5	32.0	-27.5	-117.3	
2/26	57	19.2	3.2	22.4	32.0	-9.6	-127.0	
2/27	58	16.9	3.2	20.1	32.0	-11.9	-138.9	
2/28	59	5.4	3.3	8.7	32.0	-23.3	-162.2	
2/29	60	17.7	3.3	21.0	32.0	-11.0	-173.1	
3/1	61	30.0	3.4	33.4	32.0	1.4	-171.7	
3/2	62	27.7	3.5	31.2	32.0	-0.8	-172.6	
3/3	63	16.2	3.5	19.7	32.0	-12.3	-184.8	
3/4	64	9.7	3.6	13.3	32.0	-18.7	-203.6	
3/5	65	14.2	3.7	17.9	32.0	-14.1	-217.7	
3/6	66	10.0	3.7	13.7	32.0	-18.3	-236.0	
3/7	67	23.5	3.8	27.3	32.0	-4.7	-240.7	
3/8	68	34.1	3.9	38.0	32.0	6.0	-234.7	
3/9	69	28.2	3.9	32.1	32.0	0.1	-234.6	
3/10	70	21.4	4.0	25.4	32.0	-6.6	-241.2	
3/11	71	15.5	4.1	19.6	32.0	-12.4	-253.6	
3/12	72	13.3	4.1	17.4	32.0	-14.6	-268.2	
3/13	73	7.5	4.2	11.7	32.0	-20.3	-288.5	
3/14	74	8.2	4.3	12.5	32.0	-19.5	-308.0	
3/15	75	8.9	4.4	13.3	32.0	-18.7	-326.7	
3/16	76	18.5	4.4	22.9	32.0	-9.1	-335.8	
3/17	77	26.2	4.5	30.7	32.0	-1.3	-337.1	End Freeze
3/18	78	31.2	4.6	35.8	32.0	3.8	-333.3	Start Thaw
3/19	79	33.4	4.7	38.1	32.0	6.1	-327.2	
3/20	80	38.7	4.7	43.4	32.0	11.4	-315.8	
3/21	81	36.2	4.8	41.0	32.0	9.0	-306.8	Apply SLR
3/22	82	36.2	4.9	41.1	32.0	9.1	-297.7	

Data from the Whittier, Alaska, test site during 2019–2020 exhibited a fairly “typical” winter, in that frost penetrated continuously through the winter until the onset of thawing in mid to late

March 2020. Measured temperatures beneath the pavement showed that thawing was initiated on March 23, 2020 and reached about 12 inches beneath the bottom of the pavement on March 24.

As shown in Table 11, using air temperatures measured at the site, the Berg/FS methodology shows a minimum cumulative index on March 17, 2020 and a cumulative index just exceeding 30°F-days above the minimum on March 21, 2020 (which is the date when this method would recommend placing the SLR for that spring). So, the Berg/FS method predicted placement of the SLR about three days before the thaw depth reached the 12-inch TDP sensor and was therefore slightly conservative.

As noted, the Berg/FS methodology generally starts by gathering 30-year average mean monthly air temperatures from a long-term NCDC weather station near the site. For the Whittier, Alaska, site, we selected the weather station in Whittier. The weather station in Whittier is near the southwesterly end of Passage Canal, which is a deep-water port, and the beginning of the Alaska Railroad and the Portage Glacier Highway, which connects to the Seward Highway leading to Anchorage, about 60 miles northwest. The Portage Glacier Highway and the Alaska Railroad both run through the Anton Anderson Tunnel, which is about three miles northwest of Whittier. The tunnel runs through Maynard Mountain, which is at an elevation in excess of 2,500 feet above the city of Whittier. The Whittier test site (which was selected by the Alaska DOT&PF) is just northwest of the end of the tunnel and, therefore, was expected to have a somewhat different temperature regime than that at the Whittier NOAA weather station. Whereas the Whittier weather station is in a maritime climatic region, the test site is in a transitional zone and was expected to behave somewhat like a continental climatic region.

Given that Whittier is in a maritime climatic zone, the mean monthly air temperatures vary much less than in a typical continental climate. This difference in variation is illustrated in Figure 16, which shows the annual sinusoidal temperature variation computed using the Berg/FS methodology from two NCDC weather stations in Alaska (while Whittier is in a maritime climatic zone, Fairbanks is in a continental climatic region).

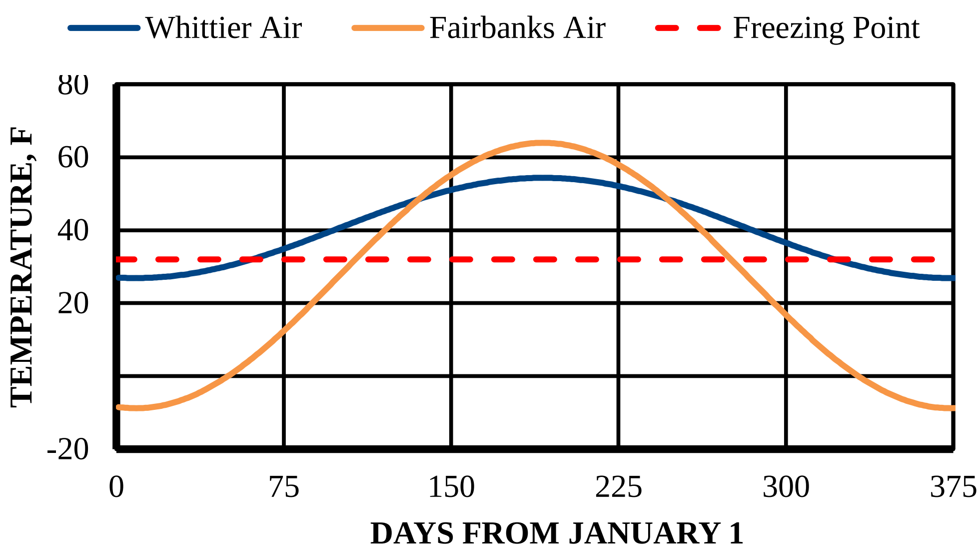


Figure 16. Air temperature variations computed from the Berg/FS methodology from two NCDC weather stations in Alaska

It can be seen that the amplitude at Whittier is much lower due to the “damping” effect of the water nearly surrounding the city of Whittier.

As noted previously, areas between the sinusoidal variations and the freezing line represent the thawing index, ATI (above), or freezing index, AFI (below). The lengths of the air freezing and thawing seasons can also be observed in Figure 16. The beginning of the freezing season is when the descending portion of the temperatures cross the freezing line, and the freezing season ends when the rising temperature line crosses the freezing line. Table 12 contains some of the properties of the freezing season variations at each site.

Table 12. Freezing season variations from Berg/FS sinusoidal approximations at Whittier and Fairbanks, Alaska

	Freeze Season				
Location	Start Date	End Date	Duration (days)	AFI (°F-days)	ATI (°F-days)
Whittier, AK	11/18	3/2	104	-348	3,520
Fairbanks, AK	10/3	4/18	197	-5,258	3,394

The differences between the AFI and ATI values measured at the Whittier site over four years (Table 10) and the AFI and ATI values computed from the Berg/FS sinusoidal approximations (Table 12) are likely due to the fact that the Whittier weather station is in a maritime climatic region, whereas the test site is in a transitional zone and behaves somewhat more like a continental climatic region.

Although the data in Figure 16 provide information about when the freezing season begins and ends in a “mean year,” variations can be significant. Examples of the possible extremes were exhibited during the original two years the study was conducted at Whittier, Alaska. During the 2014–2015 winter and spring, there were three distinct freeze-thaw periods with frost depths in excess of 45 inches. During 2015–2016, there were two complete freeze-thaw cycles (with frost penetrating to depths of about 45 inches) prior to the end of December 2015. But then the road was completely thawed by about January 5, 2016. The remainder of the winter was very mild, with freezing never reaching 10 inches below the pavement. These anomalies present significant questions, one being, “Are mid-winter thawing events beneath the roads significant?” Another is, “If they are significant, can they be predicted?”

The Berg/FS model may have the ability to predict mid-winter thawing conditions, as suggested by Figure 17.

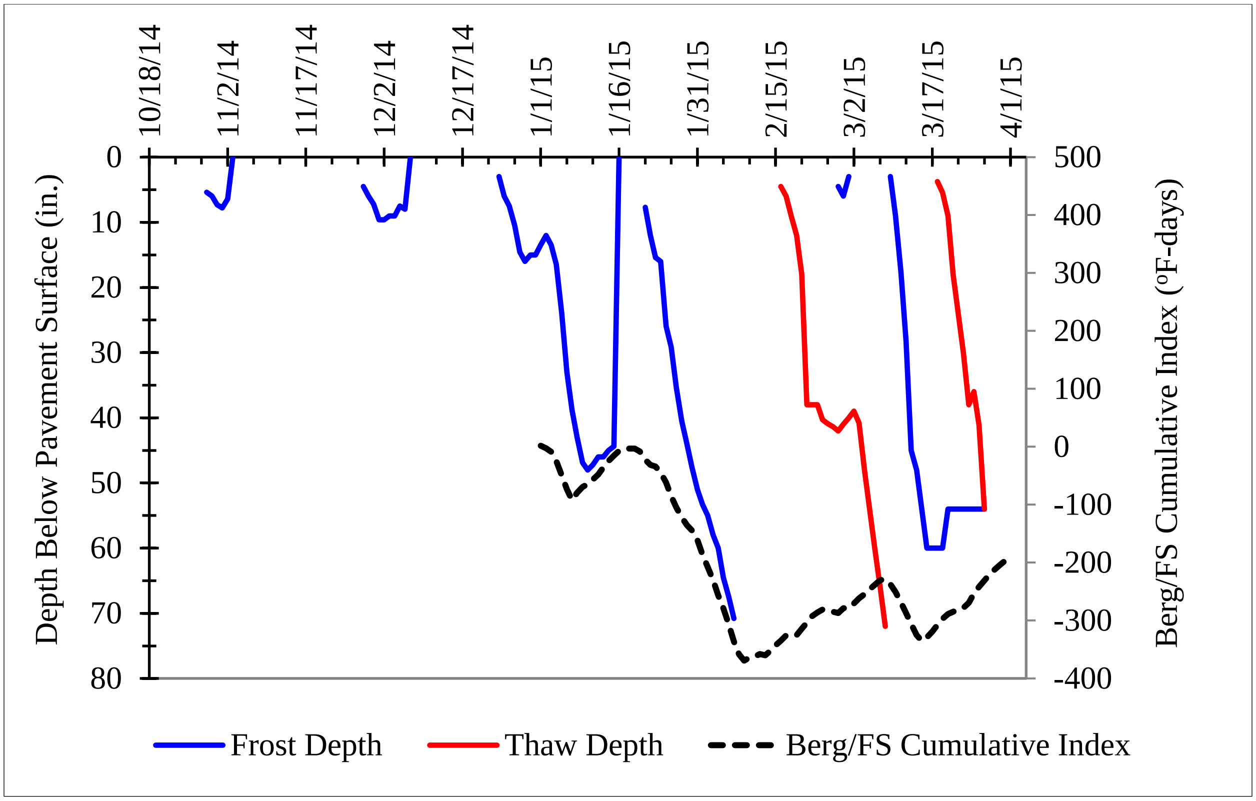


Figure 17. Berg/FS method applied to Whittier, Alaska, site in 2014–2015

Downward trends in the cumulative index represent freezing events, and upward trends in the cumulative index represent warming and/or thawing events. It can be seen that the trends in the cumulative index plot agree fairly well with the measured onset of freezing and thawing events at the Whittier, Alaska, site during 2015.

In summary, the Berg/FS method, which assumes that both average daily air temperatures and average daily pavement surface temperatures can be approximated by sinusoidal functions, provides an alternative approach for applying spring load restrictions. This method may show more promise than other degree-day threshold protocols for estimating when SLRs should be applied in regions at higher latitudes, such as Canada and Alaska.

3.2.4 FrezTrax Model and Software Interface for SLR Application and Removal

3.2.4a General

In 1993, a research project was undertaken by the South Dakota DOT (SDDOT) to develop a method to determine when to apply and remove spring load restrictions based upon threshold values of freeze and thaw indexes (computed from daily maximum and minimum air temperatures). During the winter of 1994–1995, the department began using the method developed by that research for determining the timing and duration of SLRs.

Beginning in the winter of 1999–2000, the SDDOT began contracting out the collection and analysis of data to support this process to Meridian Environmental Technology, Inc., which was acquired by Iteris, Inc. in 2011. Meridian was able to offer, through its proprietary FrezTrax software interface, improvements in spatial analysis of winter temperatures, as well as a forecast component to predict when restrictions may need to be implemented or removed. The NDDOT was previously also under contract with Meridian/Iteris to utilize the FrezTrax software interface for SLR timing decisions (note that Meridian/Iteris was recently sold to DTN). As such, the NDDOT representative for this Aurora project asked that Frost Associates include some additional analysis to evaluate the FrezTrax tool during the Phase IIb contract. Although no documentation regarding the FrezTrax model and software interface could be found in a search of peer-reviewed literature, the NDDOT provided Frost Associates with an excerpt from an in-house report describing that tool/protocol.

The freezing and thawing index calculations included in the FrezTrax model were originally developed by Mahoney et al. (1986). They were reviewed in the Phase I work for this Aurora project and are as follows:

$$CFI_n = \sum_{i=1}^{N}(32 - T_{ave.,i}) \tag{8}$$

$$CTI_n = \sum_{i=1}^{N}(T_{ave.,i} - 29) \tag{9}$$

where,
CFI_n = cumulative freezing index calculated over n days (°F-day)
CTI_n = cumulative thawing index calculated over n days (°F-day)
$T_{ave.,i}$ = average daily air temperature (°F)
N = number of cumulative days

The CTI cannot be negative and is thus reset to zero if a thawing period is interrupted by a significant refreezing event. Mahoney et al. (1986) recommended that thin pavements “should” have the SLR applied on the day when the CTI reaches 10°F-days and “must” have the SLR applied on the day when the CTI reaches 40°F-days. Thick pavements “should” have the SLR applied on the day when the CTI reaches 25°F-days and “must” have the SLR applied on the day when the CTI reaches 50°F-days.

Mahoney et al. (1986) suggested that the “should” date correlates to when the thaw front reaches the bottom of the base layer and the “must” date correlates to when the thaw front reaches 4 inches below the bottom of the base. Pavements are considered thin if the bituminous wearing surface is 2 inches or less in thickness and the base course thickness is 6 inches or less. Pavements are considered thick if the bituminous layer and base course are more than 2 and 6 inches thick, respectively.

Mahoney et al. (1986) suggested two alternative methods for determining when to remove spring load restrictions. Both of the SLR removal methods are functions of the maximum seasonal air freezing index (AFI):

$$AFI = CFI_{max.} - CFI_{min.} \tag{10}$$

where,
AFI = maximum seasonal air freezing index (°F-days)

With the maximum AFI established for the immediate past winter, Mahoney et al. (1986) suggested lifting the SLRs using either a duration threshold (Equation 11) or a CTI threshold (Equation 12).

The recommended duration (number of days the SLR should remain in place after the application date) is determined as follows:

$$Duration = 25 + 0.01(AFI) \tag{11}$$

Alternatively, the SLR may be lifted when the CTI (computed by Equation 9) reaches the following threshold:

$$CTI\ Threshold = 0.3(AFI) \tag{12}$$

The FrezTrax model appears to modify and further build upon the Mahoney et al. (1986) protocol by including regionally calibrated moisture effects in defining the critical CTI benchmark values. According to the report excerpt provided by the NDDOT,

> [t]he original SDDOT study broke South Dakota into climatological moisture zones (Dry, Moderate, and Wet). Critical moisture-dependent values of the freeze and thaw indices were then developed to determine the appropriate timing for implementation of restrictions and their subsequent duration. Beginning with the 2000–2001 winter season,

Meridian modified FrezTrax to better account for soil moisture effects on the need for road restrictions. To accomplish this, climatological fall precipitation amounts (August1 through November 30) were correlated to the pre-established climatological moisture zones. Using this data, Meridian was able to derive smoothly varying curves that relate the established critical freeze/thaw index values to observed fall precipitation amounts.

Based upon those moisture correlations, the FrezTrax protocol recommends applying the SLR when the CTI reaches the values listed in Table 13.

Table 13. FrezTrax SLR application criteria

Aug–Nov Precip. (in.)	SLR Application CTI (°F-days)
4.75	50
5.50	45
6.25	40
7.75	35

CTI values of less than 35 or more than 50 are not permitted (e.g., a location receiving 10.0 inches of fall precipitation would still maintain a critical thaw index of 35).

Meridian also derived critical values of the thaw index for use in SLR removal. In this case, the critical CTI values are expressed as a percentage of the maximum seasonal air freezing index established for the immediate past winter. The critical percentages are given approximately as shown in Table 14.

Table 14. FrezTrax SLR removal criteria

Aug–Nov Precip. (in.)	SLR Removal CTI (% of Seasonal AFI)
4.75	25
6.25	30
7.00	35
7.75	40

In this case, values of less than 25 or more than 40 are not permitted. Once the CTI at a given location reaches its critical percentage of the maximum seasonal air freezing index, restrictions can be removed.

3.2.4b Phase IIb FrezTrax Analysis

The first task under this analysis was to evaluate how well the FrezTrax protocol works for timing when to apply the SLR. This was done by comparing the FrezTrax CTI threshold date determined as per Table 13 with the date when the measured thaw depth reached the 12-inch TDP sensor for each site/season. Frost Associates ran the Mahoney et al. (1986) freeze and thaw index calculations using air temperature data from sensors at the study sites and August–November precipitation data obtained from the FHWA LTPP database (which was also checked against data recorded at https://www.usclimatedata.com/). Computations were performed for the original Aurora study sites in Alaska, Michigan, North Dakota, and Wisconsin for the original two project study years (2014–2015 and 2015–2016). In addition, for the 2020 thaw season, calculations were performed for the original Alaska, Michigan, and North Dakota sites, as well as for five other sites in North Dakota.

As noted, critical CTI benchmark values were determined based upon observed precipitation amounts during the immediately preceding fall (August 1 through November 30). For all sites/study years, with the exception of Bowman, North Dakota, in 2015–2016 the fall precipitation exceeded 7.75 inches, resulting in a CTI threshold of 35°F-days for SLR application. At the Bowman, North Dakota, site, the 2015 fall precipitation was about 5.55 inches, resulting in a CTI threshold of about 44.5°F-days for SLR application in the spring of 2016 (obtained from Table 13 using linear interpolation). The results of this part of the analysis for all sites/seasons are summarized in Table 15.

Table 15. FrezTrax SLR application dates

Original Aurora Site Location	Frost and Thaw Season	Date Thaw Depth Reaches 12 in. TDP	FrezTrax SLR Application Date	Difference (# Days)
Alaska	2014–2015	2/19/2015	1/10/2015	-40
Alaska	2015–2016	11/28/2015	11/26/2016	-2
Alaska	2019–2020	3/24/2020	4/2/2020	9
Michigan	2014–2015	3/16/2015	4/2/2015	17
Michigan	2015–2016	3/8/2016	3/9/2016	1
Michigan	2019–2020	3/9/2020	3/28/2020	19
North Dakota	2014–2015	3/10/2015	3/10/2015	0
North Dakota	2015–2016	2/19/2016	2/19/2016	0
North Dakota*	2019–2020	2/21/2020	3/5/2020	13
Wisconsin	2014–2015	3/10/2015	3/11/2015	1
Wisconsin	2015–2016	2/27/2016	3/7/2016	9
Additional ND Sites:				
Gladstone	2019–2020	2/23/2020	3/5/2020	11
Bismarck	2019–2020	2/29/2020	3/5/2020	5
Golden Valley	2019–2020	3/8/2020	3/5/2020	-3
Denhoff	2019–2020	3/27/2020	3/29/2020	2
Devils Lake	2019–2020	3/24/2020	3/30/2020	6

*Bowman, North Dakota

The results in Table 15 suggest that, in general, the FrezTrax protocol is somewhat non-conservative, with the CTI threshold dates falling after thawing had already progressed past the 12-inch TDP sensor. The main exception was at the Whittier, Alaska, site, where the FrezTrax protocol triggered the SLR on the early side for two of the three study years. When considering only the CONUS, the average FrezTrax CTI threshold dates were about six days late. This is problematic, as numerous researchers have suggested that roadways experience a rapid decrease in strength, and thus increased potential for damage, at the beginning of thaw (Mahoney et al. 1986, Van Deusen et al. 1998, Ovik et al. 2000, Kestler et al. 2007, Tighe et al. 2007, Marquis 2008, Bradley et al. 2012).

The second task under this analysis was to evaluate how well the FrezTrax protocol works for timing when to remove the SLR. This was done by comparing the FrezTrax CTI threshold dates for SLR removal with FWD data. Unfortunately, since four of the five original Aurora DOT partners were not able to provide adequate FWD data for either of the study years at their sites, validation of the FrezTrax TI benchmark values listed for SLR removal was not possible at those study sites.

Fortunately, the NDDOT provided FWD data at the Bowman, North Dakota, test site for both of the original study years and provided FWD data from 2020 at the Bowman site and at several additional sites in North Dakota. So, Frost Associates conducted an analysis of the FrezTrax SLR removal criteria using the FWD data from the eight North Dakota site/season combinations listed in Table 16.

Table 16. AFI values, critical CTI values, and FrezTrax SLR removal dates computed from air temperatures measured at test sites (Site ID numbers shown on map in Figure 4)

Site ID	ND RWIS Site Location	FWD Location	Seasonal Max. Freezing Index, AFI (°F-days)	Critical Thaw Index, CTI (°F-days)	FrezTrax Remove SLR Date
20	Bowman 2015	RWIS US 85 RP 12.0 to RP 12.2	1,308	523	4/17/2015
20	Bowman 2016	RWIS US 85 RP 12.0 to RP 12.2	823	226	3/13/2016
2020 Sites:					
20	Bowman	RWIS US 85 RP 12.0 to RP 12.2	1,046	418	5/5/2020
29	Gladstone	ND 8 RP 79 to 80	1,284	514	5/8/2020
1	Bismarck	Hwy 6, RP 62 to 63, S of Mandan	1,485	594	5/8/2020
11	Golden Valley	Hwy 200, RP 131 to RP 132	1,548	619	5/17/2020
22	Denhoff	Hwy 14, RP 44 to 45, N of Jct 200	1,827	731	5/21/2020
15	Devils Lake	Hwy 281, RP 137 to 138, N of New Rockford	2,281	912	6/2/2020

Critical CTI values for SLR removal were determined based upon the maximum seasonal air freezing index established for the immediate past winter as well as observed precipitation amounts during the immediately preceding fall. For all sites/study years, with the exception of Bowman, North Dakota, in 2015–2016 the fall precipitation exceeded 7.75 inches, resulting in a CTI threshold equal to 40% of the AFI. At the Bowman, North Dakota, site, the 2015 fall precipitation was about 5.55 inches, resulting in a CTI threshold equal to 27.5% of the AFI. The SLR removal dates corresponding to those CTI threshold values are listed in Table 14.

The results of FWD testing, as well as SLR removal dates predicted by the FrezTrax protocol, are included in plots in Appendix C. In 2020, FWD testing was conducted adjacent to three North Dakota RWIS stations (Bowman, Golden Valley, and Denhoff) and reasonably close to RWIS stations at Bismarck, Gladstone, and Devils Lake. NDDOT personnel conducted backcalculations and provided the research team with values of subgrade modulus (averaged over several test locations at each roadway site). For the original Aurora project study years (2014–2015 and 2015–2016), FWD testing was conducted adjacent to the Bowman RWIS station. NDDOT personnel conducted backcalculations and provided the research team with values of subgrade modulus (both years) and base modulus values for 2015–2016. They also provided the raw FWD data to the research team, who subsequently obtained pavement temperature data and computed adjusted center deflection (ACD) values according to procedures outlined by Mahoney et al. (1986).

Plots of the 2015 and 2016 ACD data from FWD tests are included in Figures 18 and 19, with deflection values plotted on a reverse axis.

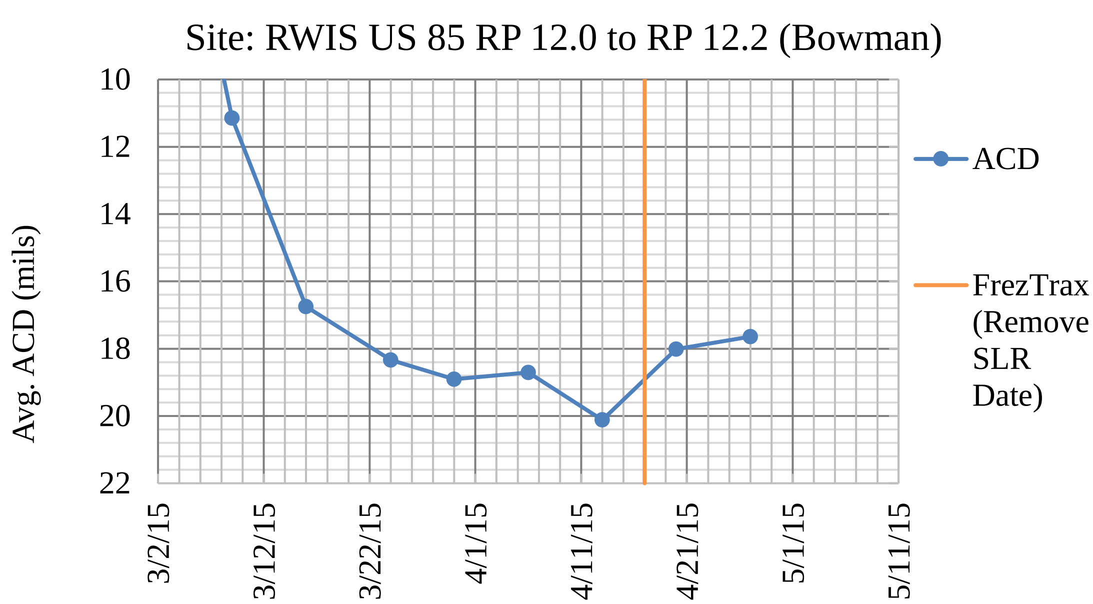


Figure 18. Average ACD values at Bowman, North Dakota, site during spring 2015

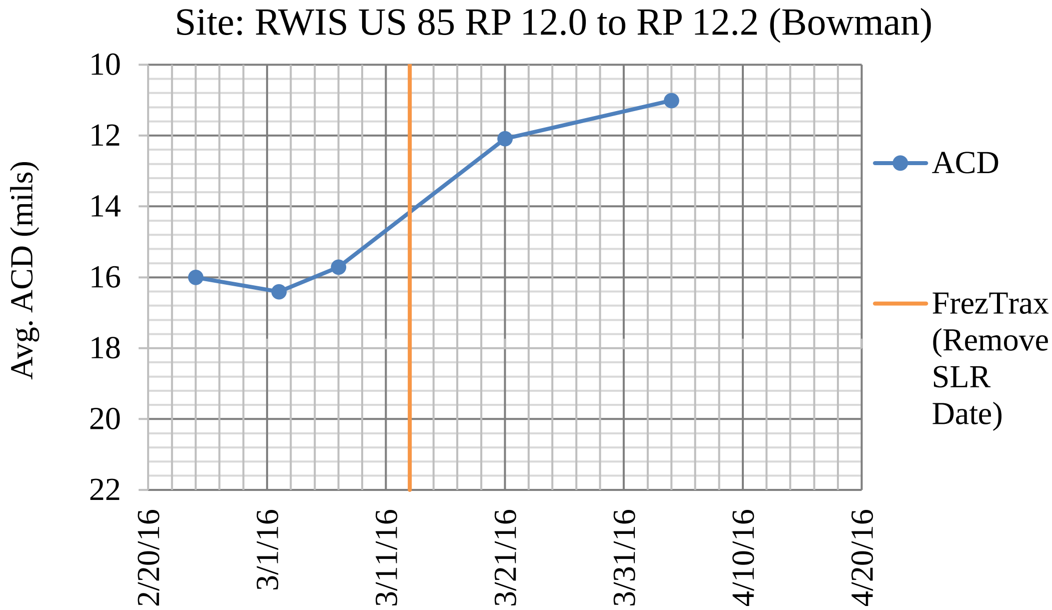


Figure 19. Average ACD values at Bowman, North Dakota, site during spring 2016

The ACD values give an indication of the stiffness of the overall pavement structure (asphalt, base, and subgrade layers), with smaller ACD values corresponding to a stiffer structure. In both years, the SLR date predicted by FrezTrax fell slightly prior to full recovery. Modulus values of the base and subgrade layers for spring 2016 are shown in Figures 20 and 21, respectively.

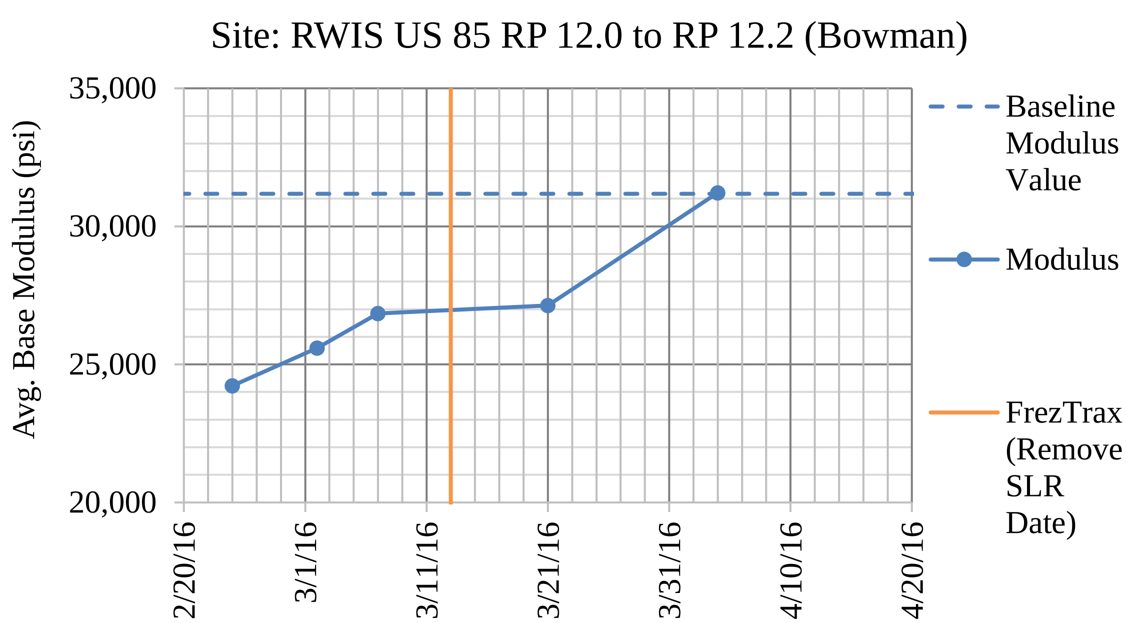


Figure 20. Average base modulus values at Bowman, North Dakota, site during spring 2016

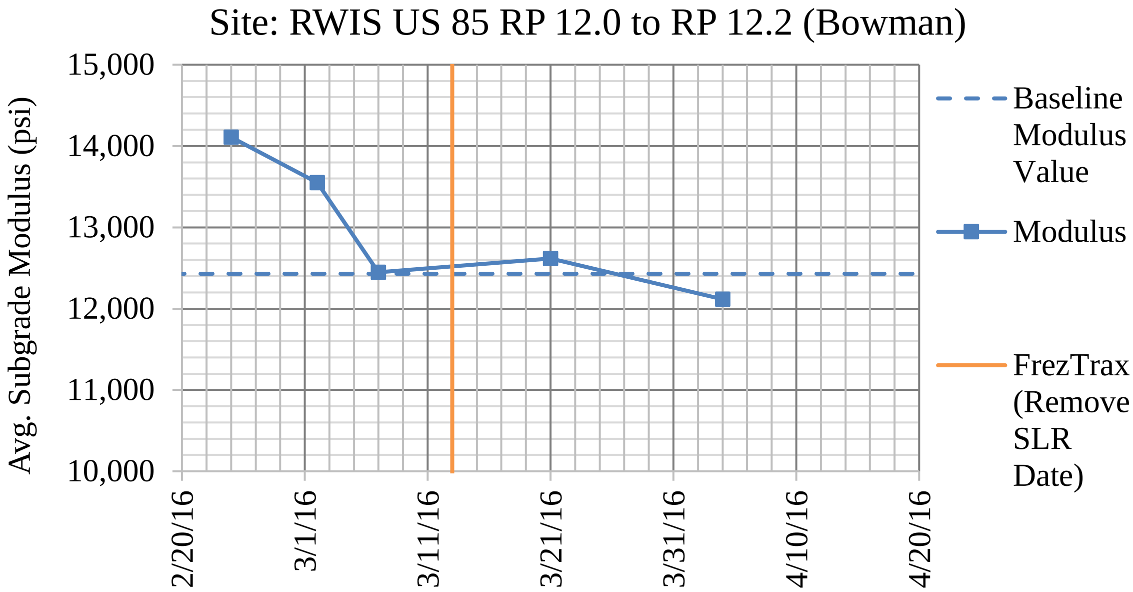


Figure 21. Average subgrade modulus values at Bowman, North Dakota, site during spring 2016

Figure 21 suggests that the subgrade did not exhibit substantial stiffness loss during that spring thaw period (i.e., the modulus values hover right around the baseline value measured during the preceding fall). This may be due to the fact that the 2015–2016 winter was unusually warm (AFI = 823°F-days), and corresponding frost penetration that winter was less than in other years. Since frost only penetrated a few inches into the subgrade and for only a brief period during January 2016, the subgrade was probably not significantly affected. On the other hand, the base layer exhibited at least a 22% reduction in stiffness during the 2016 spring thaw period, and only about half of that stiffness loss was recovered by the FrezTrax SLR removal date.

The data shown in Figures 20 and 21 are supported by Kestler et al. (2011), who conducted a study to identify how specific freeze season characteristics contribute to accelerated pavement failure in seasonal frost areas. They performed computer simulations with a mechanistic design and evaluation procedure and 21 years of environmental data from two original flexible pavement test cells at the Minnesota Road Research Project (MnROAD). Statistical analyses were conducted to determine which winter season characteristics were statistically significant contributors to, or indicators of, cumulative pavement damage. One of their conclusions was that more fatigue damage tends to occur during shorter, warmer winters with shallow maximum frost depths (such as 2015–2016 in Bowman, North Dakota).

As noted, the average subgrade modulus values shown in Figure 21, which are more strongly related to rutting damage, did not drop significantly below the baseline value during the 2016 spring thaw season. However, the base modulus values (Figure 20), which are more strongly related to fatigue damage, exhibited at least a 22% reduction during the 2016 spring thaw period and took several weeks to recover back to the baseline value. Therefore, as suggested by the

Kestler et al. (2011) study, there was likely significant potential for fatigue damage to the pavement during that multi-week recovery period when base modulus values were reduced.

Plots of average subgrade modulus values during the 2020 spring testing, along with SLR removal dates predicted by FrezTrax, are included in Appendix C. In contrast to spring 2015 and spring 2016, during the 2020 thaw season, SLR removal dates predicted by FrezTrax fell at the same time or slightly after the dates when the subgrade had fully recovered at four of the six sites (Bowman, Gladstone, Golden Valley, and Denhoff). At the site near Bismarck (Highway 6, south of Mandan), the SLR removal date predicted by FrezTrax appears to have fallen just slightly before complete recovery. And at the site near Devils Lake, the SLR removal date predicted by FrezTrax appears to have fallen significantly before complete recovery occurred.

The last task that Frost Associates conducted for the FrezTrax analysis was to examine output provided by the NDDOT from the proprietary FrezTrax software tool and determine whether obtaining input data (air temperatures and precipitation) from different sources caused significant differences in the model output/results. Those comparisons are summarized in Table 17.

Table 17. 2020 FrezTrax SLR dates obtained from meridian gridded data versus from air temperatures measured at the North Dakota test sites

	Meridian/Iteris Maps (screen shots)		Site Air Temps.	
Site	**Apply SLR**	**Remove SLR**	**Apply SLR**	**Remove SLR**
Bowman	3/5/2020	5/3/2020	3/5/2020	5/5/2020
Gladstone	3/5/2020	5/5/2020	3/5/2020	5/8/2020
Bismarck	3/5/2020	5/10/2020	3/5/2020	5/8/2020
Golden Valley	3/9/2020	5/20/2020	3/5/2020	5/17/2020
Denhoff			3/29/2020	5/21/2020
Devils Lake	4/1/2020	6/2/2020	3/30/2020	6/2/2020

The different input sources yielded SLR application dates that were identical, or within a day, at all sites except for Golden Valley. At that site, the SLR date predicted from the Meridian/Iteris data fell four days later than the SLR date predicted using measured air temperature data from sensors at the site. For SLR removal, the different input sources yielded dates that were within two to three days of each other, with no positive or negative bias between sources. Therefore, this analysis suggests that there are not significant differences in the model output/results caused by using FrezTrax predictions as opposed to using air temperature data measured by sensors at specific sites.

3.3 Frost-Thaw Depth Prediction Models

3.3.1 Freeze-Thaw Index Model(s)

3.3.1a General

During the Phase I study, several empirical models were reviewed that had been developed by means of statistical regression analyses. We refer to these collectively as “freeze-thaw index models.” These models need to be calibrated on a site-specific basis, ideally using several years of measured air temperature and subsurface temperature data. For the Phase II study, we had proposed running the following models:

- We proposed to use 2014–2015 data to determine calibration coefficients at five test sites according to linear regression procedures outlined by Miller et al. (2012) and then run the model from Miller et al. (2012) in a predictive mode at those sites during the 2015–2016 season.
- At the Ontario site (Highway 527), we proposed to run the model developed at Lakehead University (Chapin et al. 2013, Pernia et al. 2014), which is based on polynomial regression, for both the 2014–2015 and 2015–2016 seasons (since that model has already been calibrated at that site based on several years of measured frost-thaw data).
- At all other sites, we proposed to use the data obtained during 2014–2015 to calibrate the Lakehead University freeze-thaw index model for each site and then run that model in a predictive mode at those sites during the 2015–2016 season.

3.3.1b Freeze-Thaw Index Model: Linear Regression (Miller et al. 2012)

Linear regression analysis was used to determine site-specific calibration coefficients for five test sites as follows. The measured frost or thaw depth (dependent variable) was plotted against the square root of the corresponding CFI or CTI value (independent variable), and a linear trendline was fitted to the data to determine calibration coefficients for the prediction model. Using a zero intercept, the equations for frost depth (FD) and thaw depth (TD) are as follows:

$$FD = C_F \sqrt{CFI} \tag{13}$$

$$TD = C_T \sqrt{CTI} \tag{14}$$

Site-specific calibration coefficients C_F and C_T, as determined from the data sets obtained at the five demonstration sites, are presented in Table 18. The 2014–2015 coefficients were used to run this model in a predictive mode for the 2015–2016 season, and comparison plots of the measured and predicted frost and thaw depths at each test site are included in Appendix D. After the 2015–2016 subsurface temperature data were obtained, these data were combined with the 2014–2015 data, and linear regression analyses were performed on the combined data set. The calibration coefficients C_F and C_T, as determined from the combined data sets, are also presented in Table 18.

Table 18. Frost and thaw coefficients (linear regression with zero intercepts)

Site	Years	C_F	R^2	C_T	R^2
AK	2014–2015	3.8622	0.9520	3.2377	0.6262
AK	2014–2016	2.8810	0.5426	3.0048	0.5663
MI	2014–2015	1.3311	0.7114	2.7432	0.6365
MI	2014-2016	1.3220	0.6697	1.8710	0.5683
ND	2014–2015	0.7935	0.7803	1.5483	0.8276
ND	2014–2016	0.7977	0.8078	1.4125	0.6492
WI	2014–2015	2.3643	0.8096	3.1355	0.8771
WI	2014–2016	2.1724	0.8450	3.0150	0.7749
ONT-527	2014–2015	1.4832	0.9459	1.7953	0.0644
ONT-527	2014-2016	1.5114	0.9526	1.8859	0.8534

Although the linear regressions were initially performed using zero intercepts, previous studies suggested that, in some cases, using a non-zero intercept resulted in better thaw depth correlations. Modified regressions using a non-zero intercept (Equation 15), yielded the coefficients listed in Table 19.

$$\mathrm{TD} = \mathrm{C_T}\sqrt{\mathrm{CTI}} + c \qquad (15)$$

Table 19. Thaw coefficients (linear regression with non-zero intercepts)

Site	Years	C_T	c	R^2
AK	2014–2015	7.1478	-49.5110	0.9089
AK	2014–2016	5.3289	-27.1630	0.7128
MI	2014–2015	4.1958	-17.858	0.7280
MI	2014–2016	2.1392	-3.0174	0.5810
ND	2014–2015	2.0577	-4.6942	0.8847
ND	2014–2016	2.2843	-6.9714	0.7755
WI	2014–2015	3.6432	-6.0875	0.8987
WI	2014–2016	4.0982	-11.4960	0.8453
ONT-527	2014–2015	1.3405	2.9236	0.0731
ONT-527	2014-2016	1.9644	-0.9842	0.8550

The linear regression predictive model (with non-zero intercepts) was then used along with the coefficients determined from the 2014–2015 data to estimate frost and thaw depths for the 2015–2016 season. Comparison plots of measured and predicted frost and thaw depths at each test site are included in Appendix D.

After the 2015–2016 subsurface temperature data were obtained, these data were combined with the 2014–2015 data, and linear regression analyses were performed on the combined data set. The calibration coefficients C_T and c, as determined from the combined data sets, are also presented in Table 19.

3.3.1c Freeze-Thaw Index Model: Polynomial Regression (Lakehead University Method: Chapin et al. 2013, Pernia et al. 2014)

Another variation on the freeze-thaw index method for predicting frost and thaw depths is presented by Chapin et al. (2013) and Pernia et al. (2014). They recommend using the MnDOT equations and reference temperatures (described in Section 3.2.1) for computing freezing and thawing indices. They then use those CFI and CTI values to predict frost and thaw depths using an empirical model that was developed by means of a regression analysis, as follows.

The measured frost or thaw depth (dependent variable) was plotted against the day's corresponding CFI or CTI value (independent variable) to determine calibration coefficients for the prediction model. Chapin et al. (2013) and Pernia et al. (2014) examined both a linear trend line and a polynomial trend line fitted to their data and discovered that the polynomial model generally returned a better R-squared value at their study sites. As such, their prediction model uses a second-order quadratic of the following form:

$$y = ax^2 + bx + c \tag{16}$$

where,
y = frost or thaw depth, respectively, below the pavement's surface (inches)
x = CFI or CTI, respectively (°F-days)
a, b, and c = regression coefficients

Site-specific calibration coefficients a, b, and c, as determined from the data sets in this study, are presented in Tables 20 and 21.

Table 20. Frost depth coefficients (polynomial regression)

Project Site	Years	Polynomial			R^2
		a	b	c	
AK	2014–2015	-0.0006	0.3841	3.0631	0.9927
AK	2014-2016	0.0001	0.1910	3.6140	0.6720
MI	2014–2015	$1x10^{-5}$	0.0371	3.8256	0.9310
MI	2014-2016	$1x10^{-5}$	0.0368	4.2336	0.8415
ND	2014–2015	$-3x10^{-6}$	0.0261	2.9256	0.8862
ND	2014-2016	$-8x10^{-6}$	0.0317	2.6658	0.8597
WI	2014–2015	$-4x10^{-5}$	0.0853	21.0600	0.8900
WI	2014-2016	$-3x10^{-5}$	0.0786	16.6410	0.8617
ONT-527	2014–2015	$-1x10^{-6}$	0.0293	10.853	0.9904
ONT-527	2014-2016	$-4x10^{-6}$	0.0360	10.5250	0.9712

Table 21. Thaw depth coefficients (polynomial regression)

Project Site	Years	Polynomial			R^2
		a	b	c	
AK	2014–2015	-0.0006	0.4743	-20.096	0.9028
AK	2014-2016	0.0006	0.0837	7.3526	0.7709
MI	2014–2015	0.0005	0.0688	10.172	0.8919
MI	2014-2016	-0.00003	0.1412	1.8952	0.5964
ND	2014–2015	-0.0007	0.2497	-1.2897	0.9008
ND	2014-2016	-0.0007	0.2597	-1.9904	0.7925
WI	2014–2015	0.0002	0.1639	6.5291	0.9486
WI	2014-2016	-0.0003	0.2970	1.2576	0.8789
ONT-527	2014–2015	0.0045	-0.2815	14.453	0.1173
ONT-527	2014-2016	-0.00009	0.1154	6.6999	0.8562

The polynomial predictive model was then used along with the coefficients determined from the 2014–2015 data to estimate frost and thaw depths for the 2015–2016 season. Comparison plots of measured and predicted frost and thaw depths at each test site where data has been made available are included in Appendix D.

After the 2015–2016 subsurface temperature data were obtained, these data were combined with the 2014–2015 data, and polynomial regression analyses were performed on the combined data set. The calibration coefficients a, b, and c, as determined from the combined data sets, are also presented in Tables 20 and 21.

Pernia et al. (2014) noted that, since the model uses a second-order polynomial to predict the frost and thaw depths, one of the limitations of the model is that it doesn’t begin producing predictions until the depth has surpassed the *c* coefficient. In order to avoid this situation, an algorithm must be incorporated into the model that returns a frost or thaw depth of zero until the CFI or CTI, respectively, begins increasing such that the *c* coefficient is surpassed. This, in turn, often creates large jumps in the early stages of frost and thaw progression (Pernia et al. 2014).

3.3.1d Observations: Freeze-Thaw Index Models Using Regression Analyses

The results from the analyses of this class of models suggests that they perform fairly well (in most cases) for estimating the onset of freezing (important for WWP application) and the onset of thawing (important for timing the end of the WWP and start of the SLR). These models are not as accurate with regard to predicting the maximum frost depth, with predictions for some sites/seasons being too shallow and others being too deep (with no clear bias one way or the other). With regard to estimating the date when thawing was complete, all of the models tended to estimate the end-of-thaw date on the late side.

All of these models were calibrated on a site-specific basis to determine regression coefficients. There was no clear advantage to moving from simpler analyses (i.e., linear regression with zero intercept) to more sophisticated analyses (polynomial regression). Furthermore, the coefficients that were determined for each site, for any given model, were not similar enough to warrant their use over a wide region (as opposed to a specific site). That fact poses a severe limitation on the usefulness of these models.

3.3.2 U.S. Army Corps of Engineers Model 158

A review of various early frost prediction models is provided in a report from the U.S. Army Corps of Engineers – New England Division (1949). One of the equations in that report was Model 158, which can be used to estimate the seasonal maximum frost depth as follows:

$$X = -\frac{d}{2} + \left[\left(\frac{d}{2} \right)^2 + \frac{kI_{sf}}{L + c(v_o + I_{sf}/2t)} \right]^{1/2} \tag{17}$$

where,
X = seasonal maximum depth of frost (ft)
k = thermal conductivity (BTU/(ft*day*°F))
I_{sf} = seasonal surface-freezing index (°F-days)
L = volumetric latent heat of fusion (BTU/ft^3)
d = thickness of the surface asphalt layer (ft)
c = volumetric heat capacity (BTU/(ft^3*°F))
v_o = difference between the mean annual temperature and the freezing temperature (°F)
t = annual length of time below freezing (days)

Although this model was developed before reference temperatures were introduced, this equation accounts for the difference between air and pavement surface temperatures with the surface freezing index. As originally proposed, I_{sf} is the total seasonal surface freezing index; thus, the equation would compute the seasonal maximum depth of frost. The equation accounts for the difference between the seasonal air freezing index, *AFI*, and seasonal pavement surface freezing index, I_{sf}, by utilizing the "n-factor" concept (Andersland and Ladanyi 2004), where n-factors of about 0.8 have typically been used for air temperatures below freezing:

$$I_{sf} = n(AFI) \tag{18}$$

The use of computer spreadsheets now enables the Model 158 equation to predict daily frost depths by using the parameter I_{sf} summed on a daily basis rather than for an entire season (Orr and Irwin 2006). Orr and Irwin (2006) incorporated the Model 158 equations into their Cornell Pavement Frost Model (CPFM), which has shown much promise for predicting frost-thaw profiles in New York State (Orr and Irwin 2006, Duffy et al. 2016). Miller et al. (2015) made slightly different alterations to the original Model 158, and this Modified Model 158 is described in equation 19.

$$(X_f)_n = -\frac{d}{2} + \left(\left(\frac{d}{2}\right)^2 + \frac{k\,(I_{sf})_n}{L + c[v_o + (I_{sf})_n / 2t]} \right)^{1/2} \tag{19}$$

$$(X_t)_n = -\frac{d}{2} + \left(\left(\frac{d}{2}\right)^2 + \frac{k\,(I_{st})_n}{L + c[v_o + (I_{st})_n / 2t]} \right)^{1/2} \tag{20}$$

where,
$(X_f)_n$ = depth of frost on day n (ft)
$(X_t)_n$ = depth of thaw on day n (ft)
$(I_{sf})_n$ = cumulative surface freezing temperature index for day n (°F-days)
$(I_{st})_n$ = cumulative surface thawing temperature index for day n (°F-days)
k, L, d, c, v_o, and t are as described in Equation 17

Examination of Equations 17 and 19 shows that they are essentially the same, except Equation 17 only computes maximum seasonal freezing and Equation 19 is used to compute daily depths of frost penetration. Note that $(I_{sf})_n$ and $(I_{st})_n$ are cumulative values, summed on a daily basis, and cannot be less than zero. As noted previously, the differences between air freezing and thawing indices and pavement surface freezing and thawing indices are accounted for by using n-factors:

$$(I_{sf})_n = n_f\,(CFI_n) \tag{21}$$

$$(I_{st})_n = n_t\,(CTI_n) \tag{22}$$

where,
n_f = n-factor for freezing

n_t = n-factor for thawing
CFI_n = cumulative air freezing index calculated over n days (°F-days)
CTI_n = cumulative air thawing index calculated over n days (°F-days)

The cumulative freezing and cumulative thawing indices are computed as per procedures outlined in MnDOT (2009), as described in Section 3.2.1 of this report. The *CFI* and *CTI* are multiplied by values for n_f and n_t, respectively, to determine I_{sf} and I_{st}. Weighted average values are used for the thermal properties (k, c, and L). Equation 23 shows how the weighted averages in the frost-thaw depth calculations are computed.

$$\text{Weighted Average, } P = \frac{p_1 d_1 + p_2 d_2 + p_3 d_3}{X_{n-1}} \quad (23)$$

where,
P = weighted average value for property (k, c, L)
p_1, p_2, p_3 = property value for the asphalt, base-subbase, and subgrade, respectively
d_1, d_2, d_3 = thickness of frost penetration through the corresponding pavement layer from the previous day (feet)
X_{n-1} = total depth of frost (or thaw) penetration from the previous day (feet)

The Model 158 equation requires the layer thicknesses and material properties of the pavement structure. The thermal properties necessary for this model are thermal conductivity (k), volumetric heat capacity (c), and volumetric latent heat of fusion (L). Thermal conductivity is a measure of a material's ability to conduct heat through a material (or pavement layer) per unit length per temperature degree. Volumetric heat capacity is the material characteristic that quantifies the amount of heat required to change a specific volume of a substance's temperature per degree. Latent heat is a measure of the amount of heat released or absorbed by a substance that occurs without a change in temperature and accounts for the change in energy during a phase transition (i.e., water transitioning from liquid to ice). Recommended values for the thermal properties vary from reference to reference and are a function of many parameters, such as soil type, density, temperature, and moisture content.

Several researchers have set up spreadsheets to implement Model 158 (or slight variations of this model). Most of those spreadsheets, however, are not set up to incorporate changes in thermal properties as a function of those parameters (which change during the freeze-thaw process), so constant values for k, c, and L must generally be selected for use in that model.

For this project, the research team initially referred to design curves provided by the Departments of the Army and the Air Force (1988), which were based on the original correlations developed by Kersten (1949). Those relationships were subsequently converted into equations by Aitken and Berg in the late 1970s and are reported in Cortez et al. (2000). Those design curves and equations are functions of soil type, dry unit weight, and moisture content. Soil type, dry unit weight, and moisture content for each subsoil layer at the demonstration sites was provided and/or assumed based upon information provided in Tables 3 and 4 of this report.

For each of the demonstration sites, Model 158 (as modified and described herein) was run to predict frost and thaw depths for both the 2014–2015 and 2015–2016 frost and thaw seasons. The results were compared to measured frost and thaw depths and are presented in Appendix E.

Examination of those plots suggest that, similar to the models described in Section 3.3.1, Modified Model 158 performed well (in most cases) for estimating the onset of freezing and the onset of thawing. It was slightly more accurate than the regression models with regard to predicting the maximum frost depth. With regard to estimating the date when thawing was complete, Modified Model 158 also estimated the end-of-thaw date consistently on the late side. Duffy et al. (2016) suggested that this anomaly is due to the fact that bottom-up thawing is a very complex thermodynamic process (as compared to top-down thawing from the pavement surface into the subsoils).

3.3.3 Enhanced Integrated Climatic Model

3.3.3a General

Developed as a part of the American Association of State Highway and Transportation Officials (AASHTO) *Mechanistic-Empirical Pavement Design Guide* (MEPDG), the Enhanced Integrated Climatic Model is a finite difference software module that analyzes the climatic impacts on a pavement design. This computer program has the ability to estimate subsurface temperature and moisture profiles based on atmospheric weather data and soil properties. The EICM utilizes the Infiltration and Drainage Model (ID Model) developed at Texas A&M University, the Climatic-Materials-Structural Model (CMS Model) developed at the University of Illinois, and, the Frost Heave and Thaw Settlement Model (CRREL Model) developed at the United States Army Cold Regions Research and Engineering Laboratory (Zapata and Houston 2008, Berg et al. 1980). This software normally uses multiple seasons of hourly atmospheric weather data to estimate depths of frost and thaw penetration over the winter-spring period. Users can utilize the historic database available in the AASHTO software or import their own weather data. The climatic inputs required are air temperature, precipitation, wind speed, percent sunshine, and relative humidity. Similar to Model 158, the EICM requires details of the pavement structure. The user must input the thicknesses of the different layers as well as various other soil parameters and the groundwater table depth. The AASHTO software provides default values that can be used for properties like thermal conductivity, specific gravity, and even the grain size distributions for different soil types.

As part of the FHWA Clarus initiative, an automated tool was developed by Meridian/Iteris (now owned by DTN) for the Clarus Use Case #2 Project in North Dakota, South Dakota, and Montana (Cluett et al. 2011). That tool utilizes the EICM to simulate pavement, subbase, and subgrade conditions (including temperature, moisture, and strength/stiffness) based on observed and forecast weather parameters. The tool provides graphic profiles of subsurface conditions down to 48 inches and forecasts out to about three weeks. The authors of the FHWA report concluded that “the Clarus Use Case #2 seasonal load restriction tool demonstration can be viewed as reasonably successful and perceived by state DOTs and motor carriers as having great potential value.” However, the authors expressed a need to validate the forecasts through the use of more probes and sensors and concluded that “a verification and validation approach for this use case tool is needed and can provide significant impetus for increased support and adoption” (Cluett et al. 2011).

For the Phase IIa scope of work in this Aurora study, the research team had proposed to subcontract Leon Osborne (developer of the automated Clarus tool) to run that tool for estimating frost and thaw depths at the five demonstration sites for one year. As discussed previously, a subcontract for that work with Osborne was executed. However, he became ill before that work could be conducted and ultimately passed away prior to the original Phase IIa contract end date.

Since the proprietary (Clarus) version of the EICM was not available after the unfortunate passing of Osborne, Frost Associates, under the Phase IIb contract and scope of work, formulated a plan to complete the EICM evaluation using a phased approach, initially using an alternative version of the EICM (available in the AASHTOWare Pavement ME Design software). That software was used to evaluate the EICM at the original five project sites for both the 2014–2015 and 2015–2016 winter/spring seasons. The results of those analyses, which compare the frost-thaw profiles predicted by the EICM and those based upon measured subsurface profiles, are included in Appendix F.

Then, since the AASHTOWare software was developed primarily for pavement structural design and does not provide a user-friendly interface for SLR timing decisions, Frost Associates also proposed evaluating a demonstration version of the vRWIS software interface at the current project sites (Alaska, Michigan, North Dakota, and Wisconsin) for the 2020 spring thaw season. The vRWIS software tool was developed by ARA, the same firm that developed the AASHTOWare software. The vRWIS software tool automatically gathers existing atmospheric weather data (as well as forecast data) from numerous weather stations in real time, runs the EICM in the background, and presents the results of the EICM predictions of frost and thaw depths in a user-friendly graphical interface. Results comparing the output from the vRWIS interface with measured subsurface temperature profiles are included in Appendix G.

3.3.3b EICM Evaluation Using AASHTOWare Software

General. For this analysis, the research team utilized AASHTOWare Pavement ME Design version 2.5.5, released in July 2019. Enhancements to this version of the software include an updated climate selection user interface with integration of Modern-Era Retrospective Analysis for Research and Applications (MERRA) climate data for flexible pavements. At three of the five Aurora test sites (North Dakota, Wisconsin, and Ontario, Canada), a MERRA climate data grid that encompassed the test site was selected. The Michigan test site was located approximately on the border of two adjacent MERRA climate data grids. The EICM was run using the climate data from the MERRA grid just north (labeled “Project 3”) and just south of the test site (labeled “Project 3b”).

The EICM will not run if the mean annual air temperature (MAAT) is less than 32°F. That was the case for the MERRA climate data grids just north and south of the Whittier, Alaska, site.

Therefore, a MERRA grid just southeast of the Whittier, Alaska, site where the mean air annual temperature was above 32°F was selected for the EICM analysis (Project 2-2). The MAAT (37.24°F) and elevation (200 feet) of that MERRA grid actually provided a closer match to conditions specific to Whittier, Alaska, compared to the MERRA climate data grids just north and south of the Whittier site.

It should be noted that, unlike previous versions, AASHTOWare Pavement ME Design version 2.5.5 does not allow users to access frost-thaw depth output. ARA provided Frost Associates with a hotfix, which allowed us to access the frost-thaw depth output, but that feature is not available to the general users at this time.

Details of Analysis. Results from the EICM, run via AASHTOWare Pavement ME Design, are included in Appendix F. For input, default soil properties were generally used for each soil layer identified by the state DOT representatives in the sites' pavement structures. Since the NDDOT representatives provided very specific soil laboratory test data for some of the soil layers in their pavement structure, those data were used to appropriately modify some of the default soil properties included in the AASHTOWare software.

As a minimum, the model was run at each site twice: once for the 2014–2015 frost and thaw season and once for the 2015–2016 frost and thaw season (the two years stipulated for the Phase IIa Aurora study). Additional model runs were also completed at some sites to investigate sensitivity to various issues, as outlined below:

- At the Alaska site, frost and thaw patterns were quite unusual during both of the Aurora study years. During those two frost and thaw seasons, multiple freeze/thaw cycles were observed, and frost depths tended to be much shallower than what was historically observed in that location. Therefore, measured subsurface temperature data from three additional years were obtained from the following website: http://www.roadweather.alaska.gov/iways/roadweather/forms/AreaSelectForm.html. Interpolated frost and thaw depths were calculated from those data, and the EICM was run for those three years so that predicted frost and thaw depths could be compared to measured (interpolated) frost and thaw depths.
- At the Michigan site, the EICM was run twice during each of the Aurora study years, since the Michigan test site was located approximately on the border of two adjacent MERRA climate data grids, as described previously.
- At the North Dakota site, the EICM was run several times for each of the Aurora study years to investigate the sensitivity of the model to values selected for various soil properties (predominantly the percentage of fines and the moisture content).

Trends Observed. The following trends were observed:

Alaska

- For the two years stipulated for the Aurora study, the EICM generally did a good job of tracking the multiple onsets of freezing and thawing, except for the thawing event during February–March 2015 (which the EICM missed).
- For those two study years, frost depths predicted by the EICM tended to be slightly greater than measured frost depths.
- Though not required by the project scope, three additional frost and thaw seasons were studied (2009–2010, 2012–2013, and 2013–2014). For those three years, where measured frost and thaw patterns tended to be more typical of the frost and thaw patterns observed in Alaska, the following observations were made:
    - The EICM tracked the onset of freezing fairly well.
    - The EICM significantly overpredicted frost depths.
    - The EICM did not accurately predict the onset of thawing. The EICM suggested the onset of thawing about half a month to a month later than when it was actually observed.

Michigan

- For the two years stipulated for the Aurora study, the EICM generally tracked the onset of freezing fairly well.
- Frost depths extended below the lowest thermistor for much of the 2015 winter and for about two to three weeks during the 2016 winter, so measured maximum frost depths could not be determined. During the 2015 winter, the gap in the measured frost depth data was so large that comparison with EICM-predicted frost depths could not be made. The frost depths predicted by the EICM appear to match the measured frost depths reasonably well during 2016, where there was not such a large gap in measured frost depth data.
- The EICM did not accurately predict the onset of thawing. The EICM suggested the onset of thawing about half a month to a month later than when it was actually observed. Using the climate data from the MERRA grid located just south of the site produced more accurate results than using data from the MERRA grid located just north of the site, although the EICM still predicted the onset of thawing on the late side.

North Dakota

The EICM did the best job of predicting frost and thaw patterns at the North Dakota site. This may be due, in part, to the fact that much more information about the pavement structure was provided for this site. As noted, the results from the laboratory testing of site soil samples were used to appropriately modify some of the default soil properties included in the AASHTOWare software. Several model runs were conducted to investigate the sensitivity of the EICM to various soil properties. The results from two of those runs are included in Appendix F:

- Run 1B: Most reasonable inputs based on laboratory/measured soil properties

- Run 1D: Same as Run 1B, but the base layer moisture content was increased above the measured value and the base layer fines content was increased above the typical values (no sieve data were provided for that layer)

In both of these model runs, the EICM did an excellent job of predicting the onset of freezing and the onset of thawing, including the identification of intermediate thaw/refreeze events. The main difference was that the EICM-predicted frost depths were slightly deeper in Run 1B than in Run 1D, although the EICM still overpredicted frost depths to some extent in both runs.

Wisconsin

- For the two years stipulated for the Aurora study, the EICM generally tracked the onset of freezing fairly well.
- The maximum frost depths appear to be slightly overpredicted by the EICM, although this could not be confirmed during the 2015 winter because the measured frost depths extended below the lowest thermistor.
- The EICM predicted the onset of thawing very closely during the 2016 winter, although the model suggested two secondary freeze cycles that were not validated by the measured data. During the 2015 winter, the EICM predicted the onset of initial thawing in the upper 25 to 30 inches very closely in mid-March. But then the EICM suggested that there were several thaw/refreeze cycles and that complete thawing (i.e., down to 60 inches or more) did not occur until mid-April (almost a month later than indicated by the measured data).

Ontario

- For the two years stipulated for the Aurora study, the EICM generally tracked the onset of freezing fairly well.
- Maximum frost depths were significantly overpredicted by the EICM for both study years.
- During the 2015 winter, the EICM predicted the onset of thawing in the upper 40 inches very closely. During the 2016 winter, the EICM predicted the onset thawing in that same depth range about two weeks later than measured.

3.3.3c EICM Evaluation Using vRWIS Interface

As previously noted, the AASHTOWare software was developed primarily for pavement structural design and does not provide a user-friendly interface for use in SLR timing decisions. It was utilized for this project because it was the only tool available for running the EICM in hindcast for the original Aurora project study years (2014–2015 and 2015–2016).

Since a user-friendly interface is necessary for transportation agencies to effectively utilize models for SLR timing, part of the Phase IIb work included implementing the vRWIS software interface at four of the original project sites for the 2019–2020 winter/spring thaw season. Because it would have been very difficult (and expensive) to obtain the necessary climate and forecast data to run the vRWIS interface in Canada, and since Frost Associates was told that Ontario was no longer part of this study, the Ontario site was omitted from this endeavor.

The vRWIS interface was set up at the sites by ARA during February 2020. It can be accessed at http://174.129.155.72/VRWIS/2020/ using the following credentials:

Login name: bergnhfla@aol.com
Password: ara

On login, the site shows a map with an icon at each of the four test sites. Clicking on an icon opens the data screens for that particular test site. Samples are shown for the Whittier, Alaska, site. Four tabs/options for viewing and downloading data are shown in Figures 22 through 25.

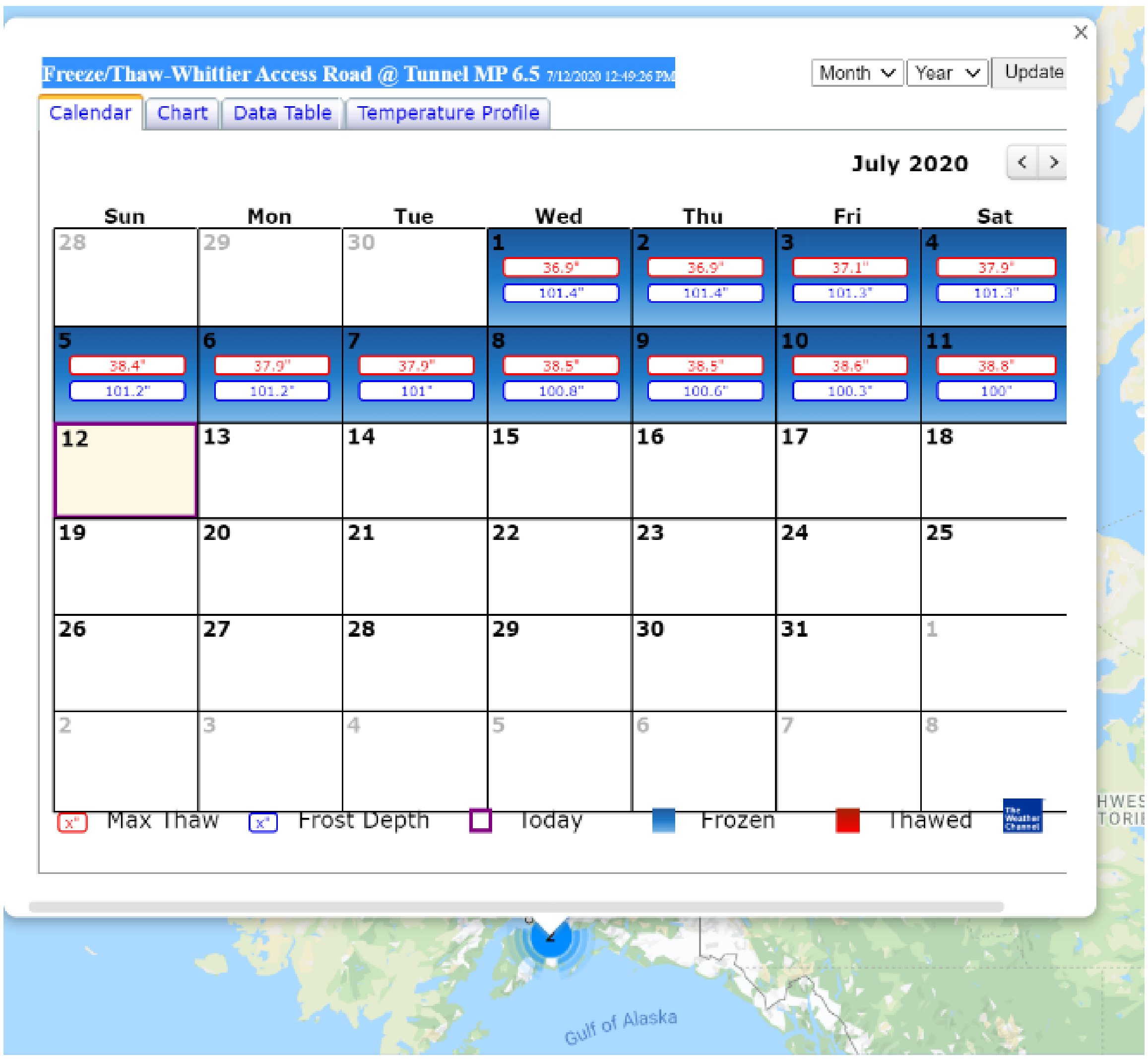


Figure 22. vRWIS Calendar tab

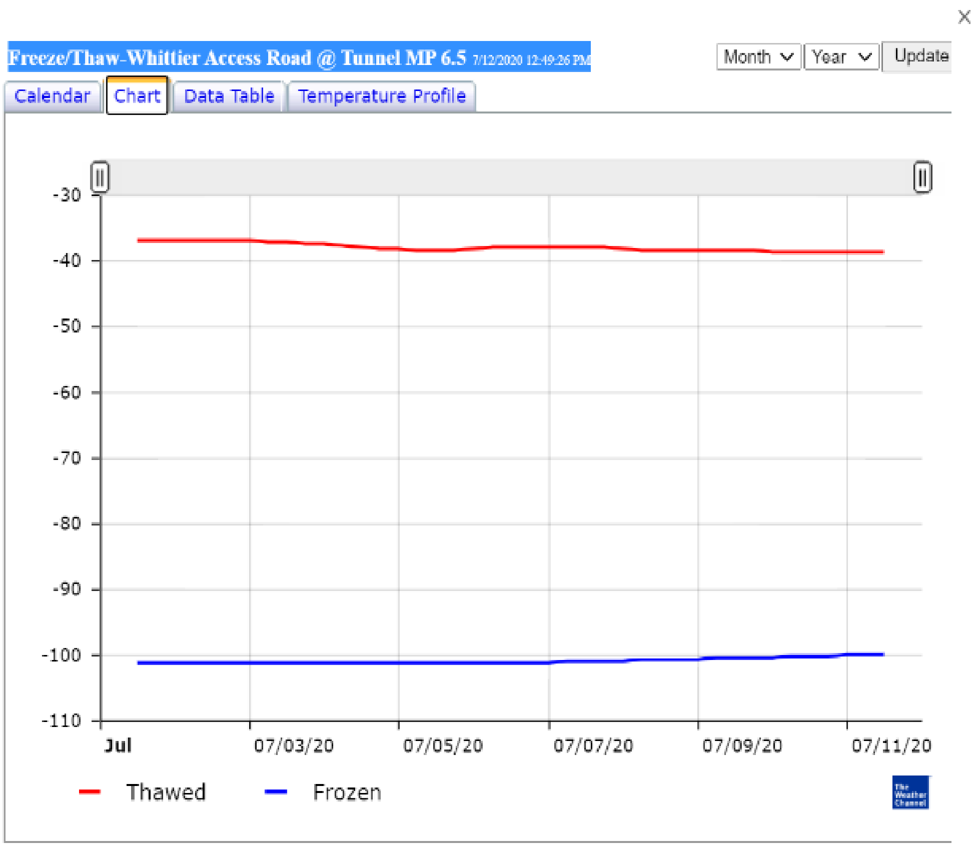


Figure 23. vRWIS Chart tab

Freeze/Thaw-Whittier Access Road @ Tunnel MP 6.5 7/12/2020 12:49:26 PM

Month | Year | Update

Calendar | Chart | Data Table | Temperature Profile

Date	Time	Thaw Depth(in.)	Frost Depth(in.
07/01/20	12:00 AM	37.2	101.4
07/01/20	1:00 AM	37.2	101.4
07/01/20	2:00 AM	37.3	101.4
07/01/20	3:00 AM	37.3	101.4
07/01/20	4:00 AM	37.3	101.4

Figure 24. vRWIS Data Table tab

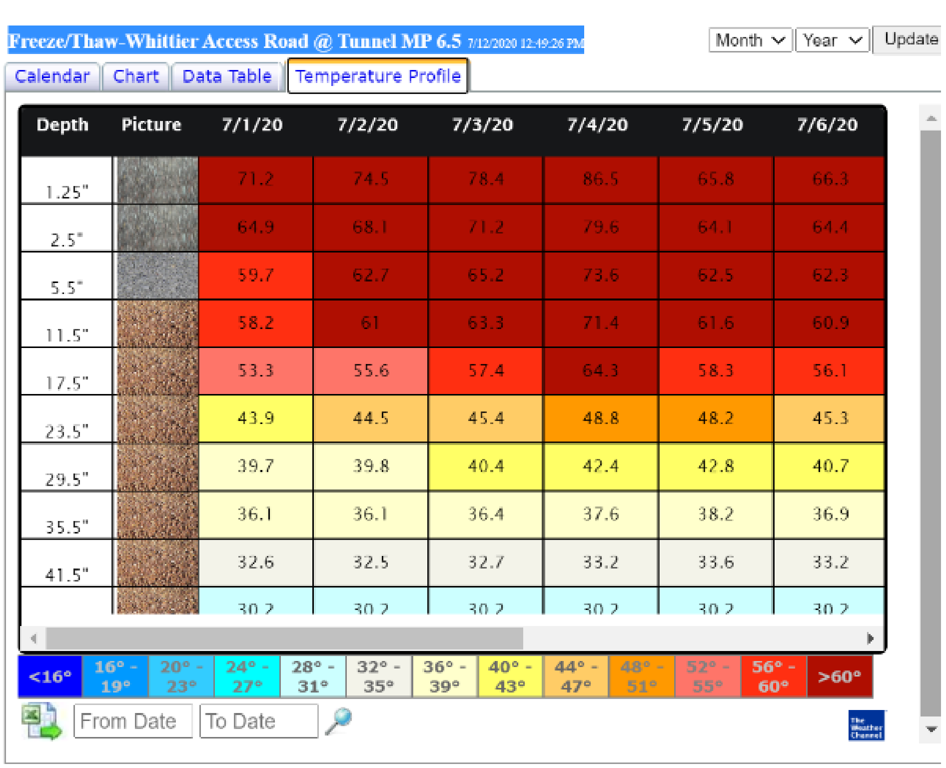


Figure 25. vRWIS Temperature Profile tab

The Calendar tab (Figure 22) shows the frost (blue) and thaw (red) depths estimated from the EICM, and the Chart tab (Figure 23) shows these depths in graphical form. The values shown on these tabs (as well as on the Temperature Profile tab) represent noontime values. Hourly values for the frost and thaw depths estimated from the EICM are shown on the Data Table tab (Figure 24).

The Temperature Profile tab (Figure 25) shows the estimated subsurface temperature at each of the model node depths. The user has the option of downloading 30 days of data at a time using the Excel icon and date range boxes in the bottom left corner of the screen. On all four tabs, the user can also view earlier predicted temperatures and frost/thaw depths using the Month, Year, and Update buttons in the upper right corner of the screen. During the winter/spring thaw season, forecast data are used to predict subsurface temperatures and frost/thaw depths 7 to 10 days in advance.

In order to evaluate how well the vRWIS interface was performing, Frost Associates obtained measured subsurface temperature data from DOT personnel in North Dakota and Michigan for the 2020 winter/spring thaw season. Additionally, subsurface temperature data from the Whittier, Alaska, site were downloaded from the following publicly available website and processed: http://www.roadweather.alaska.gov/iways/roadweather/forms/AreaSelectForm.html

Unfortunately, there were issues with the server at the site in Wisconsin, so the research team was not able to obtain subsurface temperature data from that site. The measured subsurface temperature data were compared with the output from the vRWIS interface for validation purposes. Those comparisons are presented in Appendix G.

At the Michigan site, the EICM/vRWIS output compared well with the TDP data, especially in predicting the onset of thawing in the relatively shallow depths that would be used in making SLR application decisions. Unfortunately, at the North Dakota site the EICM predicted temperatures significantly colder than the measured temperatures, and the use of the EICM would have resulted in non-conservative (quite late) SLR posting at that site for 2020. This was somewhat surprising, since Frost Associates had run the EICM using the AASHTOWare software for the 2014–2015 and 2015–2016 frost and thaw seasons and found a very good comparison between predicted and measured frost and thaw depths at the Bowman, North Dakota, site for those two seasons.

In Alaska, the measured subsurface temperatures indicate that the Whittier site had completely thawed on April 15, 2020; however, continuing through July 12, 2020, the vRWIS interface was still predicting a substantial thickness of frozen material at that site. Clearly, the end-of-thaw date was not predicted accurately this spring/summer at the Whittier, Alaska, site. That type of error might result in the SLR remaining in place much longer than necessary. Thaw was observed in the TDP sensor located 9 inches below the bottom of the asphalt layer on March 24, 2020; however, thaw was not predicted by the EICM/vRWIS at that same depth until April 15, 2020 (i.e., about three weeks later). A similar lag of about two to three weeks was also observed when comparing the thaw date measured by the TDP sensor located at a depth of 18 inches with EICM predictions from nodes at depths of 15 and 21 inches, respectively. Even when looking only at thawing predictions at relatively shallow depths (as might be done when deciding when to apply the SLR), the EICM/vRWIS predictions would have resulted in quite non-conservative (late) SLR implementation decisions, potentially leading to increased pavement damage. In summary, for this 2020 thaw season, the research team has concluded that the EICM and/or the vRWIS interface is not performing well at the Alaska test site.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 SLR and WWP Posting Based on Degree-Day Threshold Protocols

4.1.1 WWP Posting

Section 3.2 of this report described protocols that use threshold values for cumulative freezing or thawing degree-days to determine when to place and remove WWPs and SLRs, respectively. For WWP application, two protocols were examined during this study: the MnDOT protocol and the Lakehead University protocol. MnDOT (2009, 2014) recommends that the WWP can be allowed when the three-day weather forecast indicates that the CFI will exceed 280°F-days and extended forecasts predict continued freezing temperatures. The Lakehead University protocol suggests using variable CFI threshold values for applying WWPs, which must be calibrated on a site-specific basis, by determining the CFI values corresponding to the dates that the frost depths exceeded about 40 inches. The researchers who developed this protocol computed cumulative freezing indices according to MnDOT (2009), as outlined in Section 3.2.1 of this report. Both the MnDOT and the Lakehead University protocols recommend removing the WWP by the time the SLR is applied.

As noted in Section 2.3 of this report, in the original validation proposal for Phase II, one of the procedures that was planned for WWP protocol validation was to conduct FWD or LWD testing prior to the start of winter and once a week for the first three weeks of winter. Unfortunately, the FWD (or LWD) testing that was planned for the first three weeks of winter could not be conducted by the state DOTs, so complete validation of the WWP protocols was not possible. Nevertheless, the research team did examine the measured frost depths at the test sites on the dates when CFI thresholds were reached. In general, for both protocols, frost penetration was between about 10 and 30 inches when the WWP threshold was reached, and slightly deeper in a few cases.

Marquis (2008) conducted a mechanistic analysis to evaluate the MnDOT guidelines for WWP and SLR application in the state of Maine. As a follow-up to that study, the Maine DOT provided members of Frost Associates with FWD test data collected during the early winter at seven roadway test sites in Maine. The FWD data showed that ACD values ranged between about 10 and 30 mils at the test sites when CFI values were below 200°F-days. As soon as the CFI values reached about 250°F-days, ACD values dropped to between 2 and 5 mils at all of the sites. At sites where subsurface temperature sensors were installed, frost penetration was about 23 or 24 inches when the CFI threshold of 280°F-days was reached.

Based upon the relationship between CFI values and measured frost depths observed in this Aurora study, as well as the relationship between CFI values, measured frost depths, and FWD test data provided by the Maine DOT, the MnDOT protocol (CFI threshold of 280°F-days) seems like a reasonable approach for setting WWP start dates. The Lakehead University protocol is not recommended for WWP guidance based on the fact that site-specific calibration is required and the fact that there was much more scatter in the CFI threshold values obtained during those site-specific calibrations.

4.1.2 SLR Application

The SLR start dates determined in accordance with the three different degree-day protocols described in Section 3.2 are listed in Table 22 for the two original study years at all five Aurora demonstration sites. The table also includes SLR start dates determined from both the MnDOT and FrezTrax protocols at the five additional North Dakota sites for 2020.

Table 22. SLR start dates from degree-day protocols

Date Thaw Depth Reaches 12 in. TDP	Original Aurora Site Location	Frost and Thaw Season	SLR Application Date		
			MnDOT	FrezTrax	Lakehead
2/19/2015	Alaska	2014-2015	1/10/2015	1/10/2015	Calibration
11/28/2015	Alaska	2015-2016	NA	11/26/2016	1/8/2016
3/24/2020	Alaska	2019-2020	3/20/2020	4/2/2020	3/24/2020
3/16/2015	Michigan	2014-2015	3/11/2015	4/2/2015	Calibration
3/8/2016	Michigan	2015-2016	3/7/2016	3/9/2016	3/13/2016
3/9/2020	Michigan	2019-2020	3/8/2020	3/28/2020	3/26/2020
3/10/2015	North Dakota	2014-2015	3/8/2015	3/10/2015	Calibration
2/19/2016	North Dakota	2015-2016	2/15/2016	2/19/2016	2/19/2016
2/21/2020	North Dakota*	2019-2020	2/29/2020	3/5/2020	3/5/2020
4/8/2015	Ontario	2014-2015	3/13/2015	NA	4/14/2015
3/13/2016	Ontario	2015-2016	3/12/2016	NA	4/16/2016
3/10/2015	Wisconsin	2014-2015	3/9/2015	3/11/2015	Calibration
2/27/2016	Wisconsin	2015-2016	2/23/2016	3/7/2016	3/5/2016
Additional North Dakota Sites:					
2/23/2020	Gladstone	2019-2020	2/29/2020	3/5/2020	
2/29/2020	Bismark	2019-2020	2/29/2020	3/5/2020	
3/8/2020	Golden Valley	2019-2020	3/1/2020	3/5/2020	
3/27/2020	Denhoff	2019-2020	3/4/2020	3/29/2020	
3/24/2020	Devils Lake	2019-2020	3/25/2020	3/30/2020	

* Bowman, North Dakota, test site

Those dates were compared with the dates that the measured thaw depth reached the 12-inch TDP sensor, and the number of days that the SLR start dates fell early (-) or late (+) relative to the 12-inch thaw depth are summarized in Table 23.

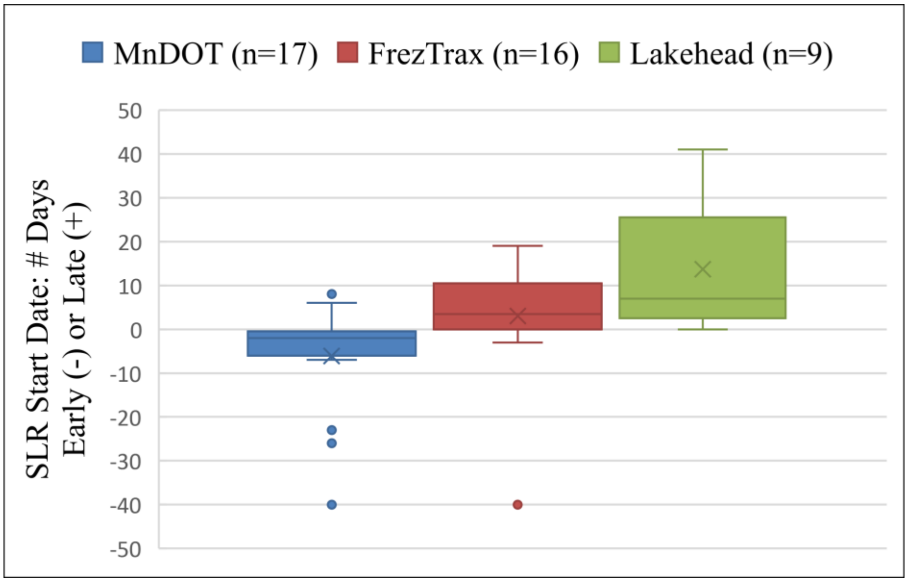
Table 23. Number of days that predicted SLR start dates fell early or late

Original Aurora Site Location	Frost and Thaw Season	No. of Days SLR Application Date Early (-) or Late (+)		
		MnDOT	FrezTrax	Lakehead
Alaska	2014–2015	-40	-40	
Alaska	2015–2016	NA	-2	41
Alaska	2019–2020	-4	9	0
Michigan	2014–2015	-5	17	
Michigan	2015–2016	-1	1	5
Michigan	2019–2020	-1	19	17
North Dakota	2014–2015	-2	0	
North Dakota	2015–2016	-4	0	0
North Dakota*	2019–2020	8	13	13
Ontario	2014–2015	-26	NA	6
Ontario	2015–2016	-1	NA	34
Wisconsin	2014–2015	-1	1	
Wisconsin	2015–2016	-4	9	7
Additional North Dakota Sites:				
Gladstone	2019–2020	6	11	
Bismark	2019–2020	0	5	
Golden Valley	2019–2020	-7	-3	
Denhoff	2019–2020	-23	2	
Devils Lake	2019–2020	1	6	

* Bowman, North Dakota, test site

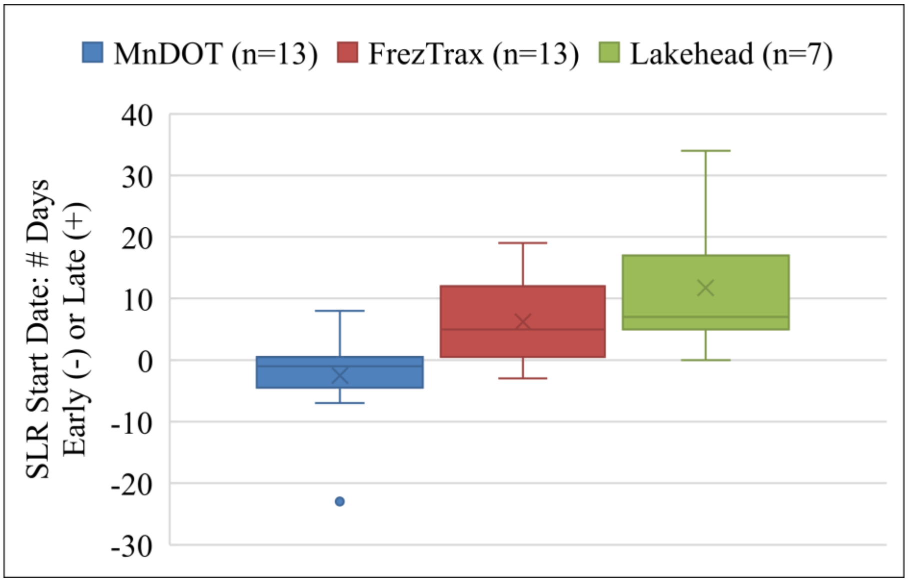
Figures 26 and 27 present boxplots showing the number of days that the SLR start date fell early (before thaw reached the 12-inch TDP) or late (after thaw reached the 12-inch TDP) for the three degree-day protocols. The numbers of data points used in the statistical analysis for each box, n, are shown in the legends.

In descriptive statistics, a boxplot is a method for graphically depicting groups of numerical data through their quartiles. At the ends of the box are the first quartile (the 25% mark, at the bottom) and the third quartile (the 75% mark, at the top), which define the percentile ranges in the number of days that SLR predictions were early (-) or late (+) relative to the measured 12-inch thaw depth. The horizontal line inside the box is plotted at the median value of the dataset, and the mean value of the dataset is plotted as an X. The spacings between the different parts of the box indicate the degree of dispersion (spread) and skewness in the data.



Data includes sites in Alaska; Ontario, Canada; and the CONUS

Figure 26. Boxplots showing the number of days that the SLR start date fell early (before thaw reached the 12-inch TDP) or late (after thaw reached the 12-inch TDP)



Data for MnDOT and FrezTrax includes only sites in the CONUS; data for Lakehead includes sites in the CONUS and Ontario, Canada

Figure 27. Boxplots showing the number of days that the SLR start date fell early (before thaw reached the 12-inch TDP) or late (after thaw reached the 12-inch TDP), excluding data from higher latitudes

Box plots also typically have lines extending from the boxes (whiskers) indicating variability outside the upper and lower quartiles. Data sets can sometimes contain outliers that are suspected to be anomalies (perhaps because of data collection errors or simply flukes). When outliers are suspected, the whisker on the appropriate side is drawn to (1.5 x IQR), where IQR is the interquartile range (the 75th percentile – 25th percentile value). The outliers (points that lie outside this range) are plotted as solid dots.

In both Figures 26 and 27, two common trends are observed:

- The MnDOT protocol shows the least amount of spread, followed by FrezTrax, with the Lakehead University protocol showing the most spread.
- The MnDOT protocol is the most conservative (early prediction bias), followed by FrezTrax, with the Lakehead University protocol being least conservative (late prediction bias).

Because these degree-day methods did not perform as well at higher latitudes, statistics were conducted on a more limited data set for Figure 27. For the MnDOT and FrezTrax protocols, a common set of 13 data points was used (all sites being in the CONUS). Since the Lakehead University method was not calibrated at five of the sites in North Dakota where data were collected in 2020, and since that method was originally calibrated at the test site in Ontario, Canada, statistics for the Lakehead University protocol in Figure 27 included data from seven available site/season combinations in the CONUS and in Ontario, Canada. In Figure 27, the median predictions were one day early, five days late and seven days late for the MnDOT, FrezTrax, and Lakehead University protocols, respectively. In that figure, one outlier was observed (at the Denhoff, North Dakota, site in 2020) for the MnDOT protocol. As explained in Section 3.2.1b, at the Denhoff site, thaw was observed in the 6-inch TDP sensor only eight days after the MnDOT CTI threshold date was exceeded; however, a subsequent cold spell brought CTI values at Denhoff down below the 25 degree-day threshold before warming again raised CTI values above the threshold and thawing was observed in the 12-inch TDP (i.e., 23 days after the CTI threshold date was originally exceeded).

The results of this study suggest that, for the CONUS, the MnDOT protocol is probably the best protocol, albeit somewhat conservative, for estimating when to apply spring load restrictions. The median prediction for that protocol was one day early, and there was far less spread in the data than observed for the other two protocols.

The FrezTrax protocol also works fairly well for estimating when to apply load restrictions in the CONUS, although it tends to be non-conservative, with the median estimated SLR start date falling five days late. This is problematic, as numerous researchers have suggested that roadways experience a rapid decrease in strength, and thus increased potential for damage, at the beginning of thaw (Mahoney et al. 1986, Van Deusen et al. 1998, Ovik et al. 2000, Kestler et al. 2007, Tighe et al. 2007, Marquis 2008, Bradley et al. 2012).

The Lakehead University protocol was the least conservative; suggested SLR start dates consistently fell after the 12-inch thaw depth was reached, with the median estimated SLR start date falling seven days late. Coupled with the fact that the Lakehead University method must be calibrated on a site-specific (or perhaps regional) basis, this protocol is considered to be less desirable than the other degree-day protocols evaluated in this study.

As discussed in Section 3.2.1a, the findings from this Aurora study, as well as a study reported by Eftekhari et al. (2018) that examined an extensive range of sites throughout the state of Alaska, suggest that the MnDOT protocol is likely to produce excessively conservative results in regions of higher latitude, such as Canada and Alaska. The FrezTrax protocol also tended to produce conservative results at the Aurora test site in Whittier, Alaska. This early prediction bias is not surprising, since the MnDOT reference temperatures were calibrated in Minnesota, and the Mahoney et al. (1986)/FrezTrax calibrations were performed in the states of Washington and South Dakota, respectively, where solar gain increases are observed much earlier in the springtime compared to Alaska. Although not part of the scope of this Aurora study, a brief examination of the Berg/FS method for estimating SLR start dates (described in Section 3.2.3c) shows promise as a potential SLR timing tool for regions of higher latitude, such as Alaska.

4.1.3 SLR Removal

Several researchers have attempted to provide SLR removal criteria linked to degree-day threshold value(s). Mahoney et al. (1986) suggested two equations (presented in Section 3.2.3a) for removing spring load restrictions. In Minnesota, the SLR end date for various frost zones is determined using measured frost and thaw depths, forecast daily air temperatures, and other key indicators at several locations within each frost zone; therefore, the duration of the spring load restrictions varies from year to year. However, the MnDOT policy states that "the spring load restrictions will last no more than 8 weeks unless extraordinary conditions exist that require additional time or route-specific signage" (MnDOT 2009, 2014).

Bradley et. al. (2012) recommended computing CTI values using the MnDOT (2009) equations but using a slightly different variable reference temperature that was calibrated in Manitoba, Canada. Bradley et. al. (2012) recommended the following policy for SLR removal: the SLR will end on the earliest of 8 weeks (56-day duration), when the CTI reaches 630°F-days, or May 31. These recommendations are similar to guidelines under consideration by the Maine DOT, which use the MnDOT (2009) equations and reference temperatures for CTI calculations and suggest an SLR removal threshold of about 700°F-days.

In Section 3.2.3, the FrezTrax protocol was described, which incorporates freezing and thawing index calculations that were originally developed by Mahoney et al. (1986). Mahoney et al. (1986) suggested two alternative methods for determining when to remove spring load restrictions. Both of the SLR removal methods are functions of the maximum seasonal air freezing index and were presented in this report as Equations 11 and 12. The FrezTrax protocol appears to modify and further build upon the Mahoney et al. (1986) protocol by including regionally calibrated moisture effects in defining the critical CTI threshold values. Under the Phase IIb scope of work, the research team evaluated how well the FrezTrax protocol works for timing when to remove the SLR by comparing the FrezTrax CTI threshold dates for SLR removal with FWD data.

For summary and comparison, Table 24 and Figures 28 and 29 present the SLR removal dates determined from the four different approaches outlined in the preceding paragraphs. It should be noted that for the MnDOT protocol, the set 56-day duration began on the SLR application date computed as per MnDOT (2009, 2014), and the Mahoney (1986) SLR removal dates were computed as per Equation 12.

Table 24. SLR removal dates at North Dakota sites determined from four different approaches

Site	MnDOT Remove SLR Date (56 days)	CTI=700 ºF-day Date	Mahoney Remove SLR Date	FrezTrax Remove SLR Date
Bowman 2015	5/3/2015	4/13/2015	4/8/2015	4/17/2015
Bowman 2016	4/11/2016	4/7/2016	3/14/2016	3/13/2016
2020 Sites:				
Bowman	4/25/2020	4/27/2020	4/30/2020	5/5/2020
Gladstone	4/25/2020	4/28/2020	5/1/2020	5/8/2020
Bismark	4/26/2020	4/27/2020	5/1/2020	5/8/2020
Golden Valley	4/25/2020	4/29/2020	5/6/2020	5/17/2020
Denhoff	4/29/2020	5/2/2020	5/16/2020	5/21/2020
Devils Lake	5/20/2020	5/5/2020	5/25/2020	6/2/2020

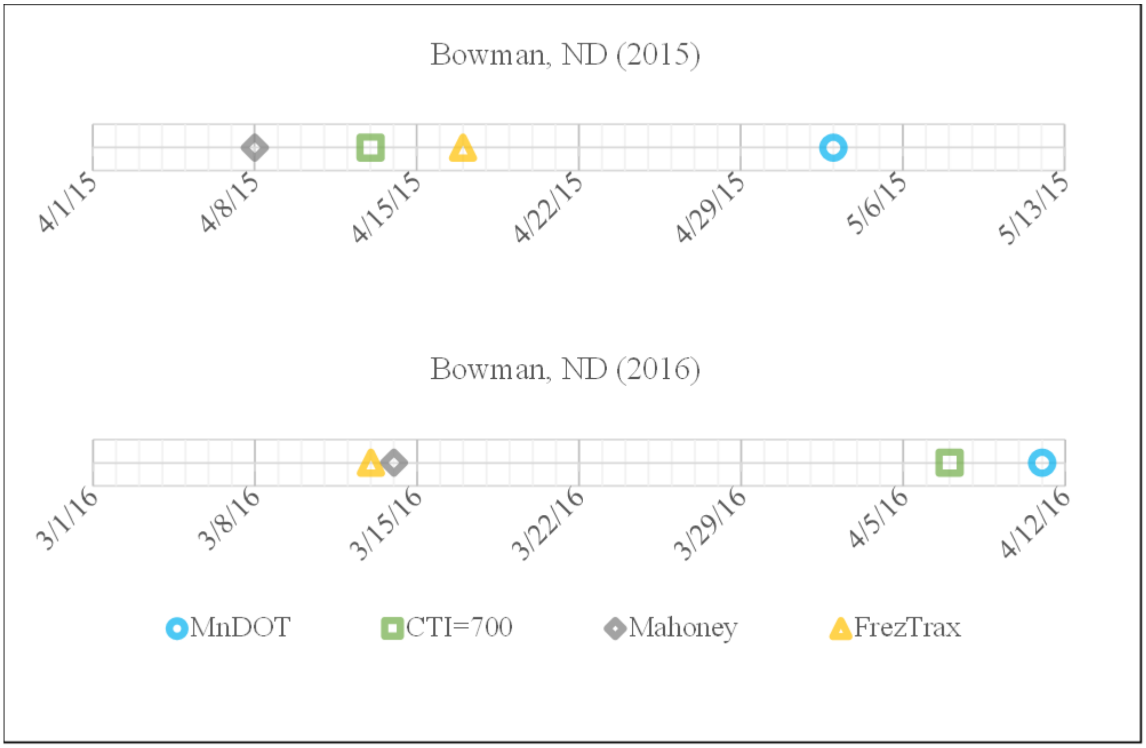


Figure 28. Comparison of SLR removal protocols at Bowman, North Dakota, for 2015 and 2016

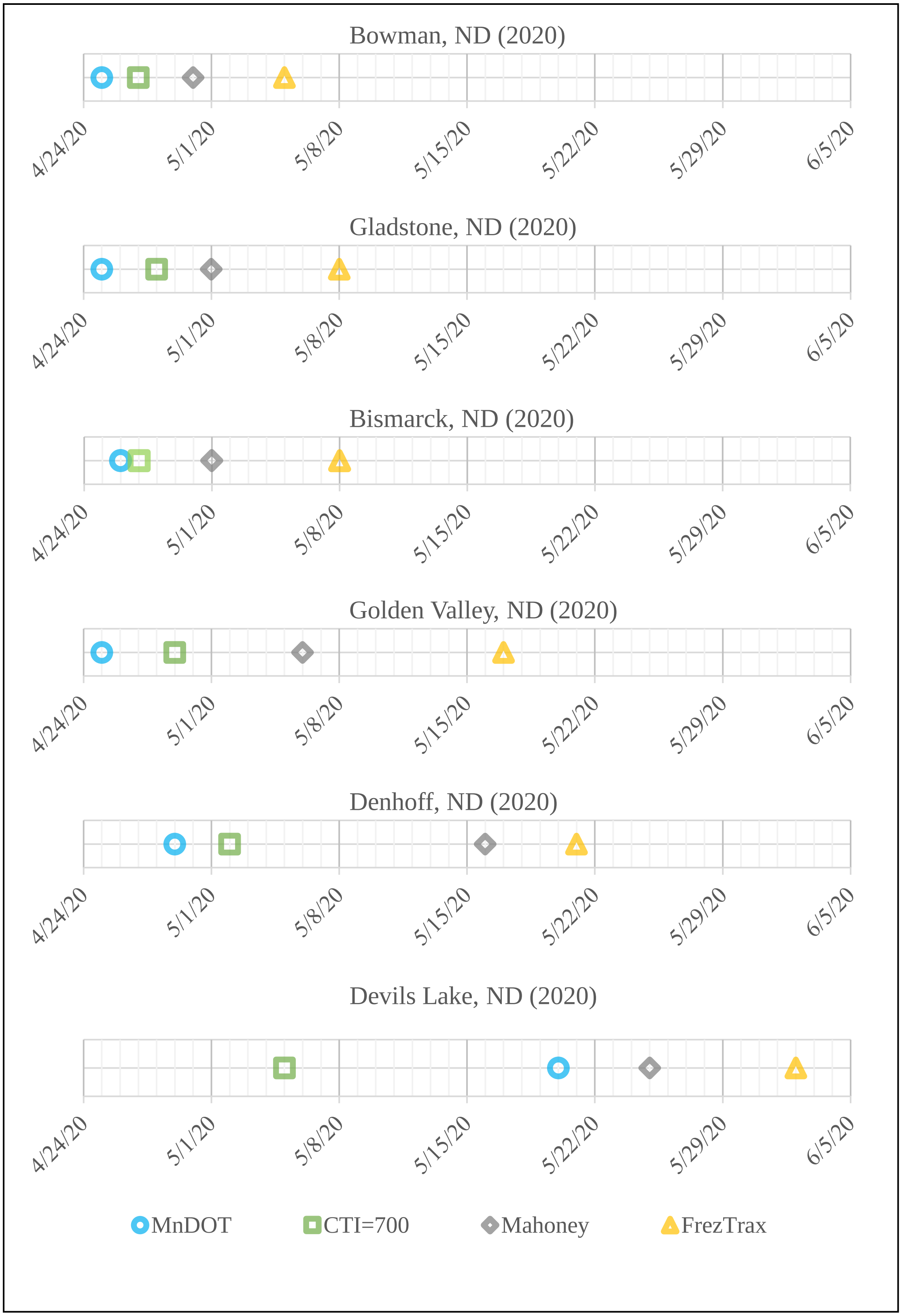


Figure 29. Comparison of SLR removal protocols at North Dakota sites for 2020

In 2020, with the exception of the CTI = 700°F-day threshold at the Devils Lake site, trends were fairly consistent; the MnDOT protocol (with a 56-day duration) yielded the earliest SLR removal date, followed by the dates determined by the CTI = 700°F-day threshold, and then the Mahoney et al. (1986) dates. The FrezTrax removal dates were the latest for all five sites in 2020. On the other hand, the trends observed in the 2015 and 2016 thaw seasons were almost the reverse of the trends observed in 2020, with the MnDOT protocol yielding the latest SLR removal dates. In 2016, the FrezTrax protocol produced the earliest SLR removal date, and in 2015 the FrezTrax date fell mid-range compared to the other three protocols.

Since the MnDOT and FrezTrax protocols tended to bracket the earliest and latest SLR removal dates, those dates were superimposed on the plots of FWD data included in Appendix C. During the spring thaw season in both 2015 and 2016, FWD data from the Bowman, North Dakota, site suggest that the SLR date from the FrezTrax protocol was too early. Backcalculated base modulus values in 2016 indicate that there was likely significant potential for fatigue damage to the pavement during that multi-week recovery period when base modulus values were reduced. Although the SLR removal date from the MnDOT protocol fell after the last FWD test in both 2015 and 2016, the FWD data trends suggest that the MnDOT removal date fell close to, or just after, full recovery of the pavement structure.

In contrast to the spring of 2015 and 2016, during the 2020 thaw season the SLR removal dates predicted by FrezTrax fell later than those computed using the MnDOT protocol for all six sites. At three of the six sites (Bowman, Golden Valley, and Denhoff), the subgrade did not exhibit substantial stiffness loss during that spring thaw period (i.e., the modulus values hovered right around the baseline value measured during the preceding fall). So, even though the MnDOT protocol was less conservative than the FrezTrax protocol for those cases, it is not clear that the MnDOT SLR removal dates were premature enough to cause significant damage (at least in terms of subgrade rutting).

At two of the six sites (the site at Gladstone and the site near Bismarck [Highway 6, south of Mandan]), the FrezTrax protocol performed much better than the MnDOT protocol. The SLR removal date predicted by the FrezTrax protocol appears to have fallen at or just slightly before complete recovery, whereas the SLR removal date predicted by the MnDOT protocol fell during the time when subgrade modulus values were still quite a bit below baseline values.

And at the site near Devils Lake, the last FWD test was conducted on May 28, 2020, when subgrade modulus values were still substantially below baseline values. At that site, the SLR removal dates predicted by all four methods were significantly premature. The MnDOT date coincided with the lowest subgrade modulus values for that season, during a time when there was likely significant potential for rutting if heavy traffic were permitted. Trends in the FWD data suggest that even the FrezTrax SLR removal date (the latest of all four methods) likely fell before complete recovery occurred. It is unclear why this anomaly occurred. Details about the subgrade soils were not provided for the five additional North Dakota sites examined in 2020; however, the research team hypothesizes that perhaps silty subgrade soils may have contributed to the anomaly. Silty soils tend to draw more moisture up due to capillary action during the fall and early winter, and because they are slower to drain in the spring, strength and stiffness recovery generally takes longer than is the case with coarser grained soils.

In summary, there is no clear-cut "winner" with regard to SLR removal protocols. The FrezTrax model is appealing, in theory, because it incorporates the effects of both fall precipitation and maximum seasonal air freezing index into its protocol. The FrezTrax model performed better than the other three protocols at the majority of the six North Dakota sites in 2020; however, it was likely not conservative enough at the Bowman, North Dakota, site during the original two study years (2014–2015 and 2015–2016). It is noteworthy that, if duration were calculated as the difference between the FrezTrax application date and the FrezTrax removal date, the SLR durations at the six North Dakota sites in 2020 ranged from 53 to 73 days, with an average duration of 63 days. At the Bowman, North Dakota, site during spring 2015 and 2016, the duration would have been 38 and 23 days, respectively.

While the MnDOT protocol (a set 56-day duration) worked well at the Bowman, North Dakota, site during spring 2015 and 2016, it was not conservative enough at several of the study sites in 2020. The research team believes that perhaps some slight modification to the MnDOT protocol might make sense, such as a guideline to use a removal date corresponding to the latter of a 56-day duration or the date when the CTI reaches 700°F-days. If that criterion were applied to the study sites, the duration would have remained as 56 days at the Bowman, North Dakota, site during spring 2015 and 2016 and at the Devils Lake site in 2020. At the other five test sites in 2020, the duration would have slightly increased (ranging from 57 to 60 days).

4.2 SLR Posting Based on Frost-Thaw Depth Prediction Models

Section 3.3 of this report described the evaluation of several different models for predicting subsurface frost and thaw depths. If these models were utilized for SLR timing, the WWP would be applied when the predicted frost depth reaches some specific threshold value, and the SLR would be applied when the predicted thaw depth reaches some other threshold value. Pernia et al. (2014) have suggested that pavement structures in Ontario, Canada, are sufficiently strong to permit WWP overloads when frost depths exceed about 40 inches, although other studies conducted by the Maine DOT have suggested that frost depths on the order of 25 to 30 inches may be sufficient.

For SLR application, many studies have suggested that the pavement structure is weakened to the point of permanent damage when the thaw depth exceeds about 12 inches (for example, Mahoney et al. 1986, Ovik et al. 2000, Pernia et al. 2014). The freeze-thaw index models (Section 3.3.1) and Modified Model 158 (summarized in Section 3.3.2) generally performed very well in terms of tracking the onset of freezing and the onset of thawing and therefore could be useful in deciding when to apply WWPs and SLRs. In contrast, in many cases the EICM (summarized in Section 3.3.3) predicted temperatures significantly colder than the measured temperatures. By predicting the onset of thawing on the late side, use of the EICM could result in non-conservative SLR posting, which could lead to increased pavement damage.

In terms of SLR removal, a potential advantage that accurate frost-thaw depth prediction models have over degree-day protocols is knowledge of when the subsoils are completely thawed, since the SLR certainly should not be removed prior to that point. However, in many cases most of the models described in Section 3.3 of this report did not accurately estimate the end-of-thaw dates. Furthermore, as discussed in Section 1.2 of this report, numerous studies have suggested that strength and stiffness recovery requires some time after thawing is complete to allow excess moisture in the base and subgrade layers to dissipate. It was originally hoped that perhaps the moisture calculations embedded in the EICM might be helpful in this regard. However, recent discussions with personnel at ARA who developed the EICM module in the AASHTOWare software indicate that a 60-day recovery time is programmed into the module, regardless of subsoil type and moisture conditions at the site. So, in terms of a tool to assist in deciding when to remove SLRs, the EICM (as well as the other frost-thaw depth prediction models) do not appear to provide great advantage.

4.3 Intellectual Property and Implementation Issues

There are no intellectual property issues with any of the SLR posting protocols described in this report that are based upon degree-day thresholds. The main implementation issue for those SLR posting methods relates to calibration (in some cases). Although the method suggested by MnDOT (2009) does not specifically require calibration, the reference temperatures utilized in that protocol are not generally applicable to regions at very different latitudes, such as Alaska. Berg et al. (2006) suggested a method to estimate pavement surface temperatures for use in cumulative thawing index computations for SLR timing. Although this method shows much promise as a more accurate SLR timing tool for regions at higher latitudes, it does require local, or perhaps regional, calibration. The SLR protocol developed by the MTO/Lakehead University (Chapin et al. 2013, Pernia et al. 2014) uses an identical approach to that suggested by MnDOT (2009), with the following exception: the creators of the the MTO/Lakehead University protocol recommend calibrating the threshold values for applying WWPs and SLRs on a site-specific basis by determining the CFI and CTI values corresponding to the dates that the frost and thaw depths exceeded about 40 and 12 inches (100 cm and 30 cm), respectively. Again, this required calibration may render the MTO/Lakehead University protocol less desirable than the MnDOT (2009) protocol from an implementation standpoint.

Although all of the SLR degree-day threshold protocols described in this report could be implemented using Excel spreadsheets, that would be extremely tedious to do for numerous roadway locations throughout a state. To help make these protocols easier to use for SLR timing, a simple-to-use GUI is recommended. For this project, two GUIs were examined:

- The NRCC constructed a demonstration GUI for applying the MnDOT protocol across the state of North Dakota for the 2020 spring thaw season (see Section 3.2.1b) and recently constructed similar demonstration GUIs for Michigan and Wisconsin. The interfaces for these states can be accessed at the following sites:

  http://www.nrcc.cornell.edu/industry/roads-nd/
  http://www.nrcc.cornell.edu/industry/roads-mi/

http://www.nrcc.cornell.edu/industry/roads-wi/

The NRCC has also constructed similar GUIs for several states in the northeastern US at a relatively low cost. The estimated cost is about $1,000 per state. In some states (such as Alaska), the construction of such a GUI may be limited by the fact that insufficient data feeds are available to accurately run the model.

- Meridian/Iteris formerly provided a GUI through its proprietary FrezTrax software. The FrezTrax model appears to modify and further build upon the Mahoney et al. (1986) protocol by including regionally calibrated moisture effects in defining critical CTI benchmark values for SLR application and removal. Meridian/Iteris was recently sold to DTN. DTN plans to continue executing the FrezTrax program for the SDDOT and NDDOT. DTN is currently evaluating whether to extend FrezTrax to other locations. The company is not sure what the cost would be or whether additional calibration would be required if it does decide to offer FrezTrax to DOTs in other states.

In terms of SLR posting methods based on frost-thaw depth prediction models, there are several procedures based upon freezing and thawing indices, as described in Section 3.3.1 of this report. These methods can generally be set up to run on spreadsheets (and therefore have no associated intellectual property issues or software fees), but all of them require at least one year (preferably several years) of measured frost-thaw data for accurate calibration. The models described in Section 3.3.1b (Miller et al. 2012) and Section 3.3.1c (Chapin et al. 2013; Pernia et al. 2014) require some statistical analysis to determine the calibration coefficients, but that analysis can be done fairly easily in Excel spreadsheets.

A modified version of the U.S. Army Corps of Engineers Model 158 has been developed to predict daily frost and thaw depths, as described in Section 3.3.2. Input for that model includes cumulative degree-days (based upon average daily air temperatures) as well as the material properties and thicknesses of the pavement layers. There are no intellectual property issues associated with that model; however, to implement that model, some skill is required to set the model up in a spreadsheet and/or to write computer code to run the model. Additionally, a soil boring and occasionally some minimal laboratory testing are generally required to properly determine the thicknesses and material properties of the subsurface layers.

Finite element and/or finite difference computer programs, such as the various versions of the EICM described in Section 3.3.3, are very robust and theoretically should be more accurate than the various frost and thaw index (degree-day) methods. However, they are also much more complicated to use, and the software is fairly expensive to purchase. For example, at the time this project was conducted, the annual software usage fee for a single station for the AASHTOWare software was $6,400. Furthermore, while it is fairly easy to predict frost and thaw depths in hindcast, the AASHTOWare software is not set up well at all for predicting frost and thaw depths in forecast mode, which is necessary for deciding when to apply SLRs (since three to five days advance notice is usually required in most states for posting roads).

As an alternative, some consultants now provide services to set up and run finite element and/or finite difference software on a subcontract basis; however, there is still a substantial cost involved. For example, at the time this project was conducted, the annual software usage fee for the vRWIS interface was $2,500 per site.

4.4 Final Recommendations

4.4.1 General

In this report, dates for imposing and removing WWPs and SLRs were determined using a number of different protocols and models. Computed dates were compared with frost and thaw depths obtained from subsurface temperature measurements at numerous demonstration sites and, in some cases, with data obtained from FWD tests. Finally, based on accuracy, simplicity of use, and cost, the recommendations described in this section were developed to aid road management agencies in selecting the most appropriate model or protocol for their intended purposes, personnel, and specific conditions.

Since the start of Phase I of this project in early 2014, several state DOTs have greatly expanded their suite of subsurface temperature sensors through the federal RWIS and other initiatives. However, many state DOTs in seasonal frost areas still have relatively few instrumented roadways in their states. Selection of the most appropriate protocols to assist transportation agencies with SLR posting decisions may depend, in part, upon the number of subsurface temperature probes available within a state. Final recommendations are described in the remainder of this section.

4.4.2 Degree-Day Threshold Protocols

4.4.2a MnDOT Protocol

- **WWP Application.** In the absence of extensive subsurface temperature monitoring instrumentation, the MnDOT protocol (outlined in Section 3.2.1a) is recommended for setting WWP start dates.
- **SLR Application.** For deciding when to apply SLRs, the MnDOT protocol is also highly recommended for locations within the CONUS at a similar latitude to Minnesota. This protocol is recommended even if extensive subsurface temperature monitoring instrumentation is available in order to allow for the three to five days of advance notice required in most states. If an agency waits until after thawing is observed in a TDP and then adds another three to five days (or more) to actually get the road posted, considerable pavement damage could occur during that week or so before heavy traffic is prohibited.
- **SLR Removal.** While the MnDOT protocol tends to be conservative with regard to SLR application (predicting SLR start dates slightly before thaw progresses into the base layer), the duration limit of 56 days suggested by MnDOT may be non-conservative for deciding when to remove the SLR. The FWD data provided during this project suggest that the pavement at several of the North Dakota study sites did not fully recover within the 56-day

duration. For SLR removal, the research team believes that perhaps some slight modification to the MnDOT protocol might make sense, such as a guideline to use a removal date corresponding to the latter of a 56-day duration or the date when the CTI reaches 700°F-days.

- **Overall Recommendation.** The MnDOT protocol is easy to use and is generally one of the more accurate protocols for deciding when to place and remove WWPs and SLRs. However, the MnDOT protocol is not recommended for regions at higher latitudes, such as Canada and Alaska. For these regions, the Berg/FS method (outlined in Section 3.2.3c) or the approach outlined by Eftekhari et al. (2018) shows more promise.
- **GUI Availability and Cost.** Graphical interfaces based upon the MnDOT protocol have already been set up by the NRCC for some states and could be expanded to include other states at minimal cost.

4.4.2b FrezTrax Protocol

- **WWP Application.** The FrezTrax protocol (outlined in Section 3.2.4) does not provide any guidance for WWP application.
- **SLR Application.** The FrezTrax protocol may be useful for deciding when to apply SLRs in the CONUS. However, it is less conservative than the MnDOT protocol and tends to estimate SLR start dates after thawing has progressed into or below the pavement base layer. This may be problematic, as numerous researchers have suggested that roadways experience a rapid decrease in strength, and thus increased potential for damage, at the beginning of thaw.
- **SLR Removal.** On the other hand, if an agency wants to err on the side of caution when deciding when to remove SLRs, the FrezTrax protocol may be preferred since it tends to be more conservative than the MnDOT protocol (although the results were mixed to some extent).
- **Overall Recommendation.** Overall, although the FrezTrax protocol is appealing because it considers moisture conditions in addition to air temperatures, the MnDOT protocol may be the safer choice if a DOT wants to use a single protocol for both SLR application and removal decisions. This recommendation is based on conclusions from the extensive Ovik et al. (2000) study, which suggested that conditions are far worse at the beginning of the spring thaw than at the end, and therefore it is far more effective to place restrictions early than to delay their removal.
- **GUI Availability and Cost.** Graphical interfaces based upon the FrezTrax protocol are available for North Dakota and South Dakota through DTN (formerly Meridian/Iteris). DTN has not decided whether it will make its FrezTrax interface available to other states or what the cost would be if it does.

4.4.3 Frost-Thaw Depth Prediction Models

- **Modified Model 158.** Of the several models evaluated for predicting frost and thaw depths, Modified Model 158 (outlined in Section 3.3.2) was found to be one of the most accurate; it generally performed very well in terms of tracking the onset of freezing and the onset of thawing and therefore could be useful in deciding when to apply WWPs and SLRs. This model was preferred over the degree-day class of models because it does not require site-specific calibration. However, to implement this model, some skill is required to set the model up in a spreadsheet and/or to write computer code to run the model.

- **EICM/vRWIS.** The EICM (outlined in Section 3.3.3) is theoretically the most robust method for estimating frost and thaw depths because it accounts for numerous factors that influence freeze-thaw processes, such as air temperature, precipitation, wind speed, percent sunshine, and relative humidity. However, the EICM results were somewhat of a surprise and disappointment to the authors of this report. In many cases, the results of the EICM predictions were not accurate and tended to estimate the onset of thawing after substantial thawing had actually occurred. Because that would lead to the SLR being applied late, and thus greatly increase the potential risk of pavement damage, the EICM is not highly recommended for use as an SLR timing tool at this point.
- **Overall Recommendation.** Overall, the frost-thaw depth prediction models did not provide any significant advantages over the degree-day threshold protocols (i.e., MnDOT and/or FrezTrax). Additionally, these more complex models require input data that are not always available. For example, at every location where a model prediction is desired, a soil boring and occasionally some minimal laboratory testing would generally be required to properly determine the thicknesses and material properties of the pavement subsurface layers. While some DOTs may have this information archived in construction records for many of their roadways, many DOTs do not have that information readily available.
- **GUI Availability and Cost.** There is currently no commercially available, simple-to-use graphical interface for Modified Model 158. Although the EICM can be run easily in hindcast mode using the AASHTOWare software, this software is not recommended for use in making SLR timing decisions in forecast mode. The vRWIS interface (owned by ARA) is a simple-to-use GUI for the EICM. At the time this project was conducted, the annual software usage fee for the vRWIS interface was $2,500 per site. If a state DOT wanted information at multiple sites across the state, it is possible that ARA might negotiate a less expensive rate per site.

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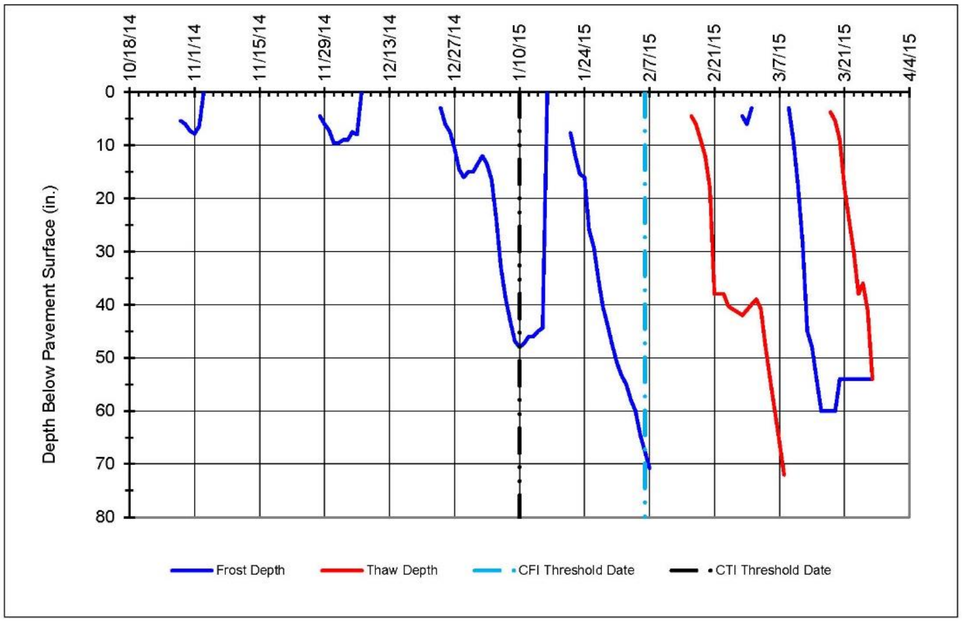
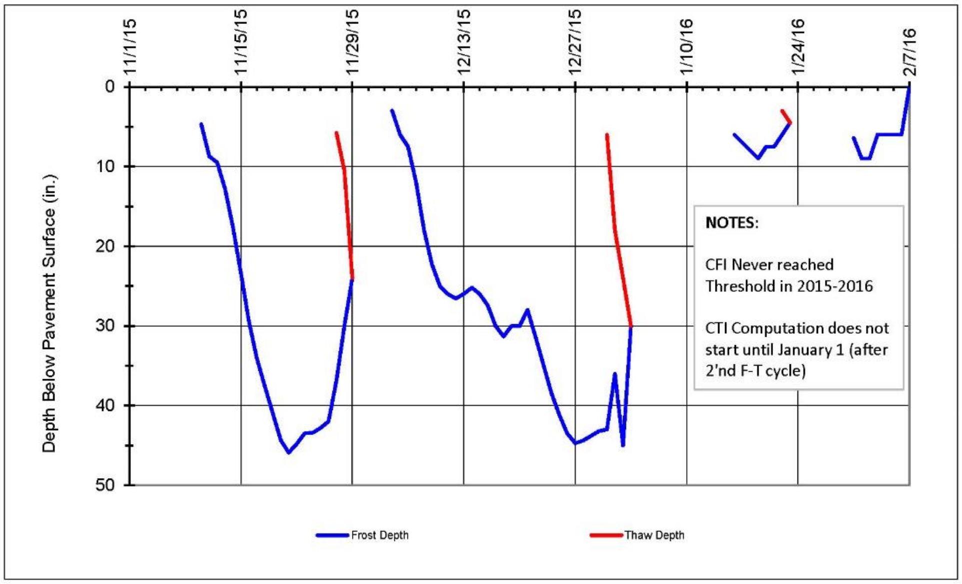
APPENDIX A. SLR POSTING BASED ON DEGREE-DAY THRESHOLD MODELS: MINNESOTA DEPARTMENT OF TRANSPORTATION (MNDOT 2009)

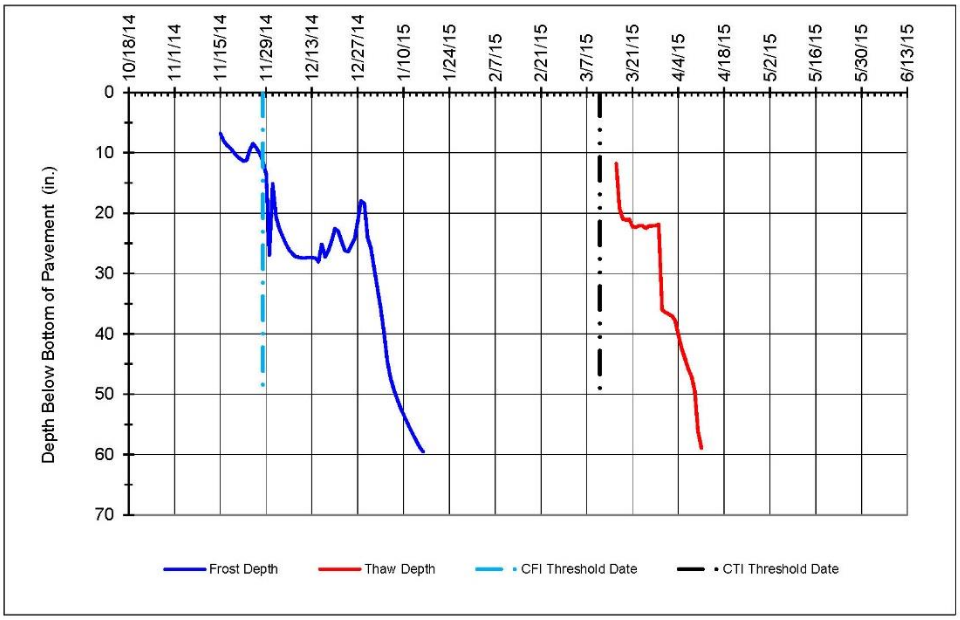
2014-2015_Interpolated Frost-Thaw Depths_AK



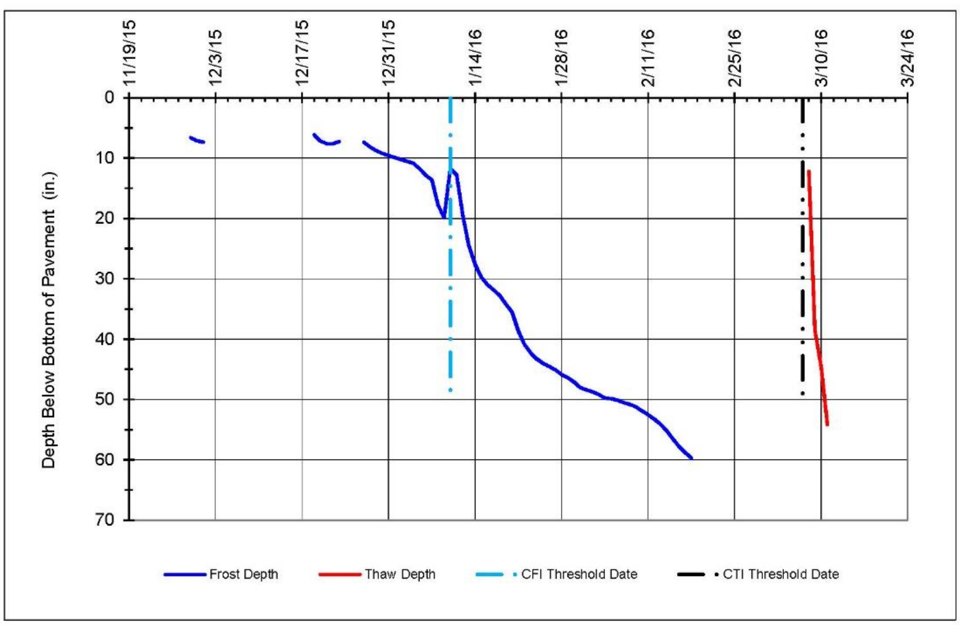
2015-2016_Interpolated Frost-Thaw Depths_AK



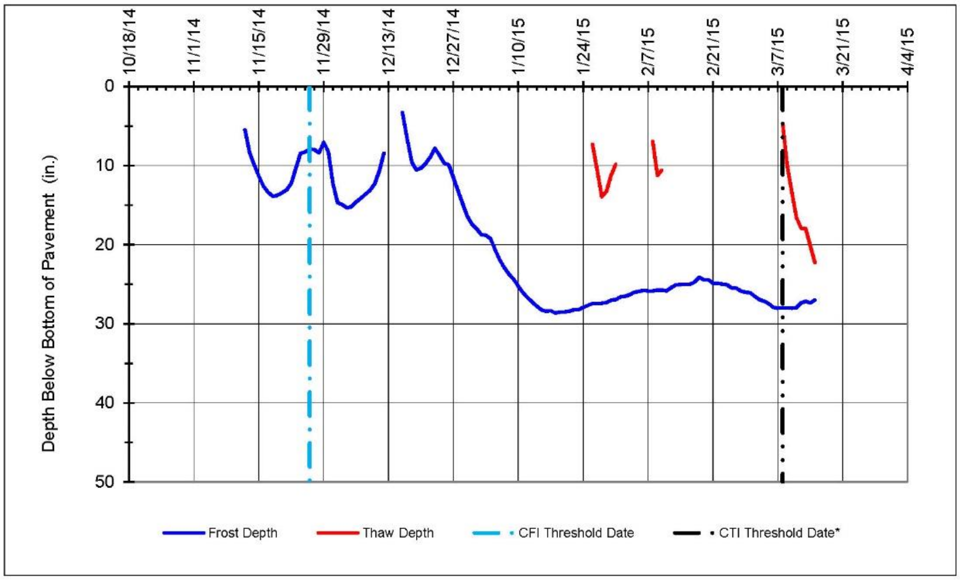
2014-2015_Interpolated Frost-Thaw Depths_MI.xls



2015-2016_Interpolated Frost-Thaw Depths_MI.xls

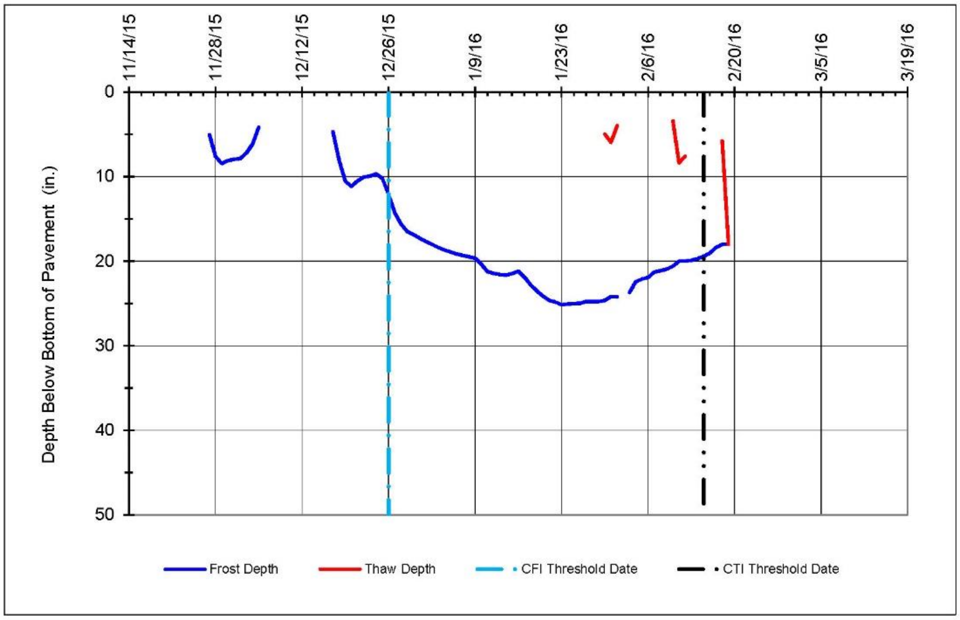


2014-2015_ND_Interpolated Frost-Thaw Depths.xls



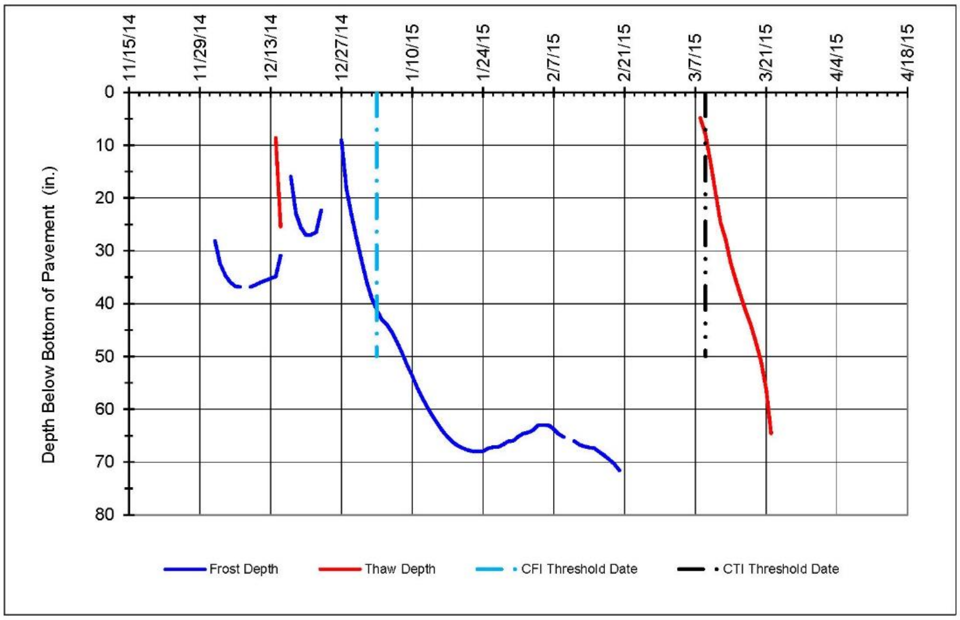
*NOTE: CTI Exceeded Threshold on 1/25/15 and 2/7/15

2015-2016_Interpolated Frost-Thaw Depths_ND.xls

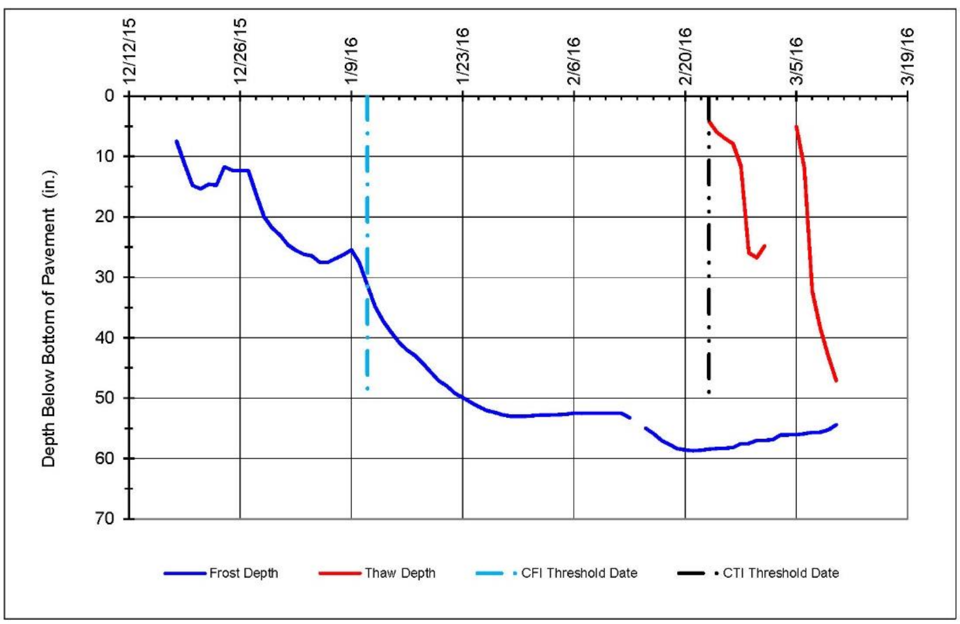


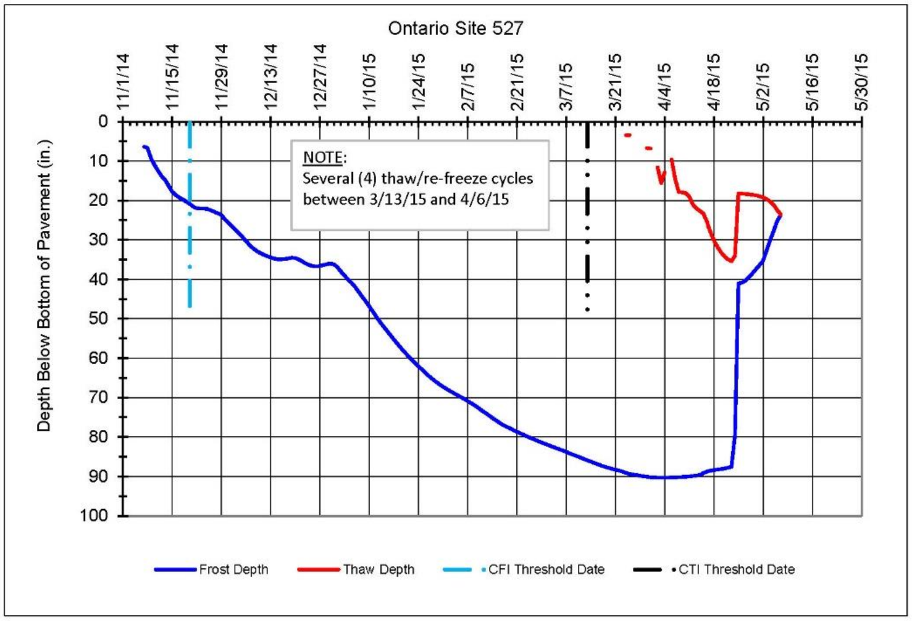
*NOTE: CTI Exceeded Threshold on 2/10/16 and then dropped back down

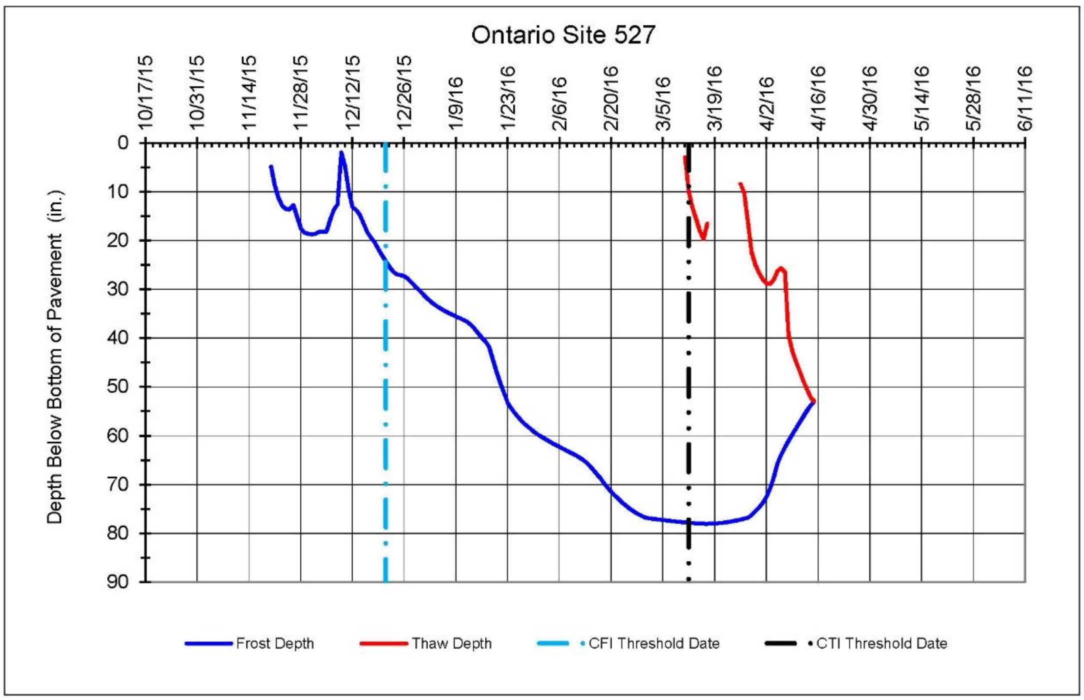
2014-2015_Interpolated Frost-Thaw Depths_WI.xls



2015-2016_Interpolated Frost-Thaw Depths_WI.xls

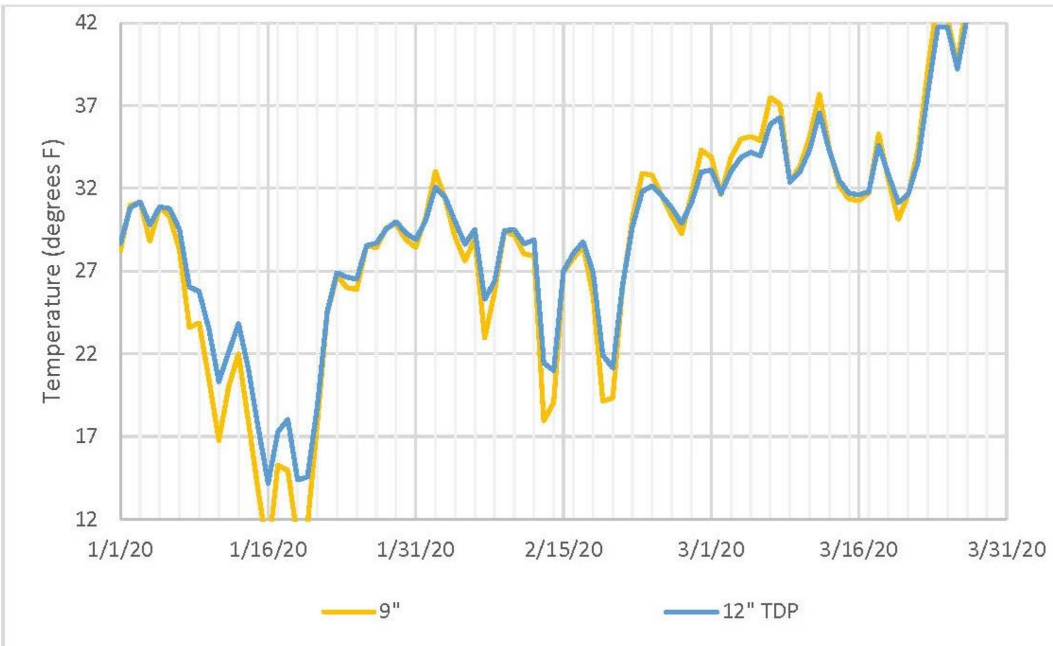


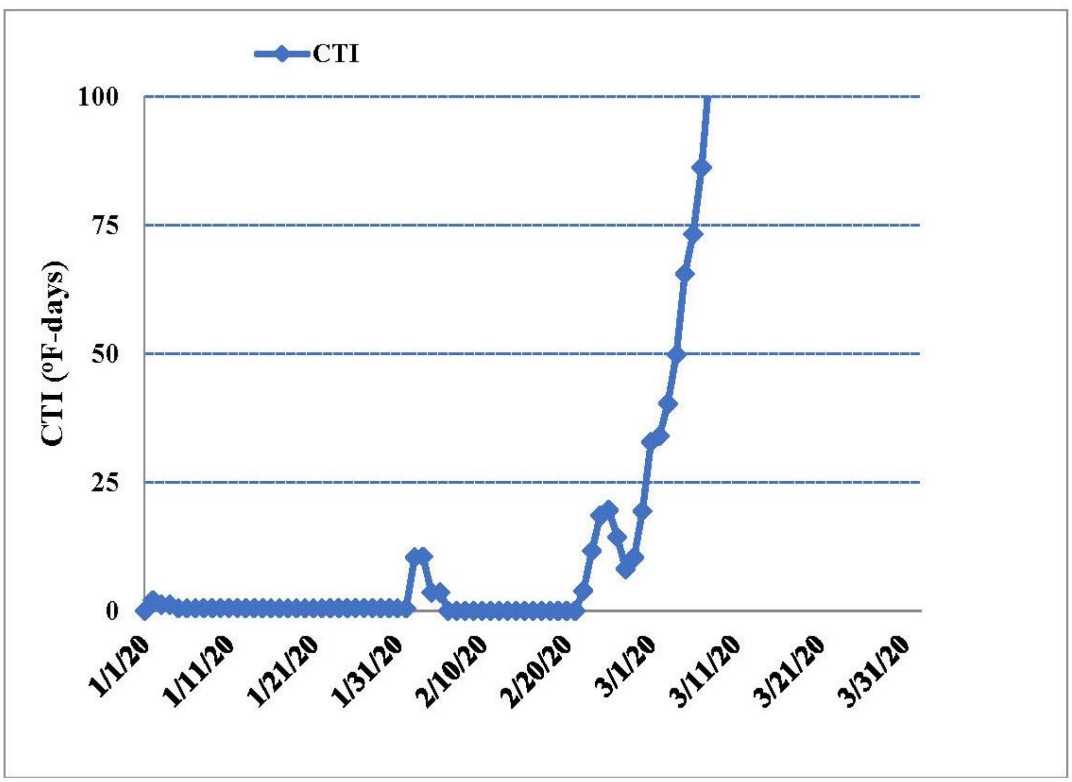

Ontario Site 527
11/1/14
11/15/14
11/29/14
12/13/14
12/27/14
1/10/15
1/24/15
2/7/15
2/21/15
3/7/15
3/21/15
4/4/15
4/18/15
5/2/15
5/16/15
5/30/15
Depth Below Bottom of Pavement (in.)
0
10
20
30
40
50
60
70
80
90
100
NOTE:
Several (4) thaw/re-freeze cycles between 3/13/15 and 4/6/15
Frost Depth
Thaw Depth
CFI Threshold Date
CTI Threshold Date


Ontario Site 527
10/17/15
10/31/15
11/14/15
11/28/15
12/12/15
12/26/15
1/9/16
1/23/16
2/6/16
2/20/16
3/5/16
3/19/16
4/2/16
4/16/16
4/30/16
5/14/16
5/28/16
6/11/16
Depth Below Bottom of Pavement (in.)
0
10
20
30
40
50
60
70
80
90
Frost Depth
Thaw Depth
CFI Threshold Date
CTI Threshold Date

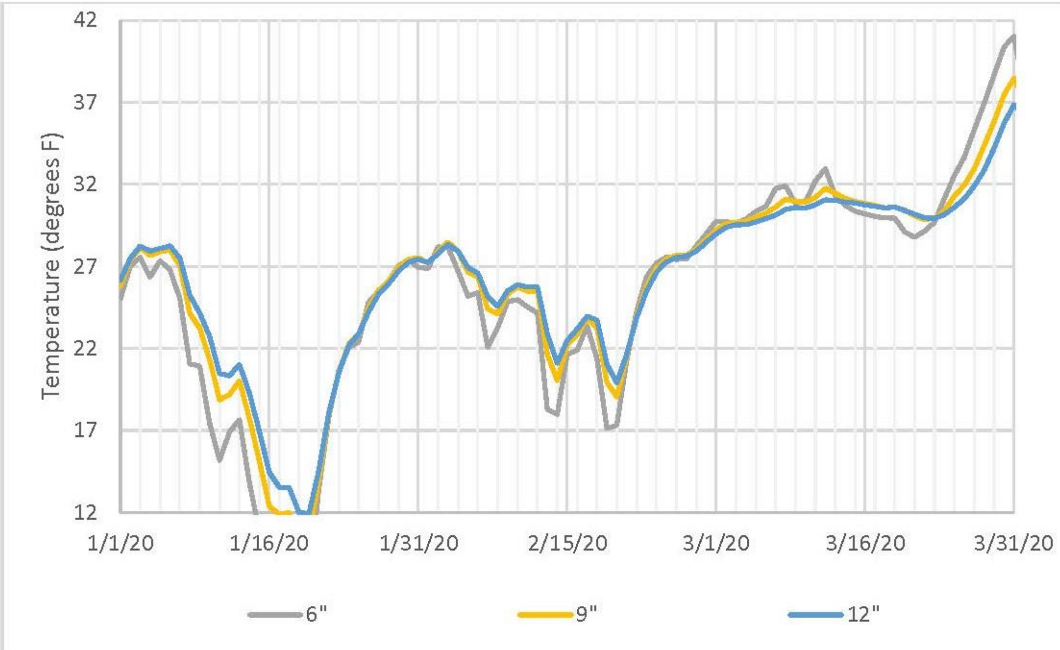
APPENDIX B. SLR POSTING BASED ON DEGREE-DAY THRESHOLD MODELS: MINNESOTA DEPARTMENT OF TRANSPORTATION (MNDOT 2009) PROTOCOL, 2020 ANALYSIS USING GRAPHICAL USER INTERFACE CONSTRUCTED BY THE NORTHEAST REGIONAL CLIMATE CENTER

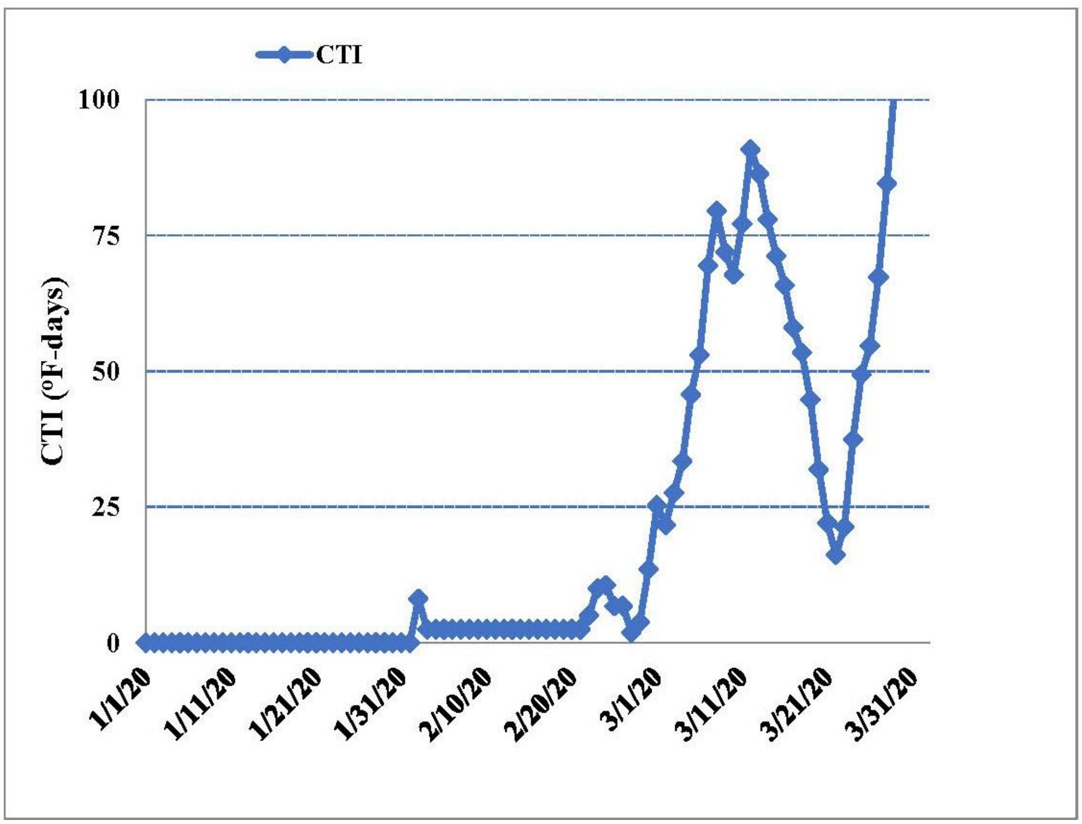
Bismark, ND



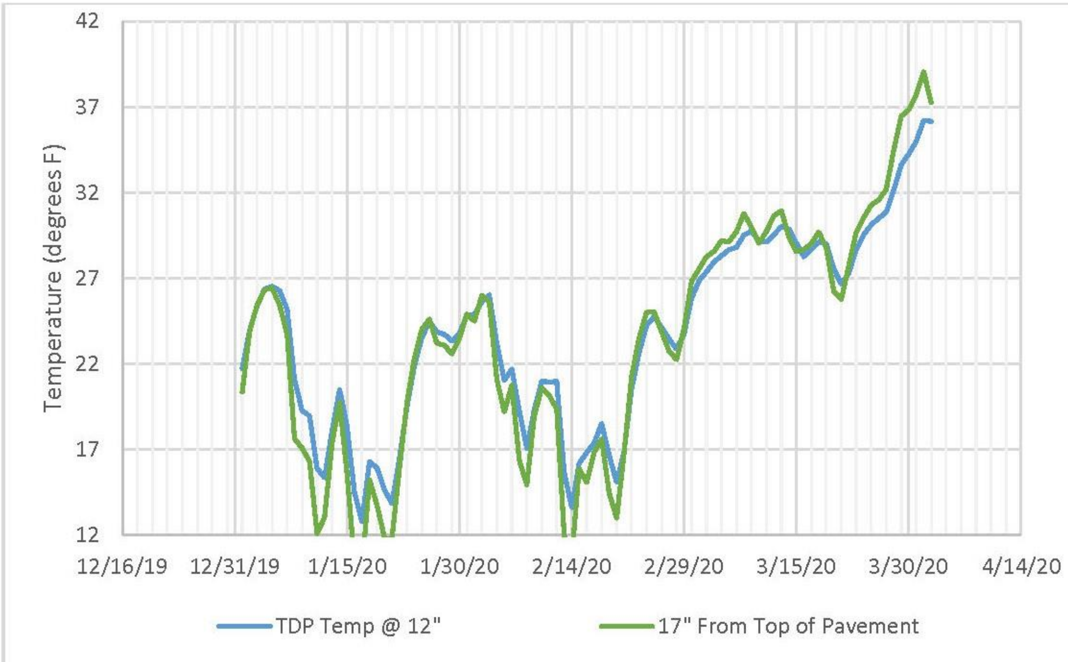


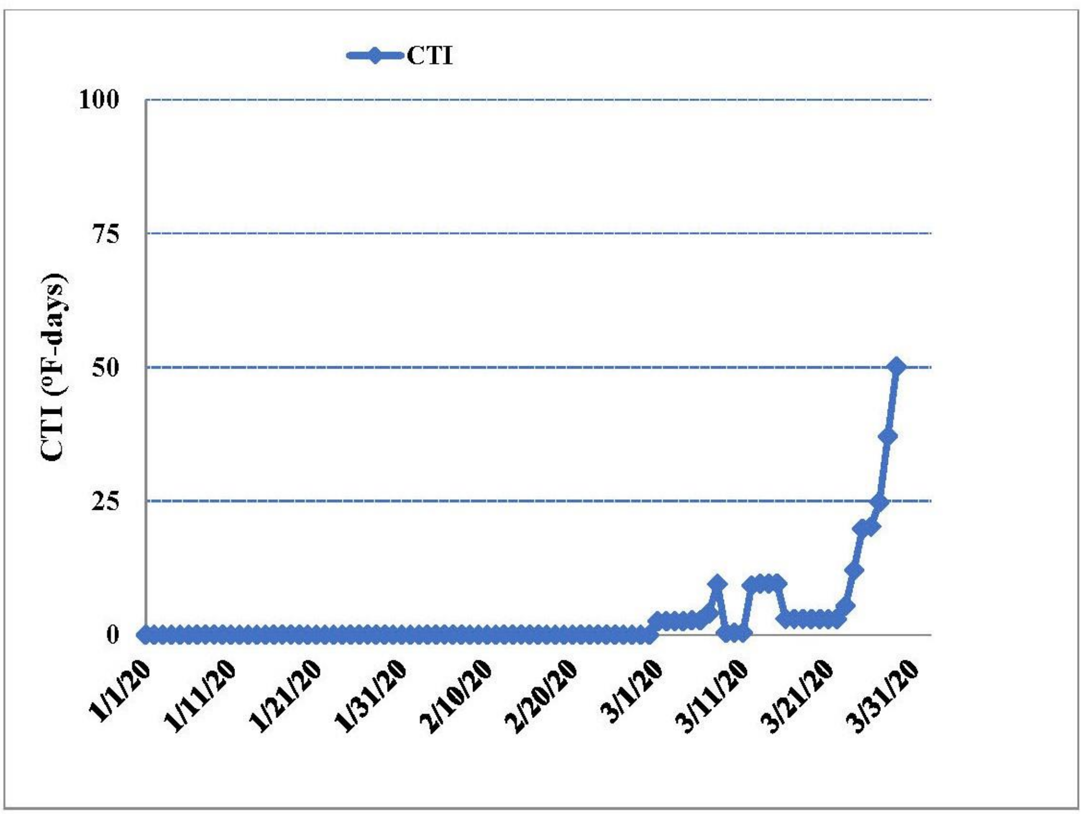
Blaisdell, ND



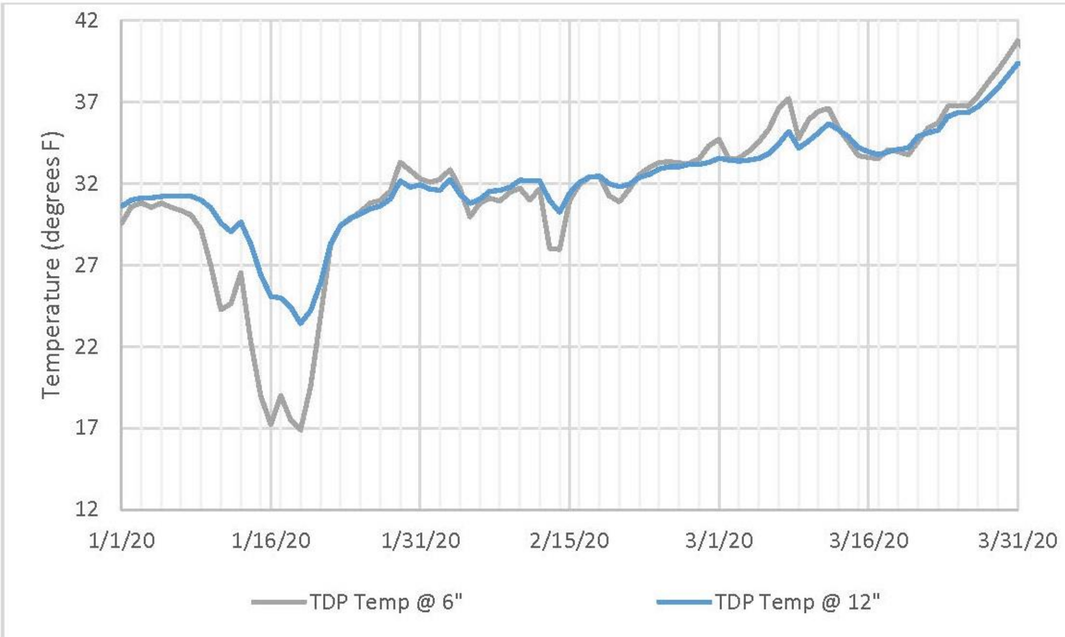


Bowesmont, ND

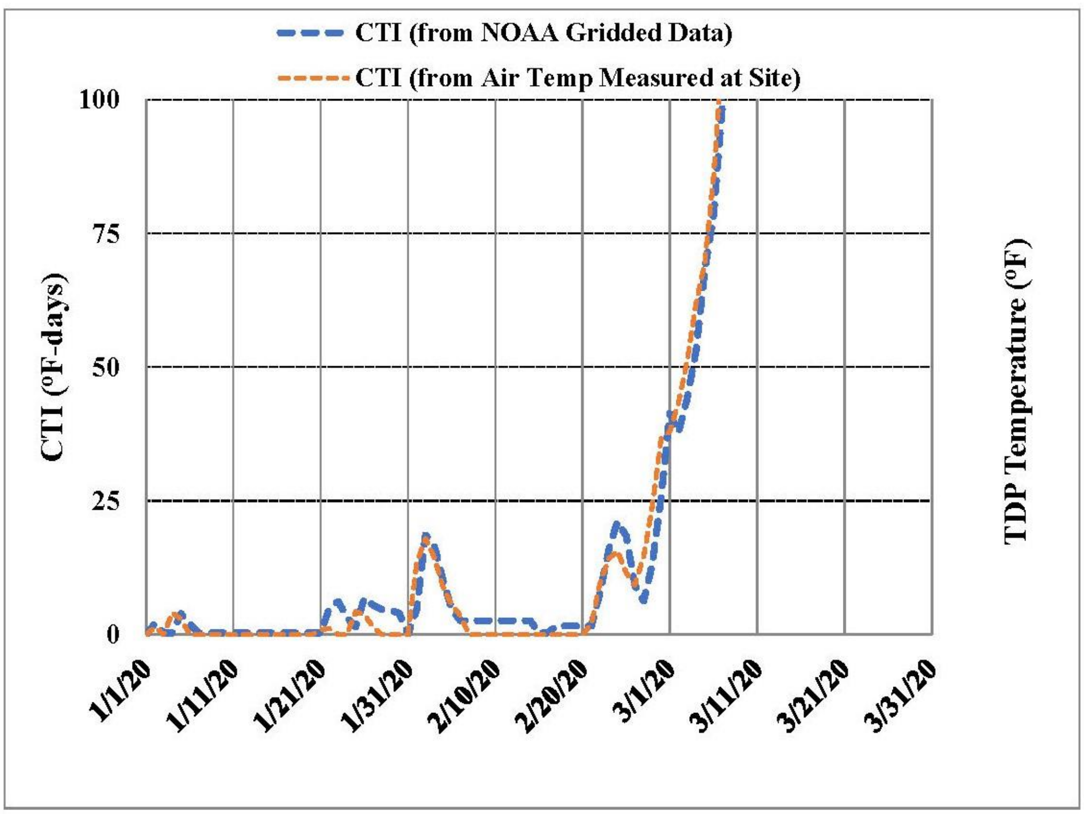




Bowman, ND

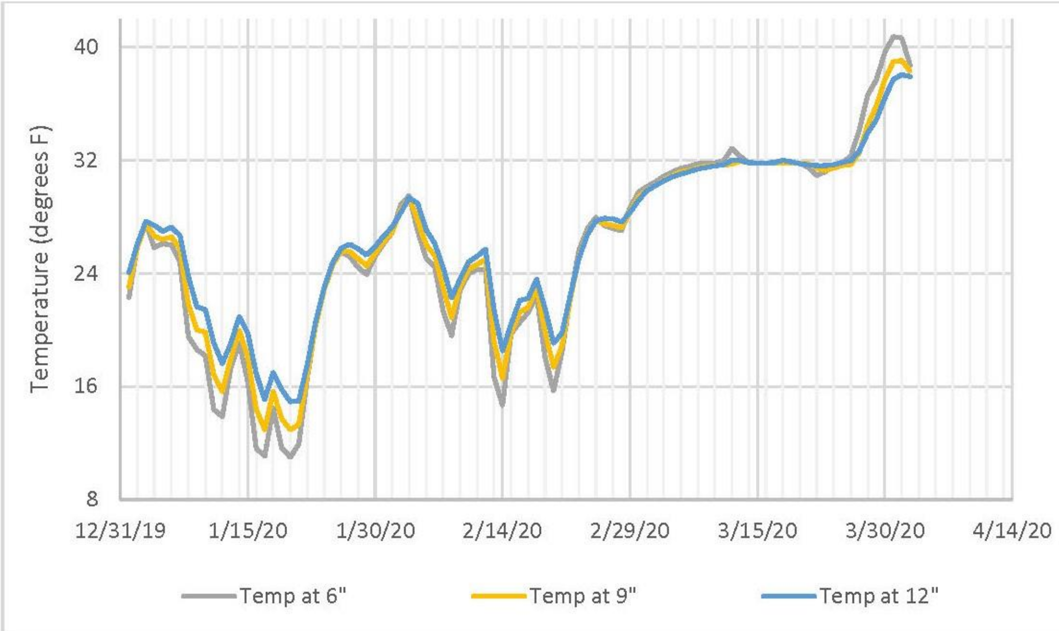


Temperature (degrees F)
42
37
32
27
22
17
12
1/1/20
1/16/20
1/31/20
2/15/20
3/1/20
3/16/20
3/31/20
TDP Temp @ 6"
TDP Temp @ 12"

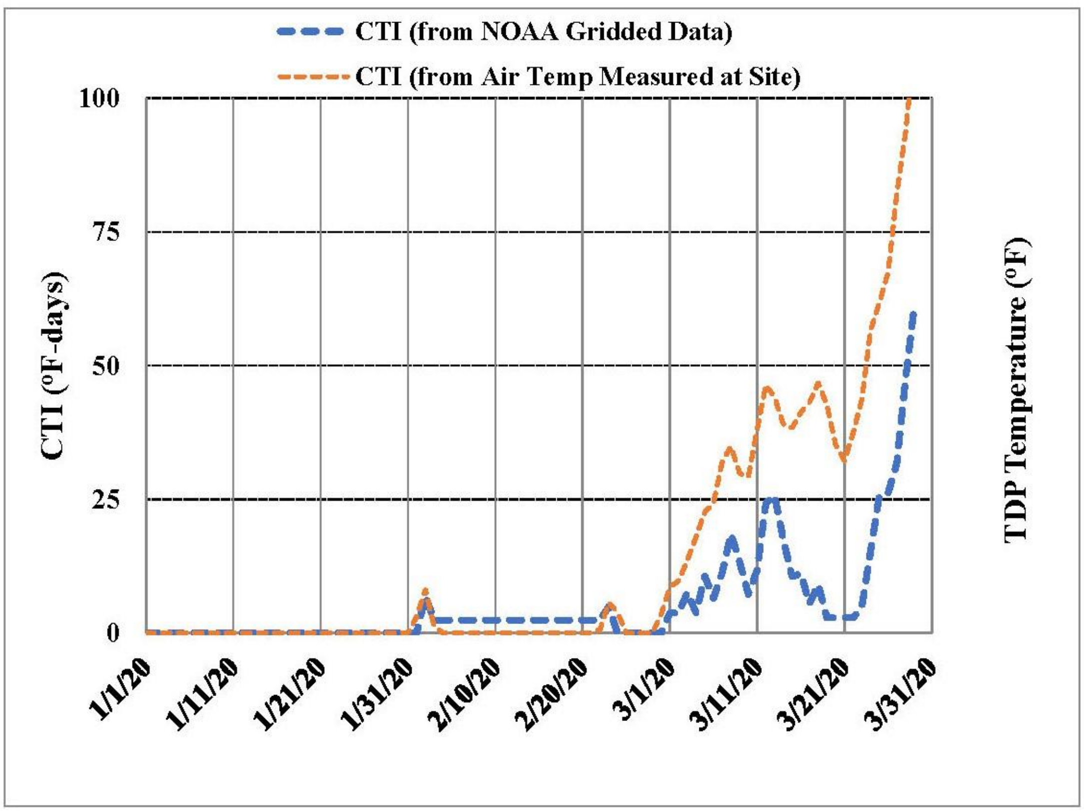


CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
TDP Temperature (ºF)
100
75
50
25
0
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Buffalo, ND

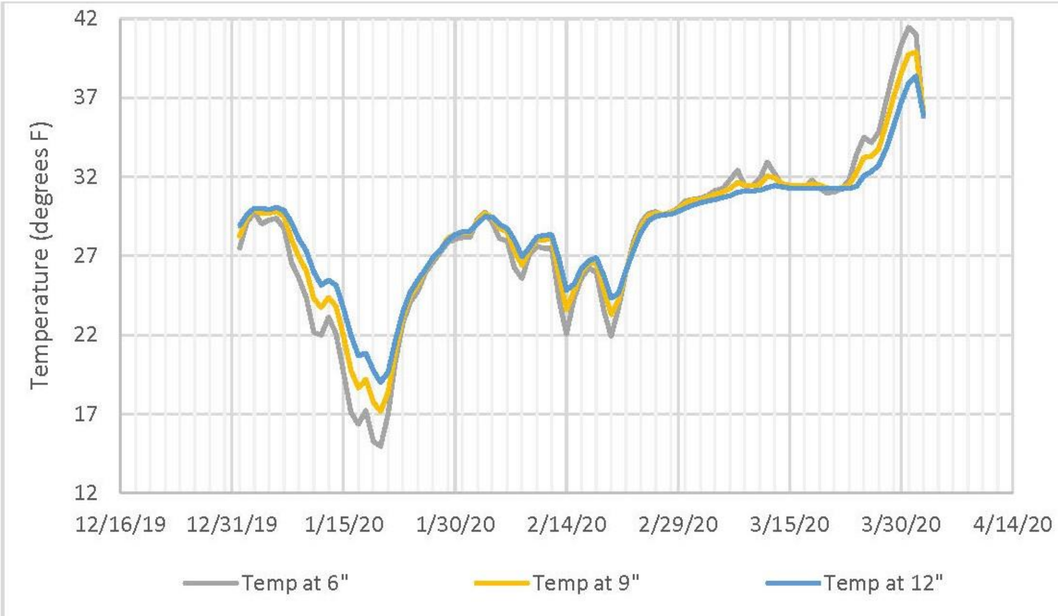


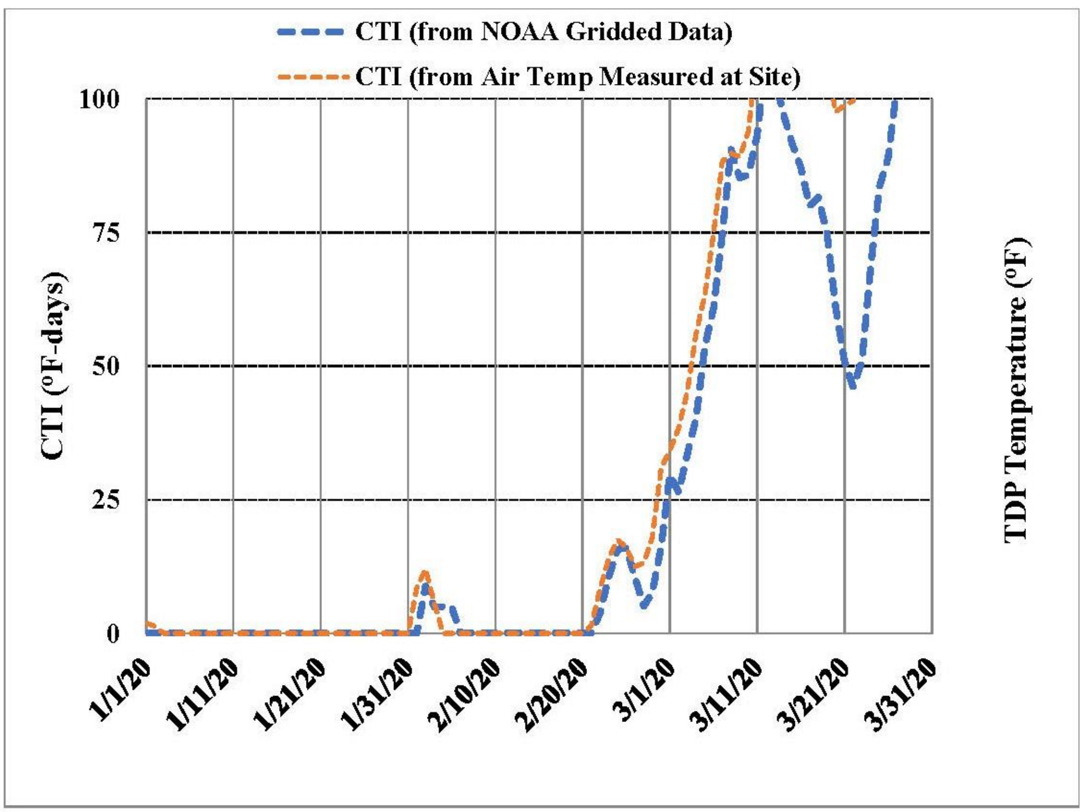
Temperature (degrees F)
40
32
24
16
8
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"



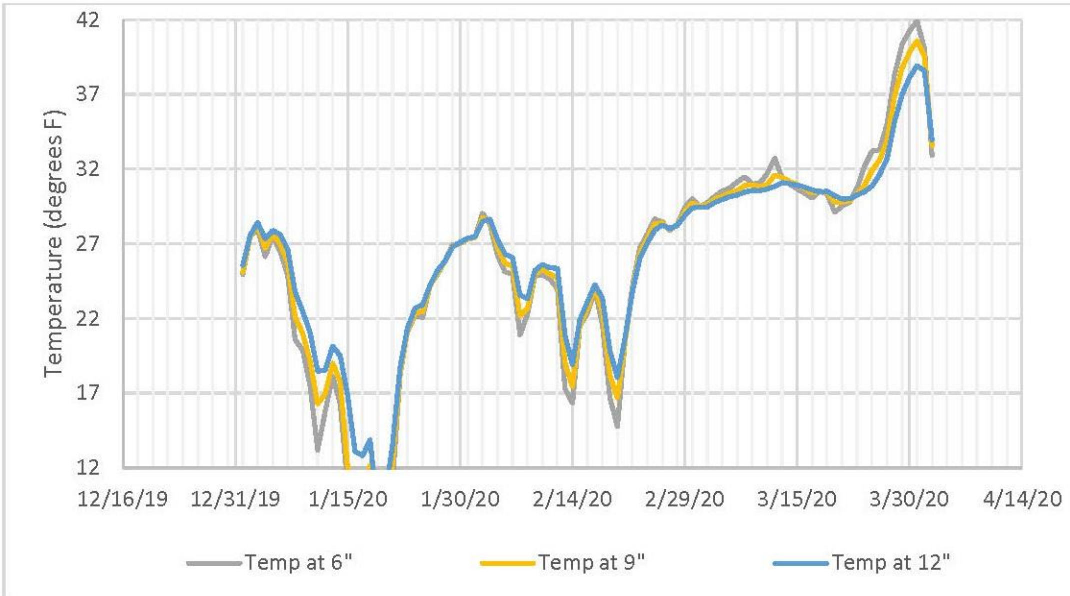
CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
TDP Temperature (ºF)
100
75
50
25
0
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Coleharbor, ND

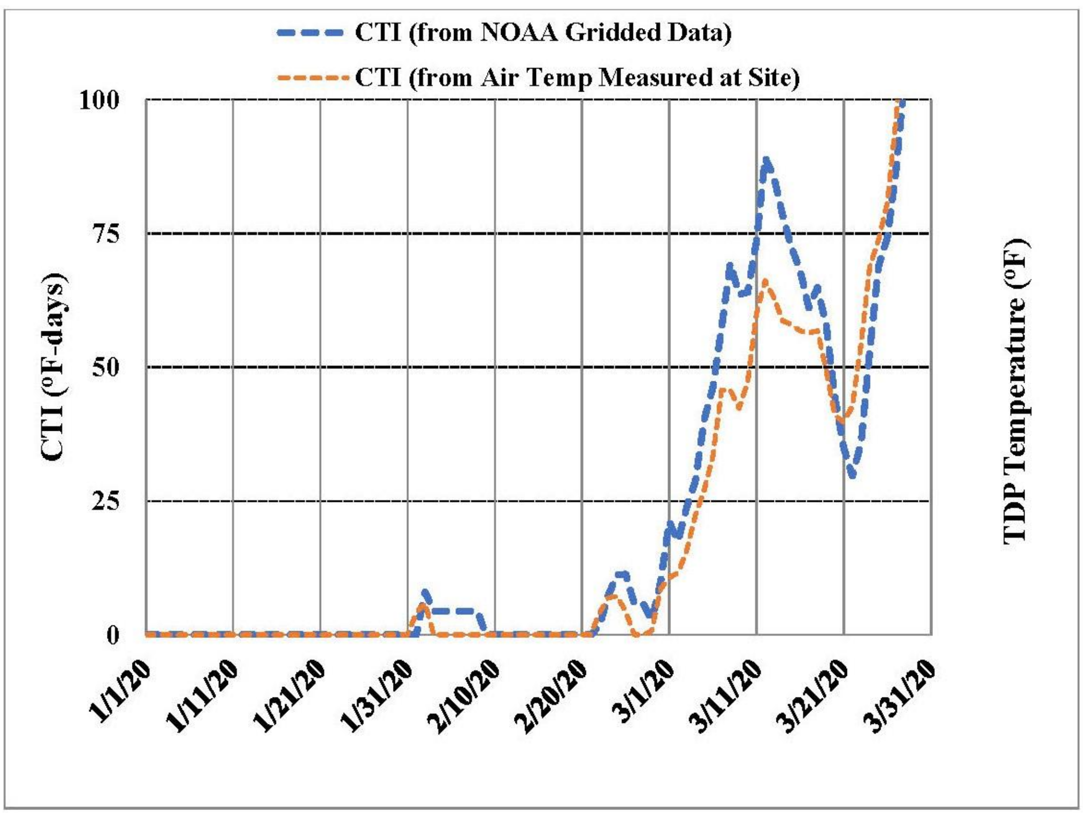




Denhoff, ND

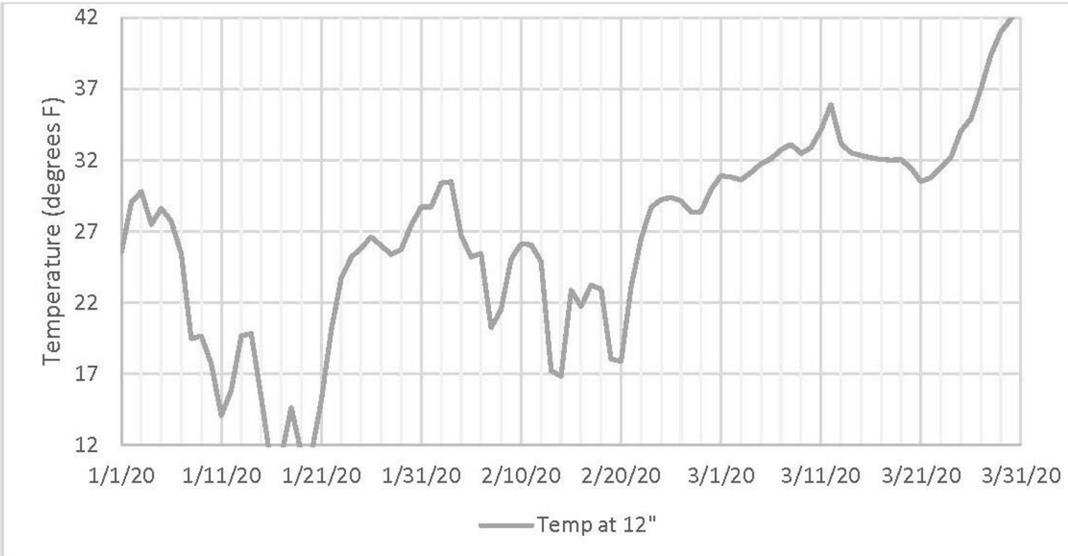


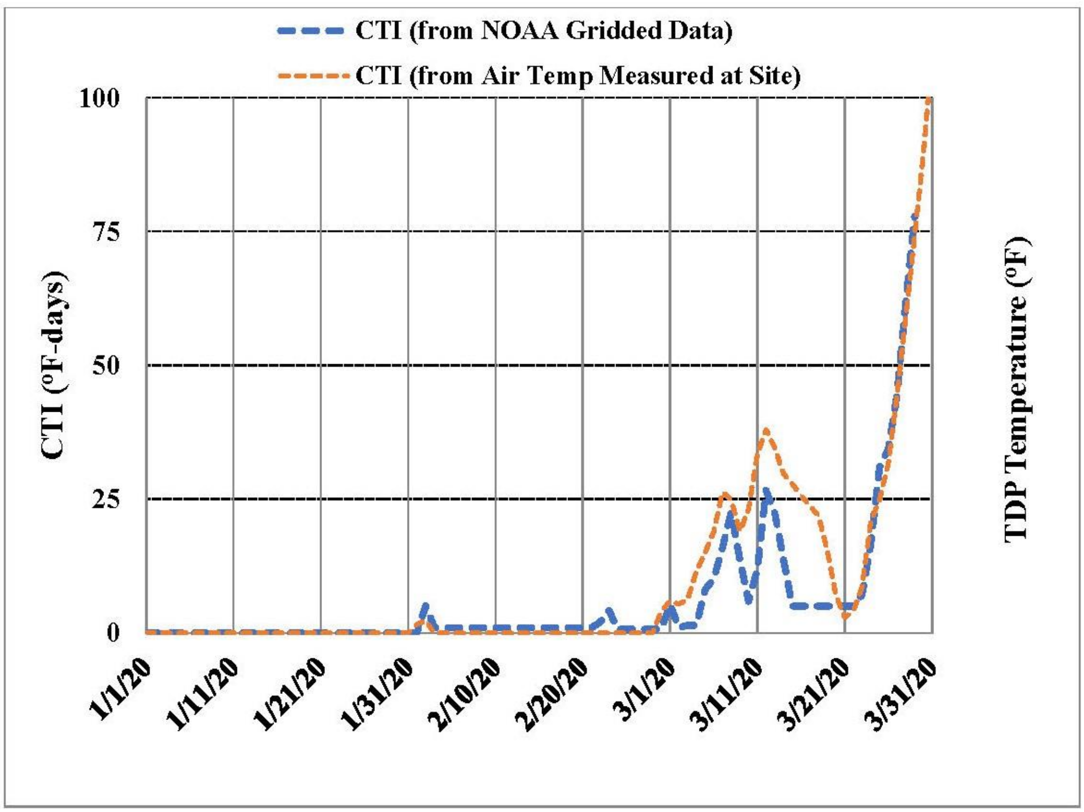
Temperature (degrees F)
42
37
32
27
22
17
12
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"



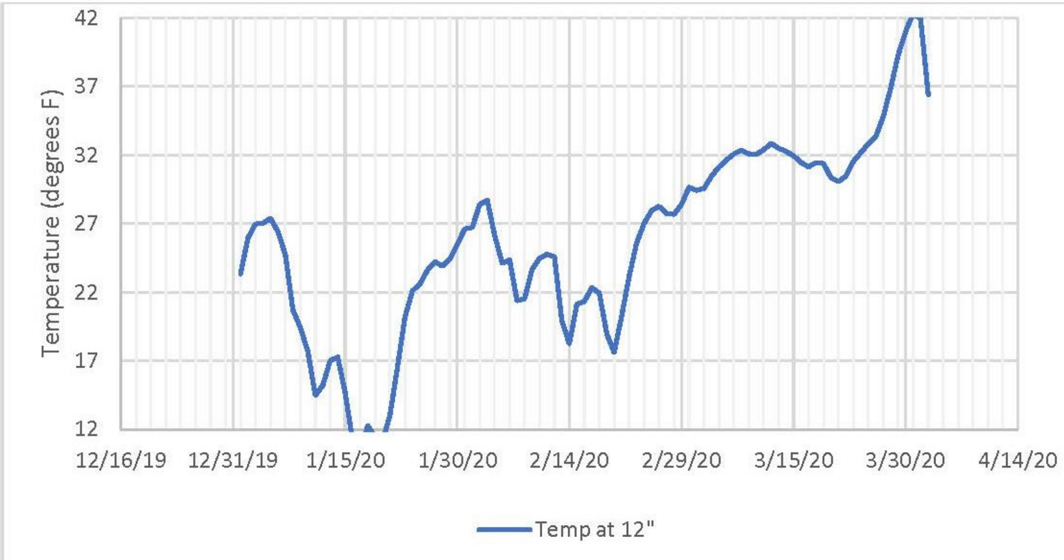
CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
100
75
50
25
0
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Devils Lake, ND

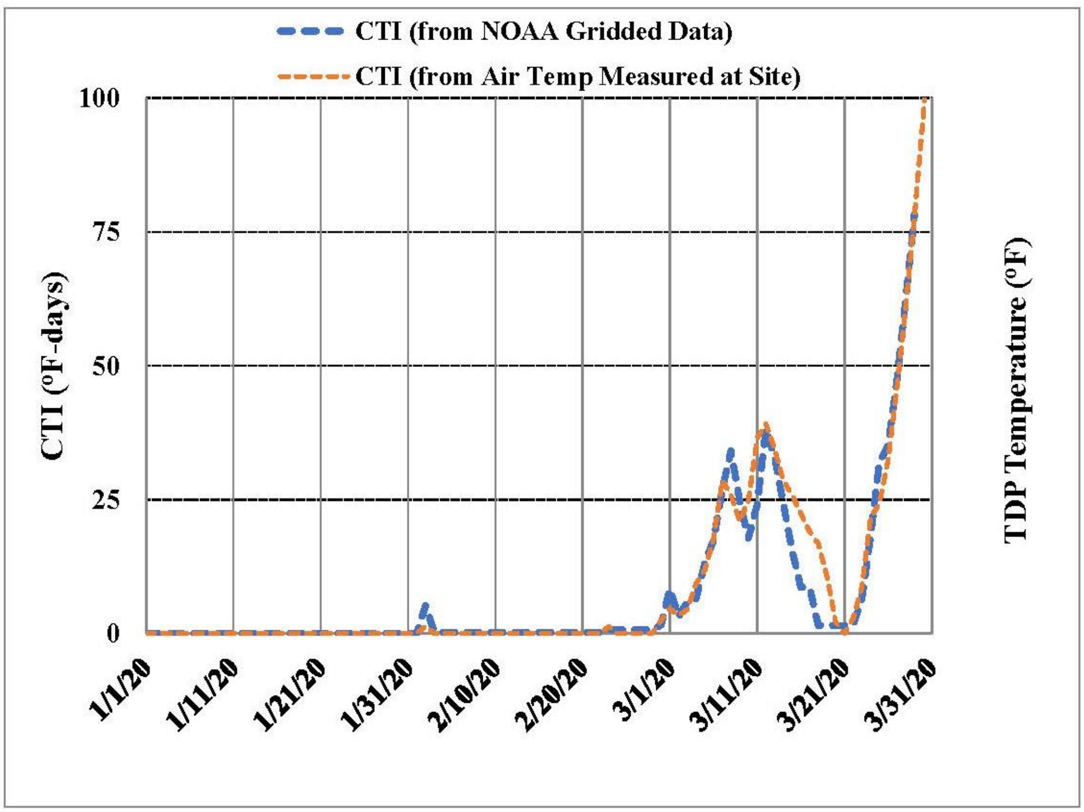




Dunseith, ND

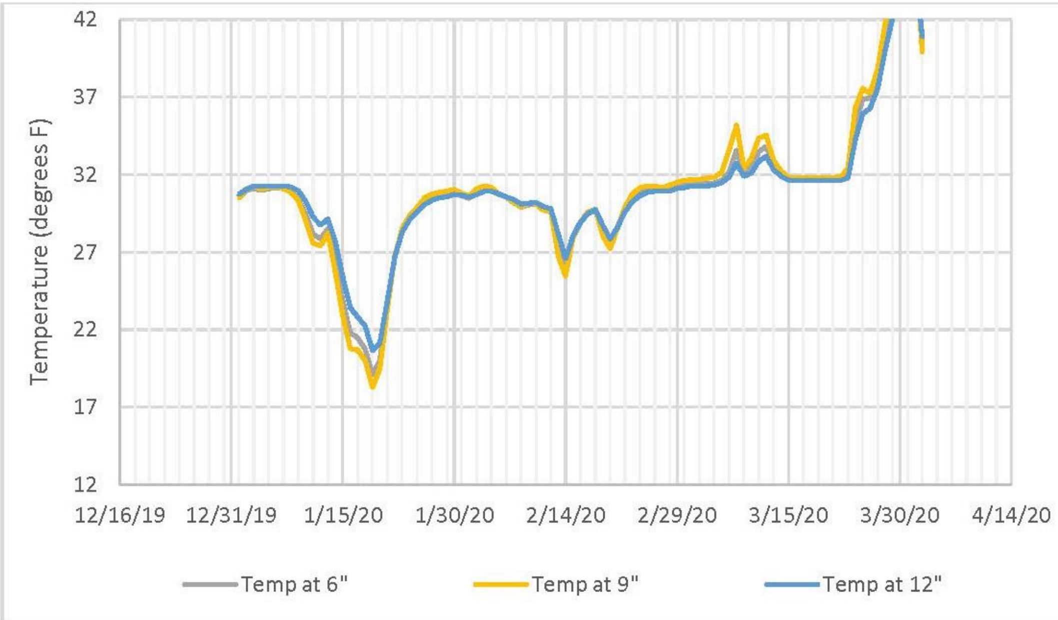


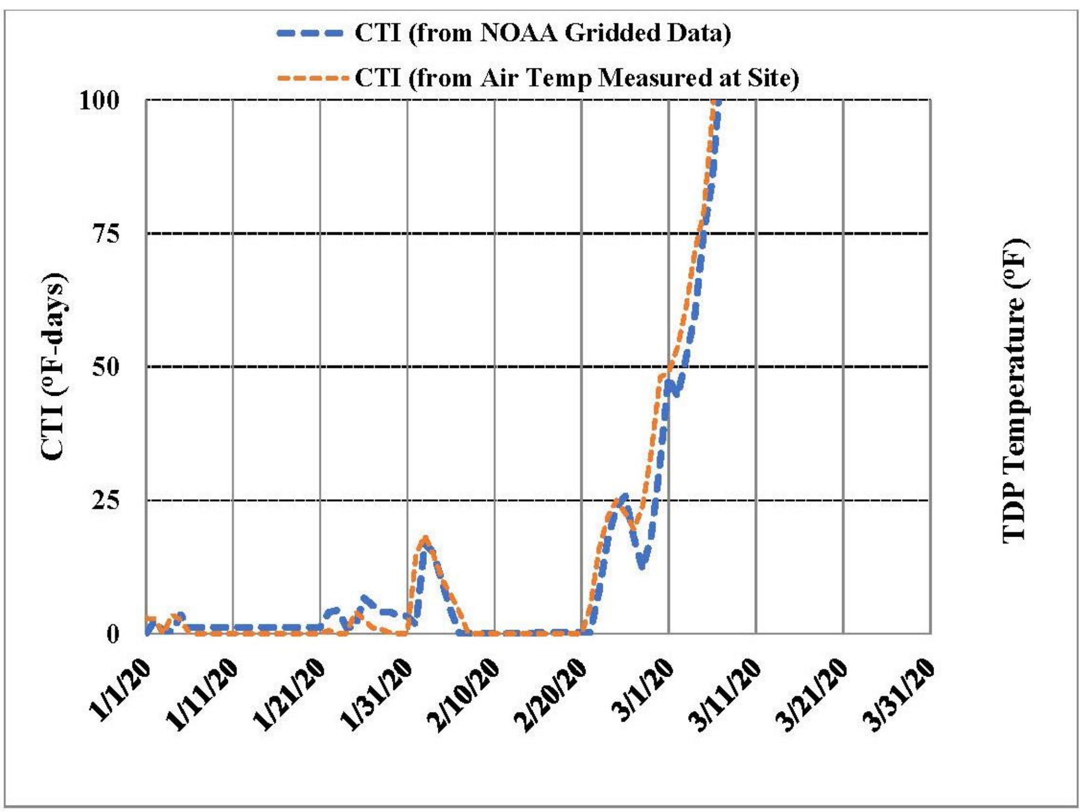
Temperature (degrees F)
42
37
32
27
22
17
12
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 12"



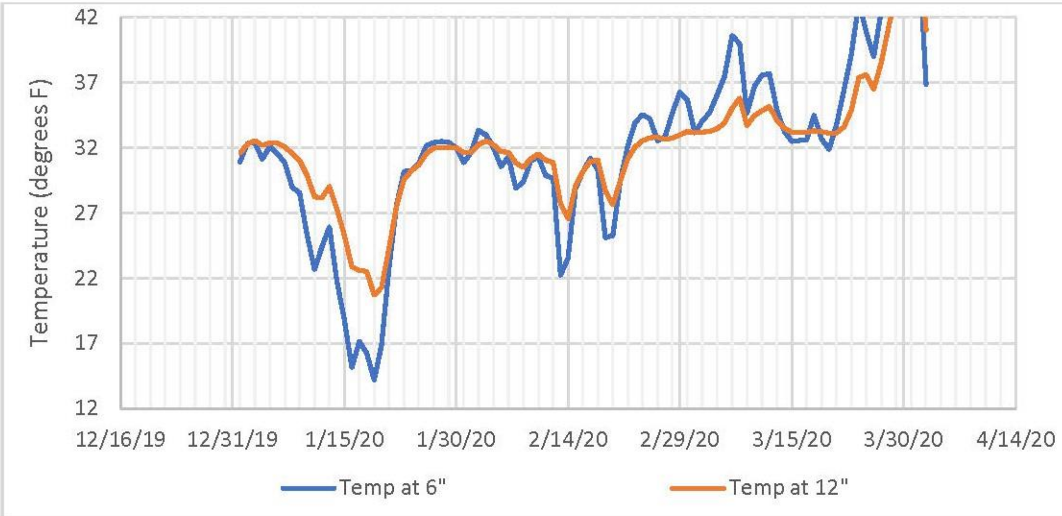
CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
100
75
50
25
0
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

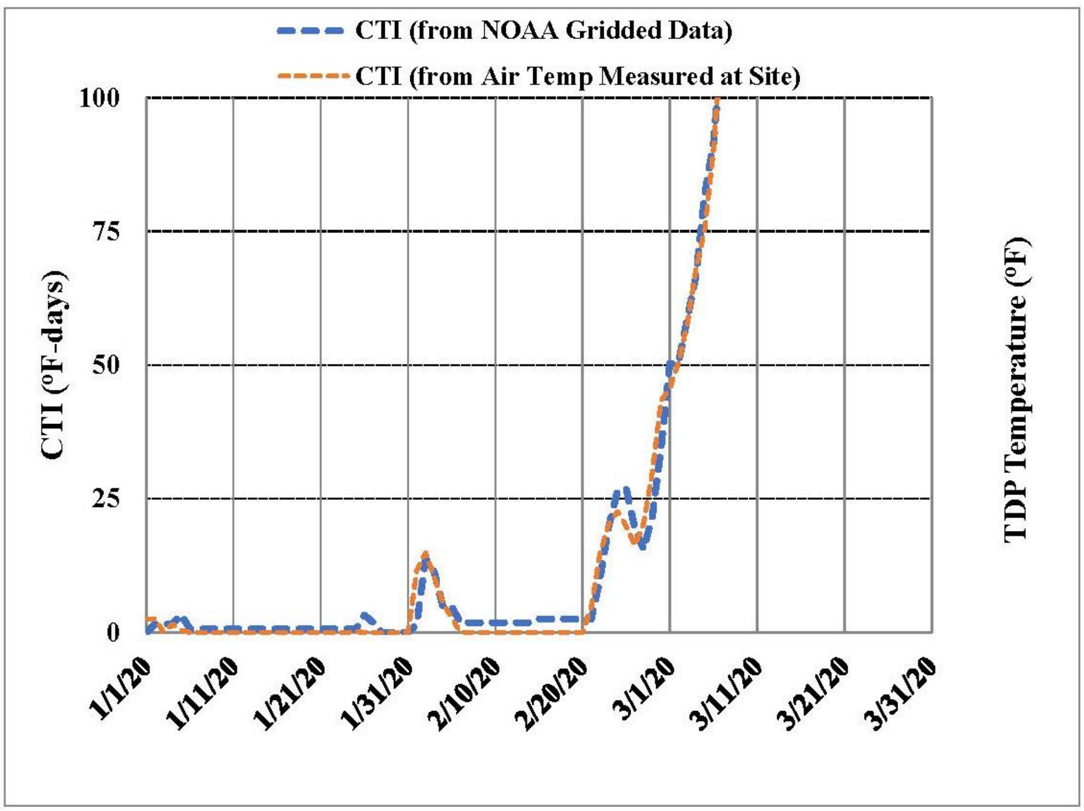
Fryburg, ND


42
37
32
27
22
17
12
Temperature (degrees F)
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"

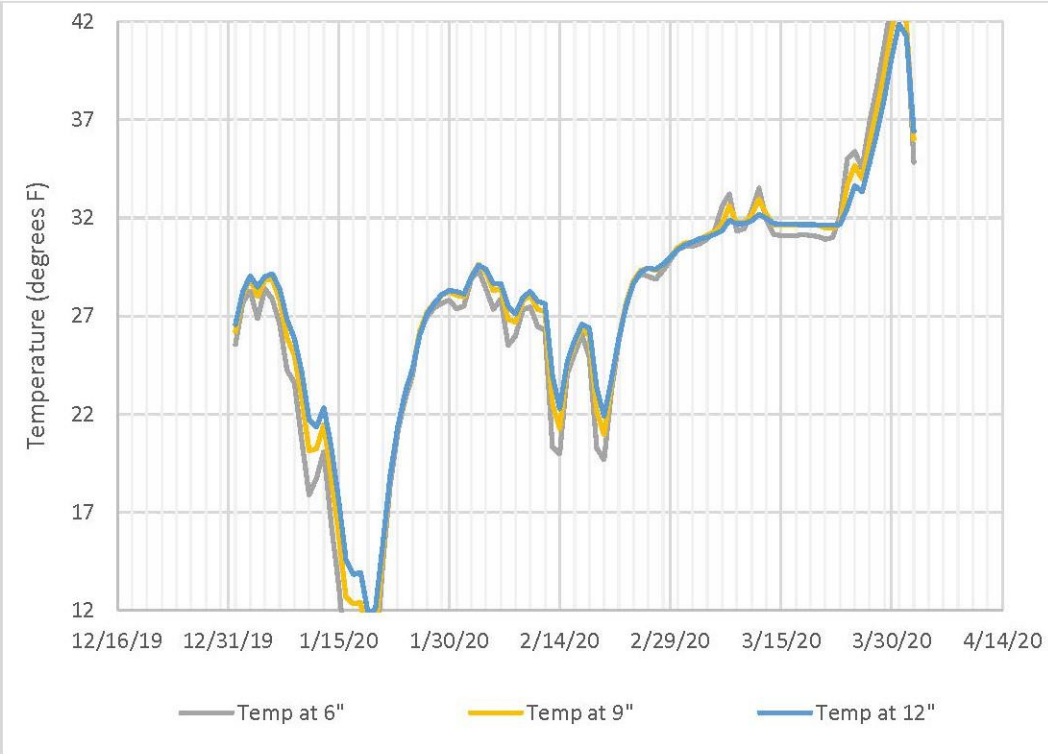

CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
100
75
50
25
0
CTI (ºF-days)
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

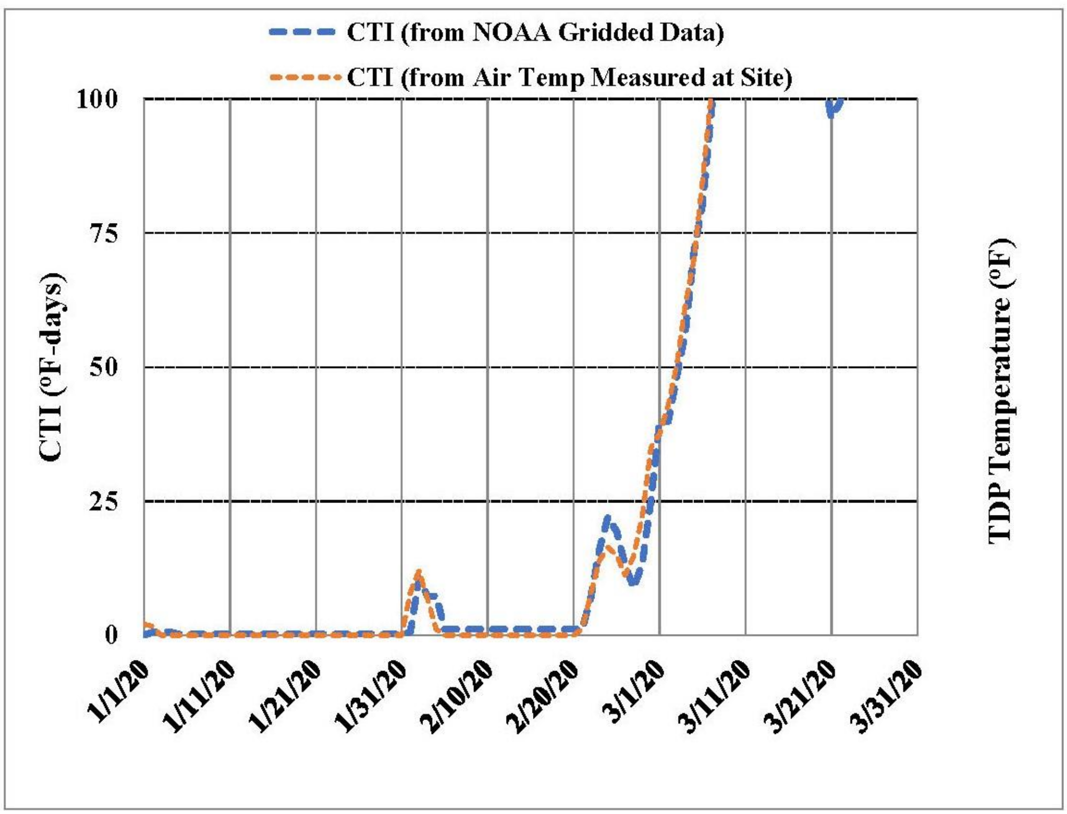
Gladstone, ND



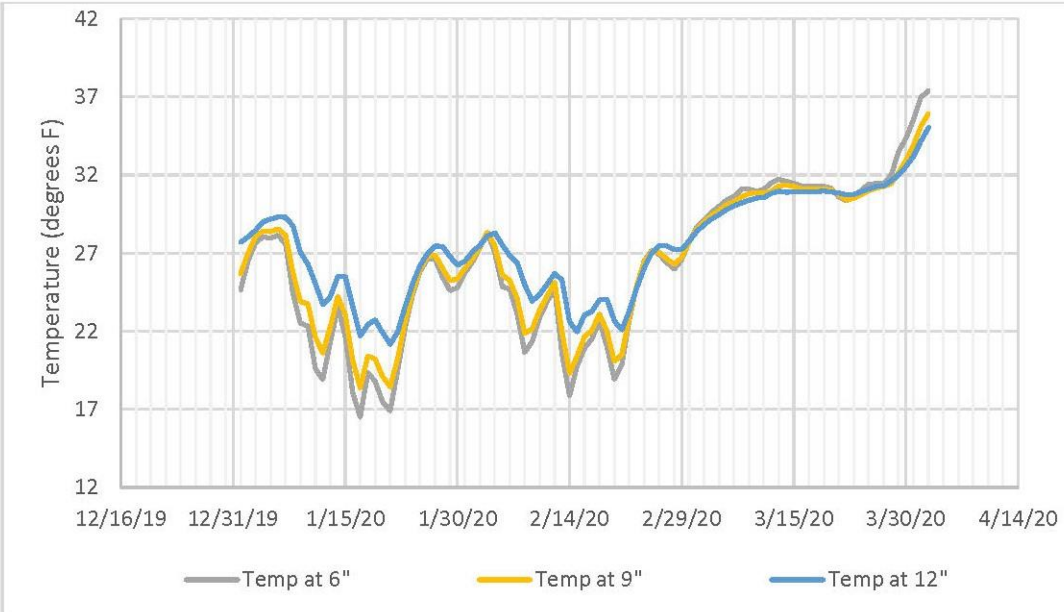


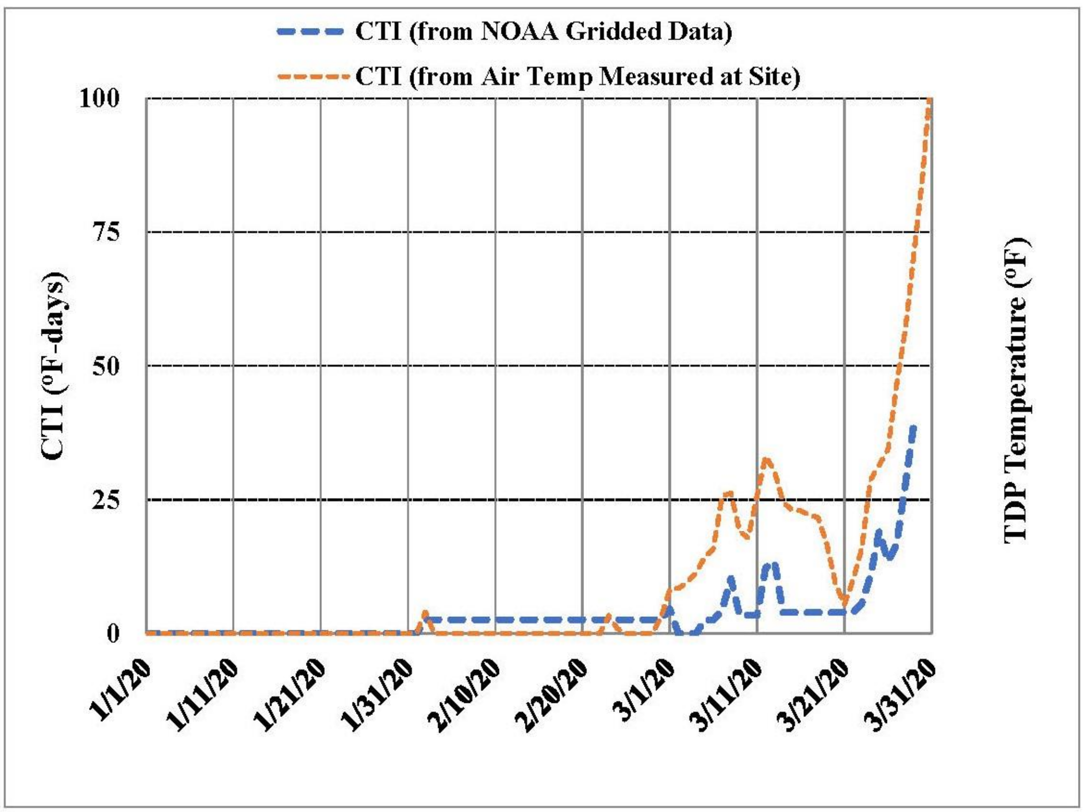
Golden Valley



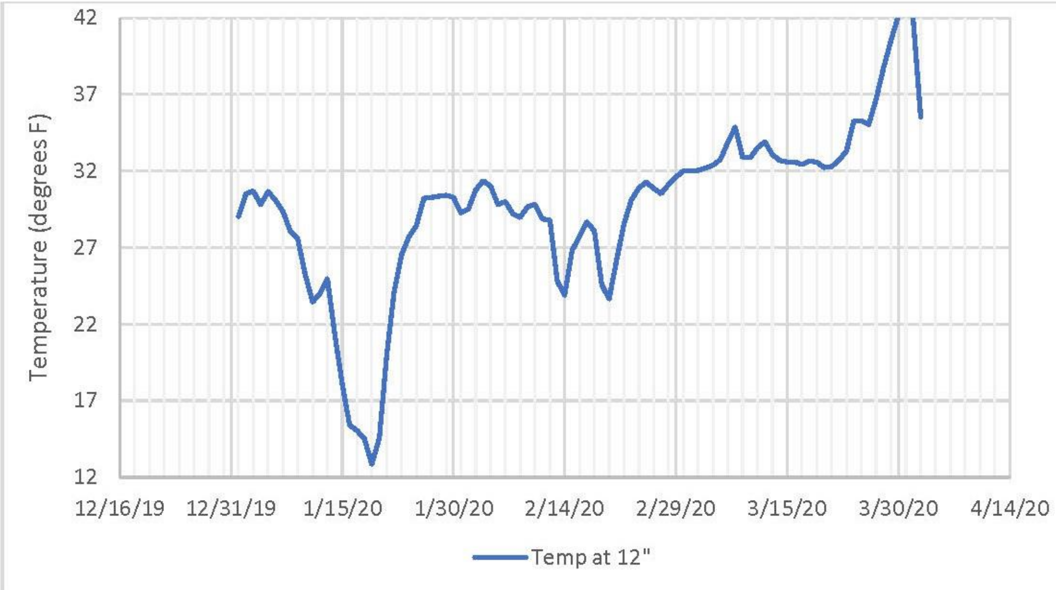


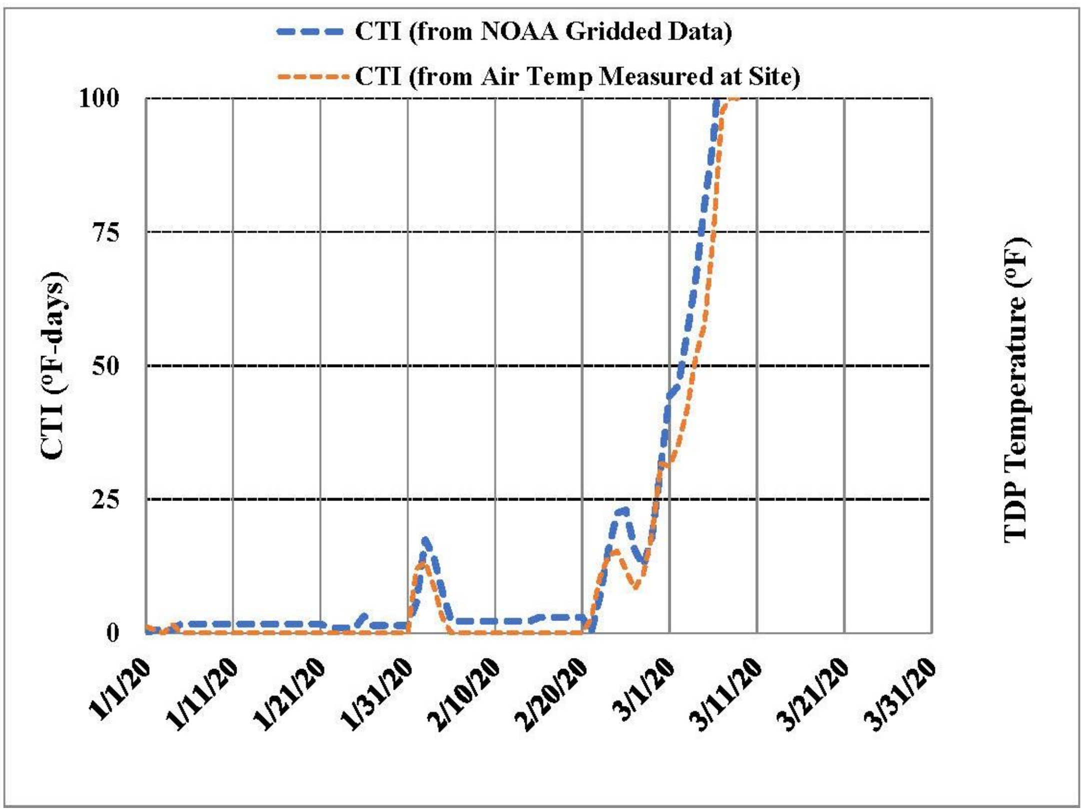
Grand Forks, ND



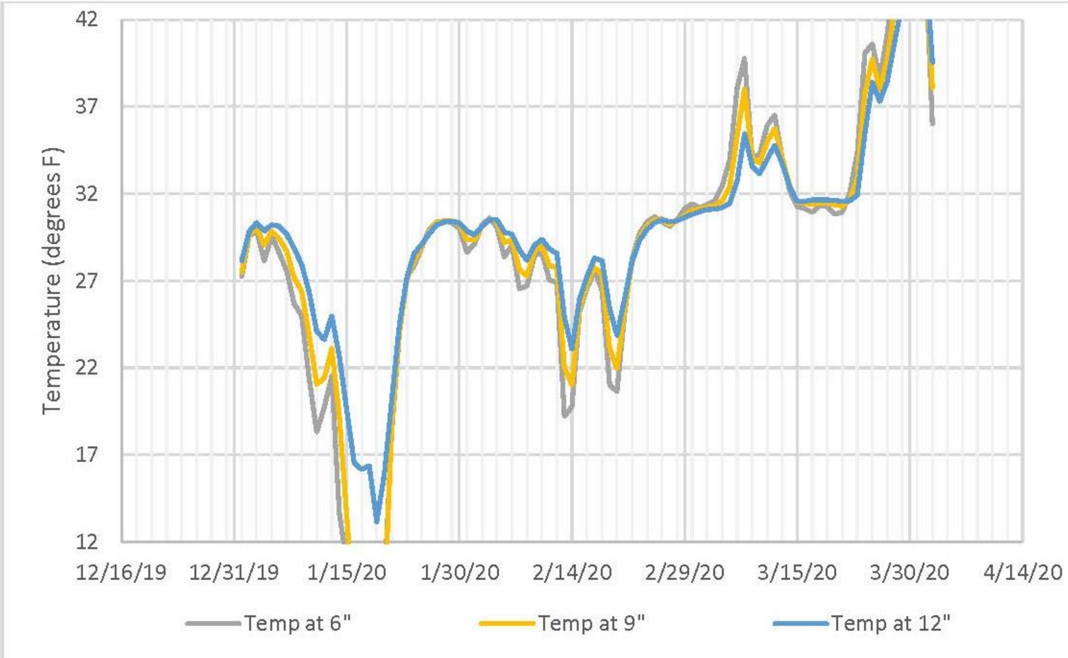


Grassy Butte, ND

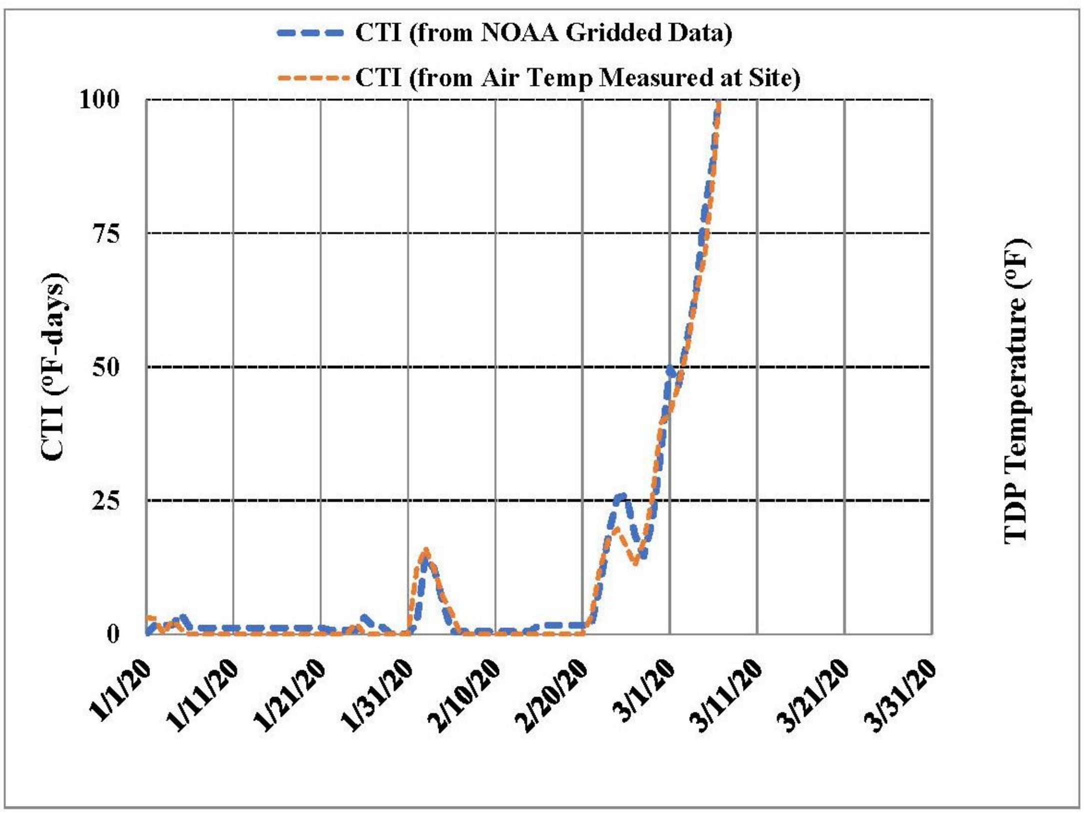




Manning, ND

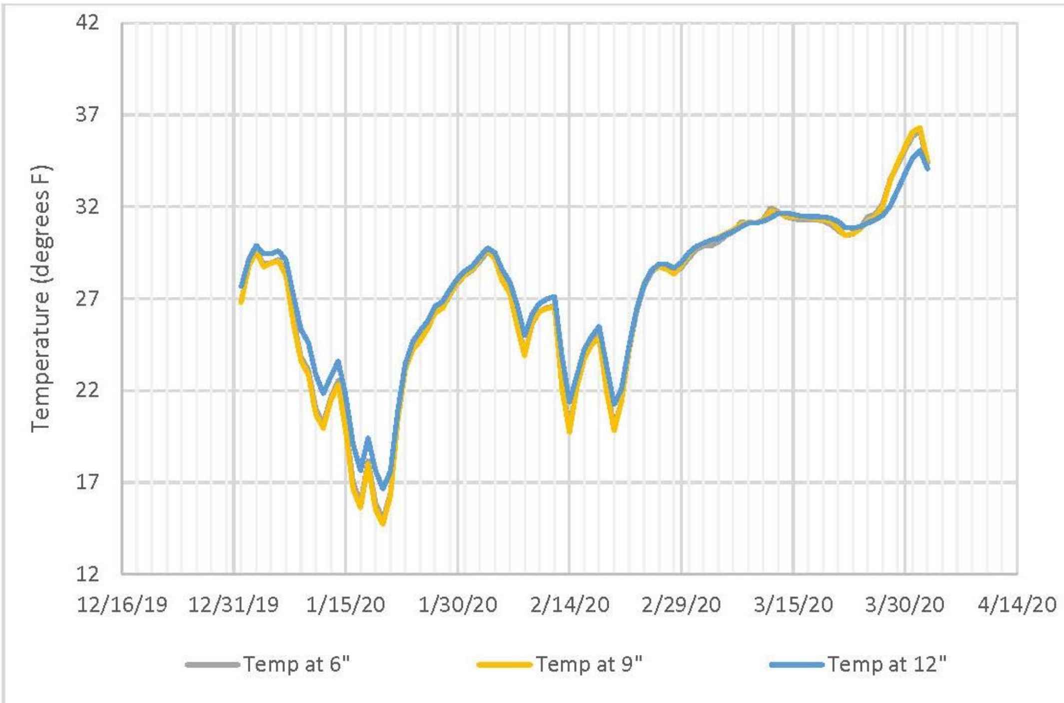


42
37
32
27
22
17
12
Temperature (degrees F)
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"

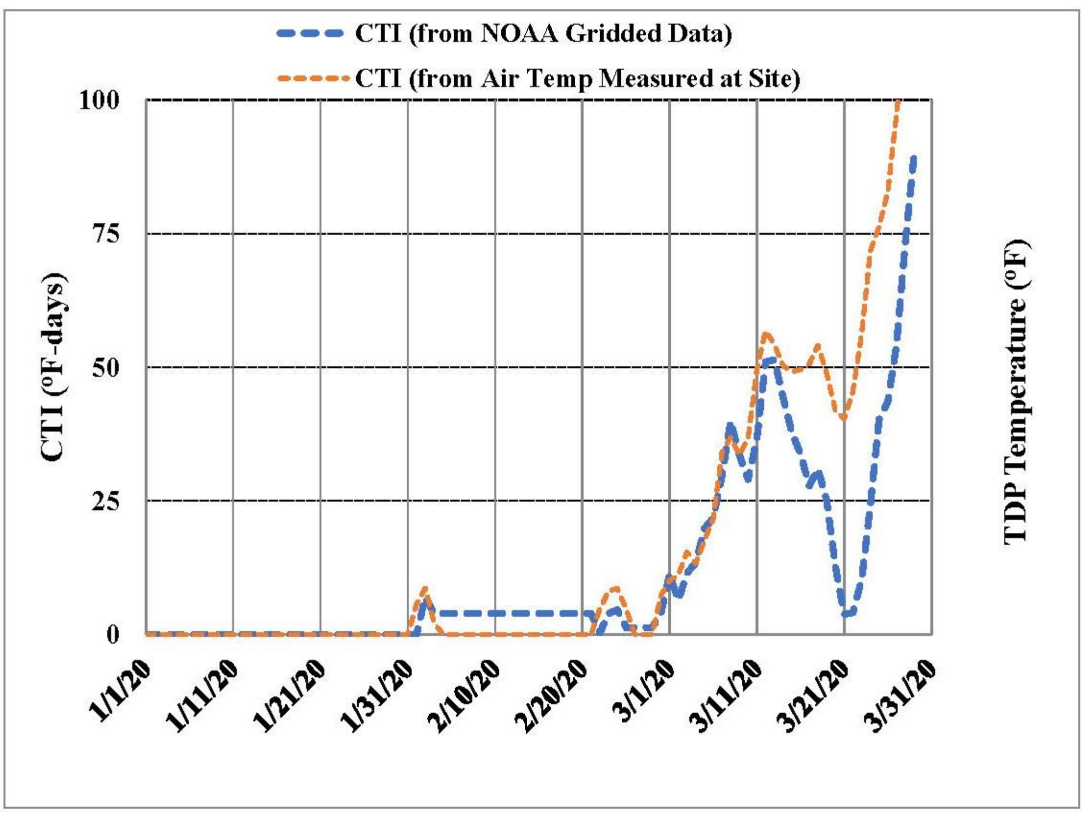


CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
100
75
50
25
0
CTI (ºF-days)
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Medina, ND

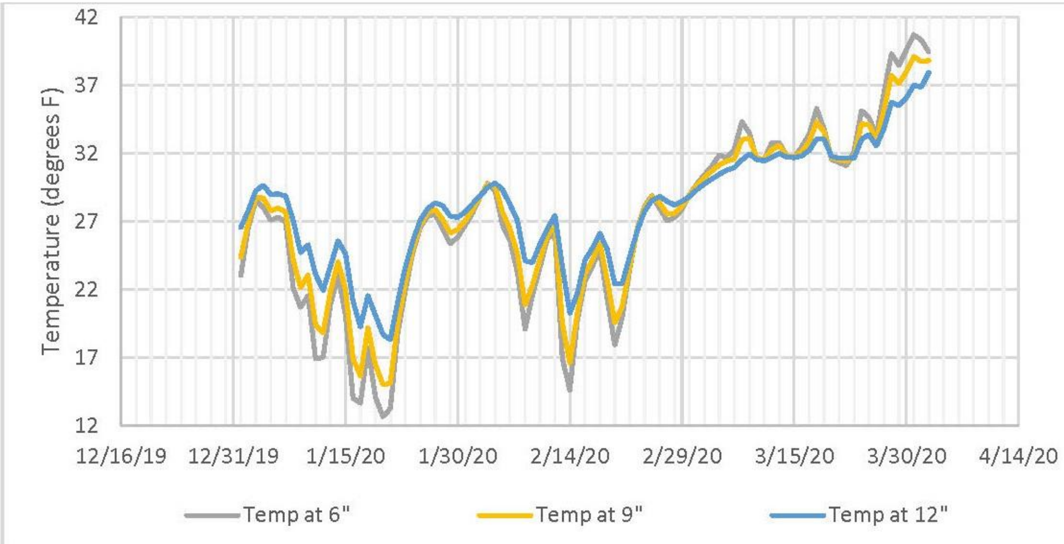


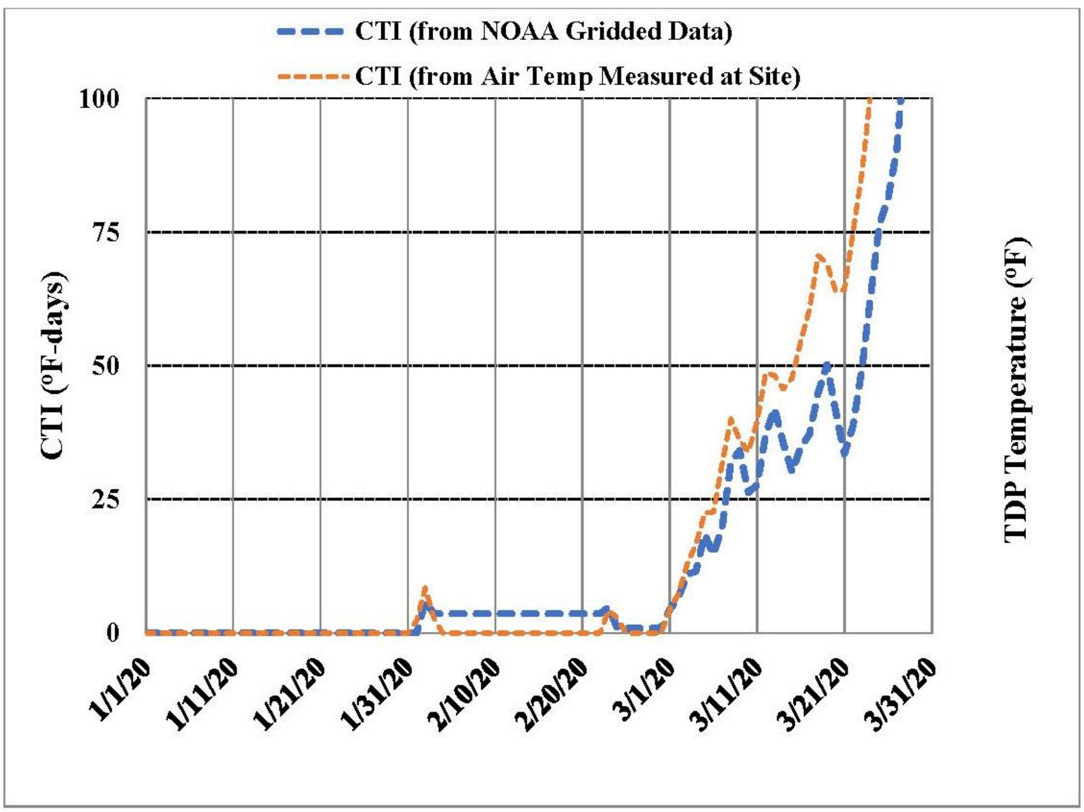
Temperature (degrees F)
42
37
32
27
22
17
12
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"



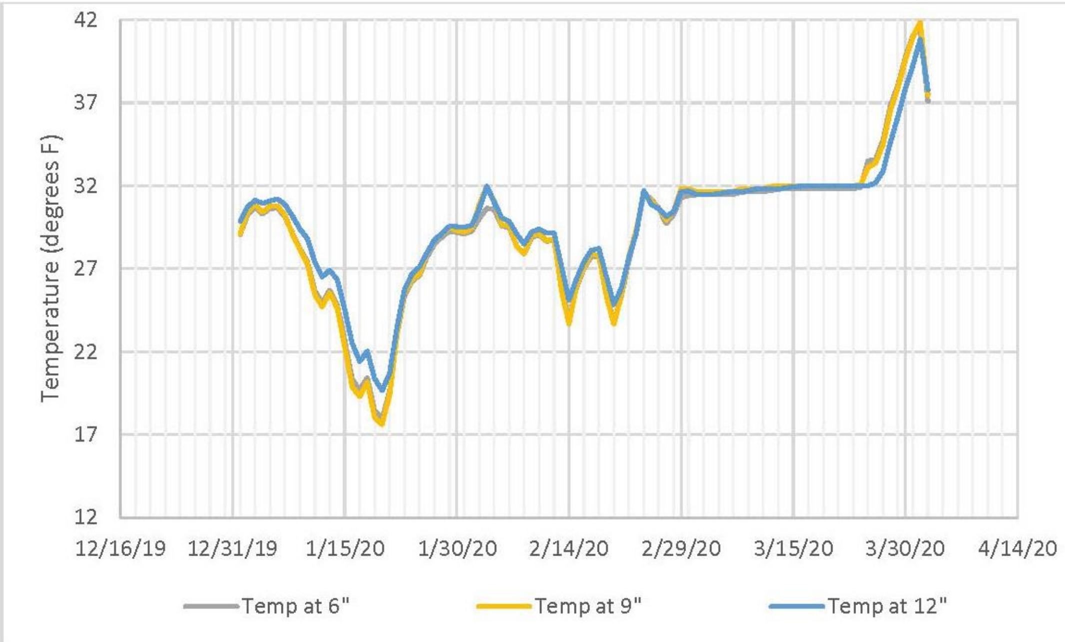
CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
100
75
50
25
0
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Mooreton, ND

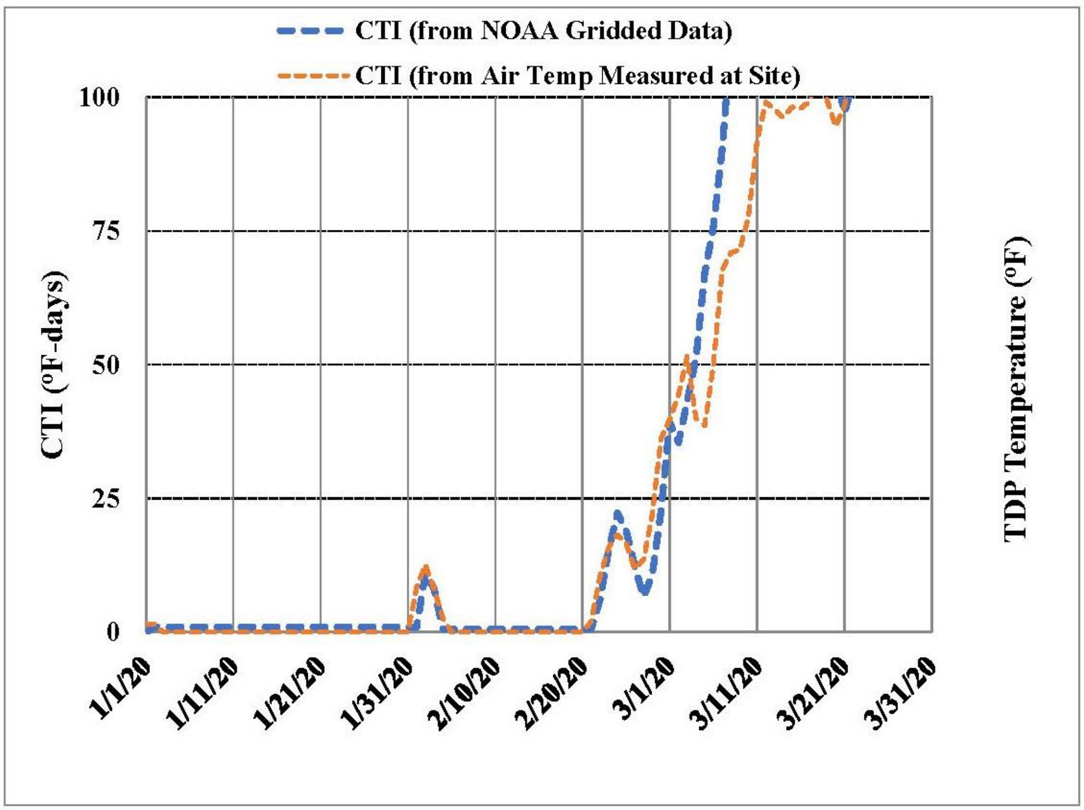

Temperature (degrees F)
42
37
32
27
22
17
12
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"


CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
TDP Temperature (ºF)
100
75
50
25
0
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

New Salem, ND

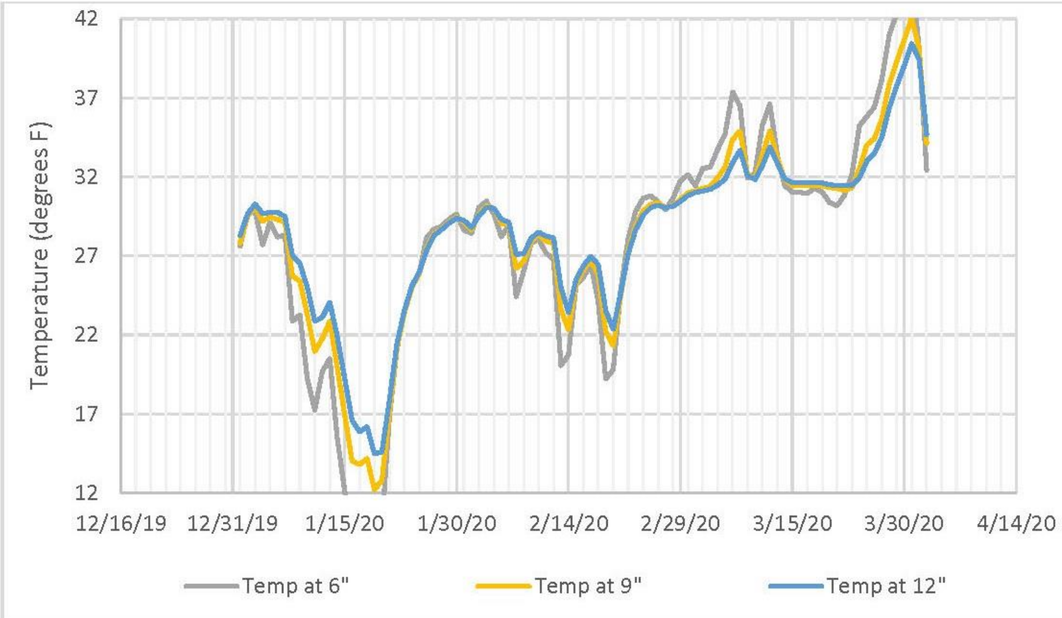


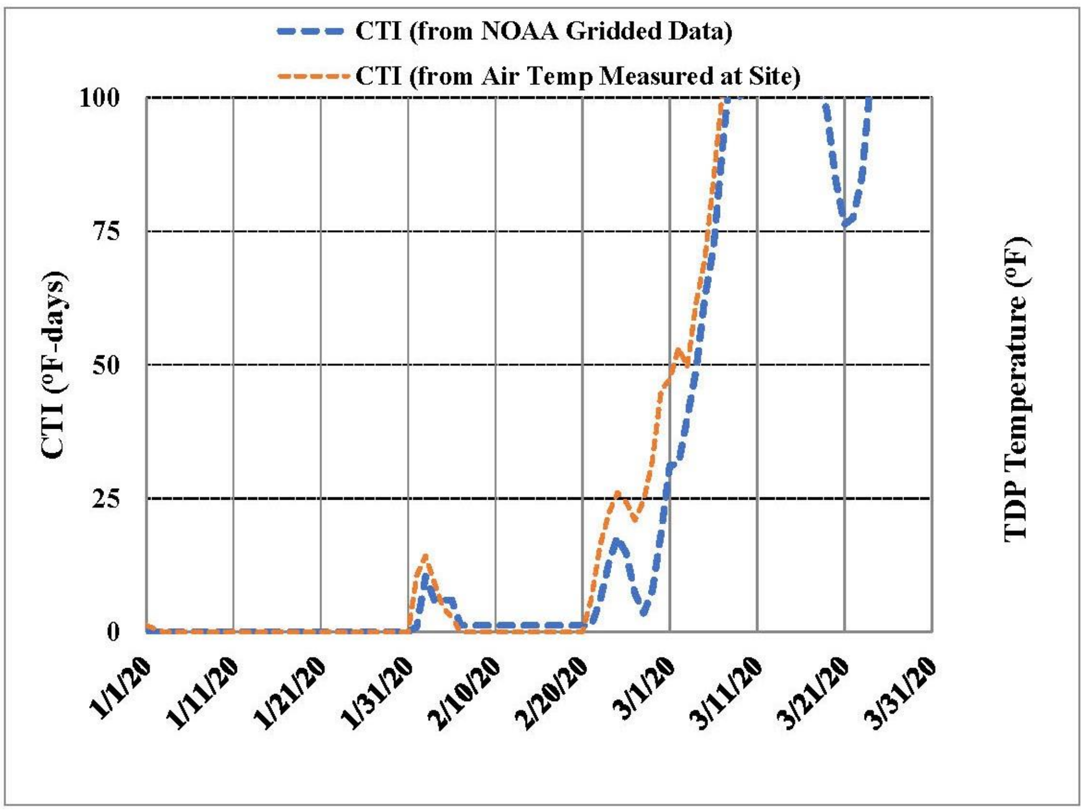
42
37
32
27
22
17
12
Temperature (degrees F)
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"



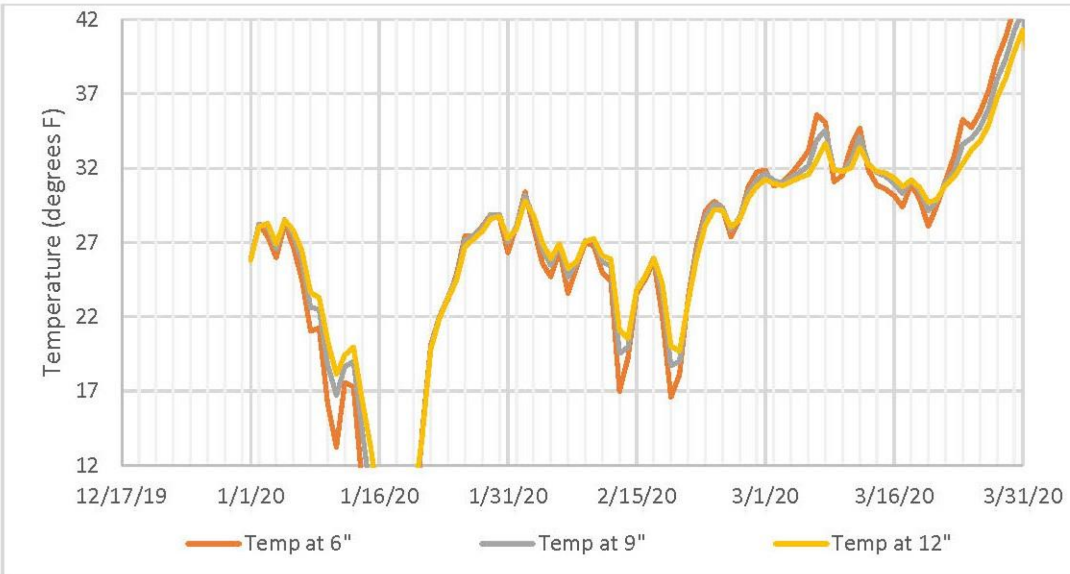
CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
100
75
50
25
0
CTI (ºF-days)
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

New Town, ND

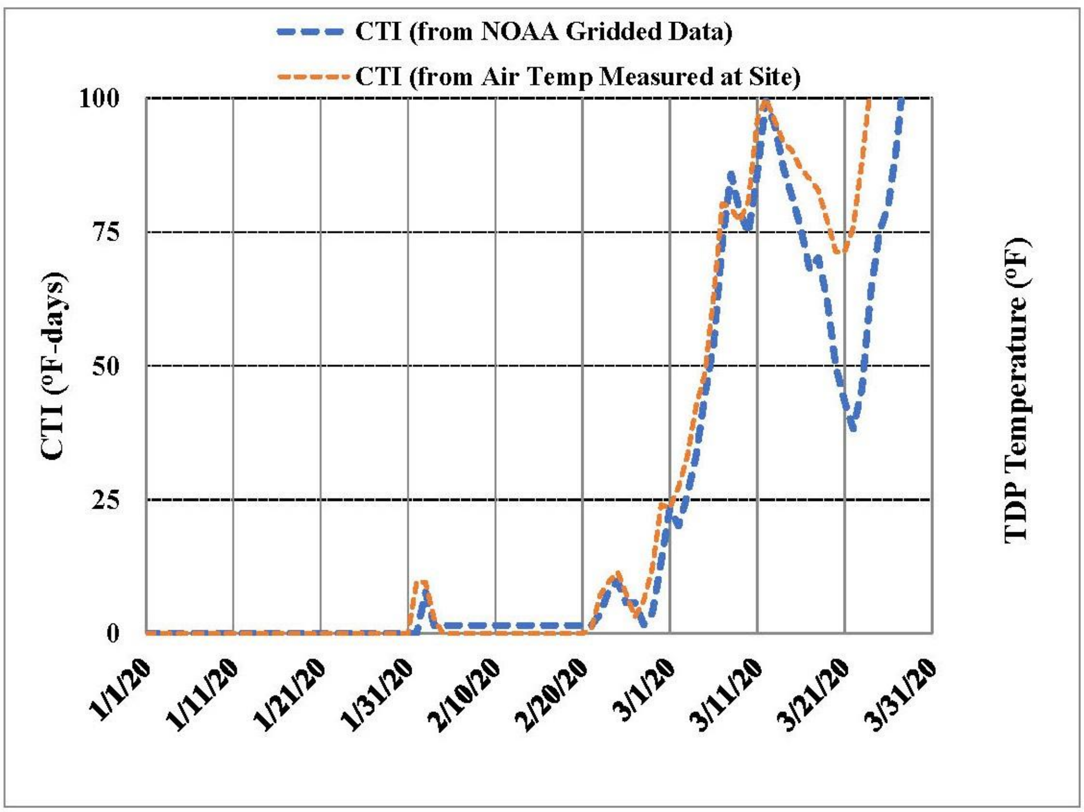

Temperature (degrees F)
42
37
32
27
22
17
12
12/16/19
12/31/19
1/15/20
1/30/20
2/14/20
2/29/20
3/15/20
3/30/20
4/14/20
Temp at 6"
Temp at 9"
Temp at 12"


CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
TDP Temperature (ºF)
100
75
50
25
0
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Ray, ND

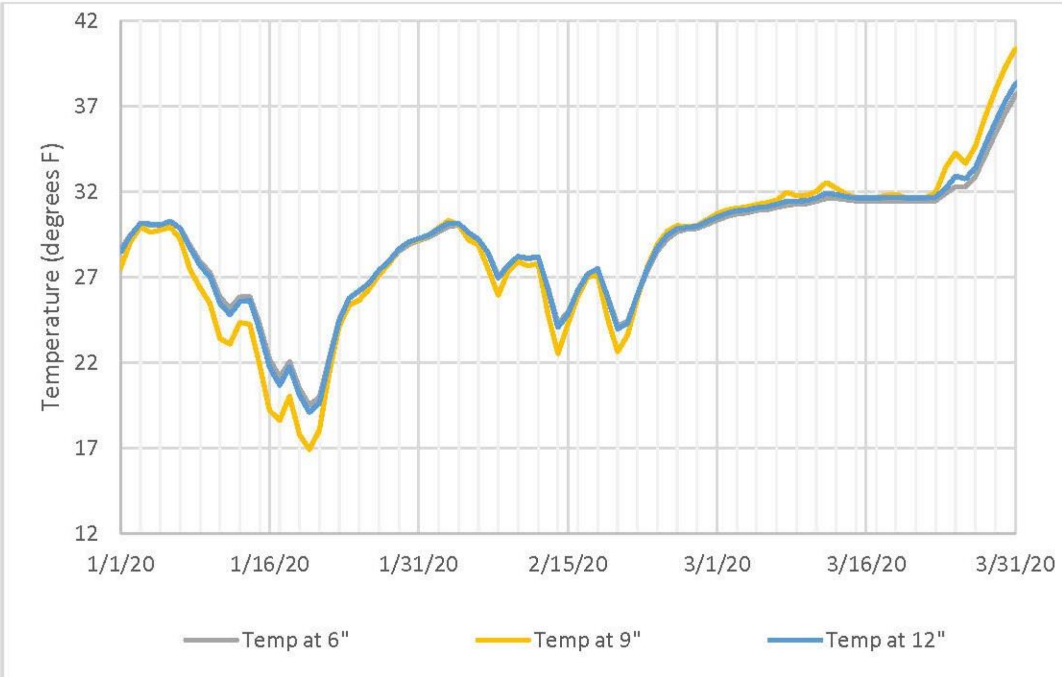


Temperature (degrees F)
42
37
32
27
22
17
12
12/17/19
1/1/20
1/16/20
1/31/20
2/15/20
3/1/20
3/16/20
3/31/20
Temp at 6"
Temp at 9"
Temp at 12"

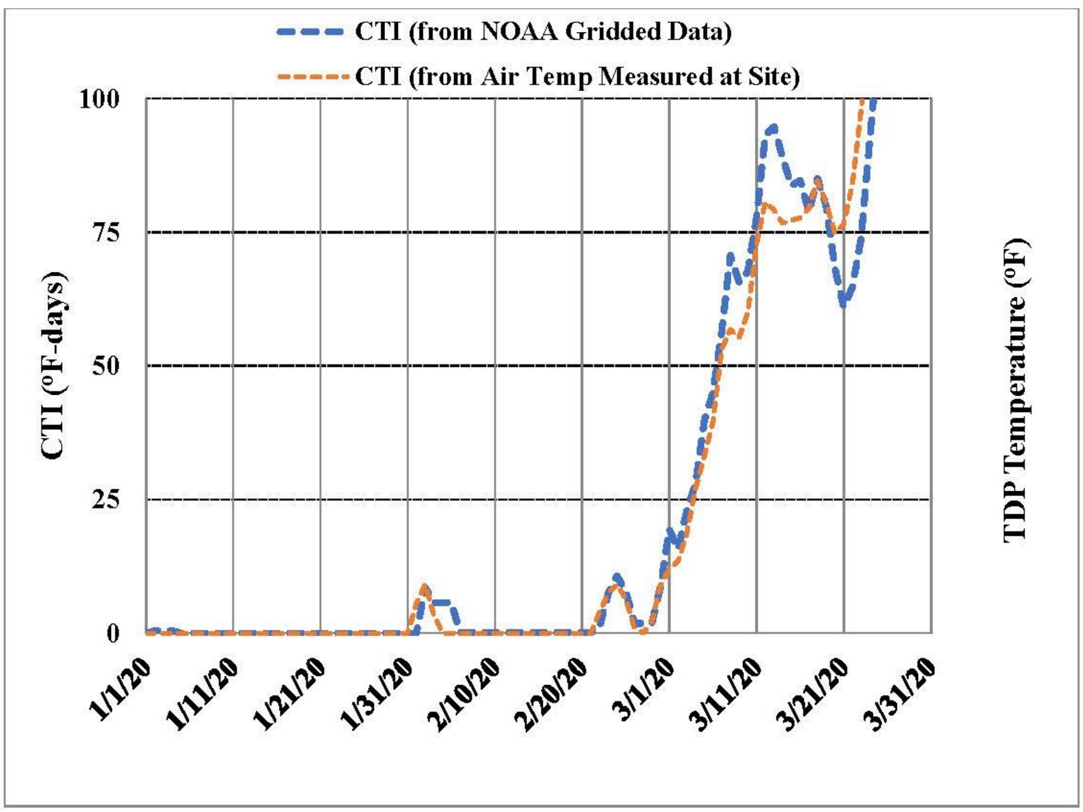


CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
TDP Temperature (ºF)
100
75
50
25
0
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Sterling, ND

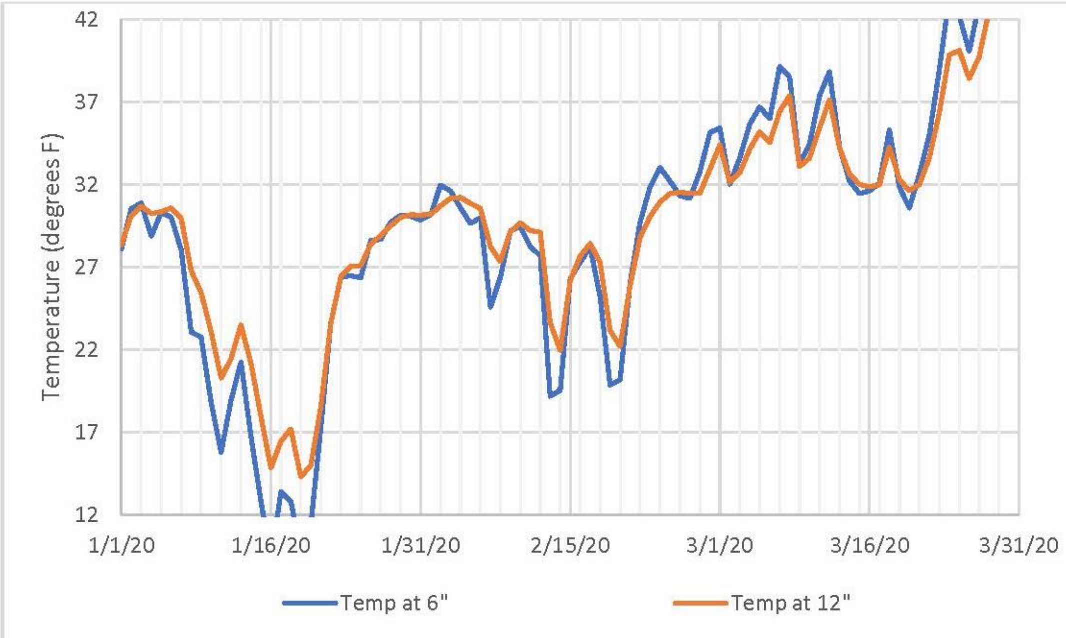


Temperature (degrees F)
42
37
32
27
22
17
12
1/1/20
1/16/20
1/31/20
2/15/20
3/1/20
3/16/20
3/31/20
Temp at 6"
Temp at 9"
Temp at 12"

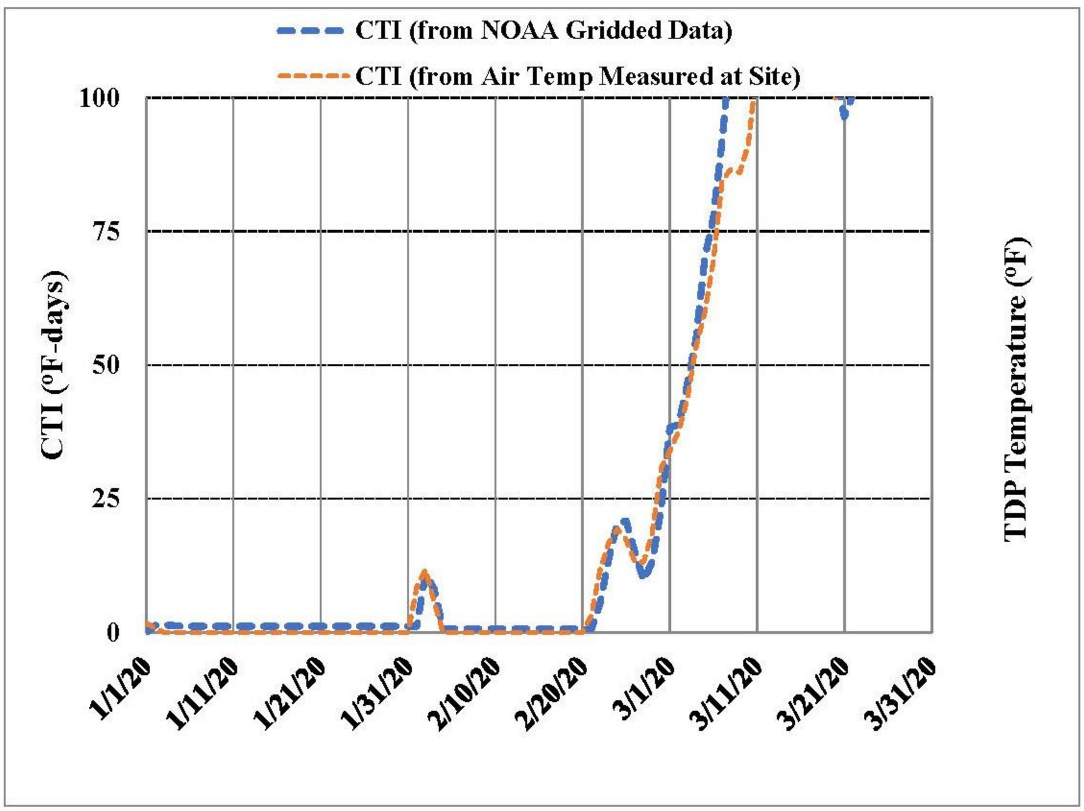


CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
CTI (ºF-days)
TDP Temperature (ºF)
100
75
50
25
0
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

Washburn, ND

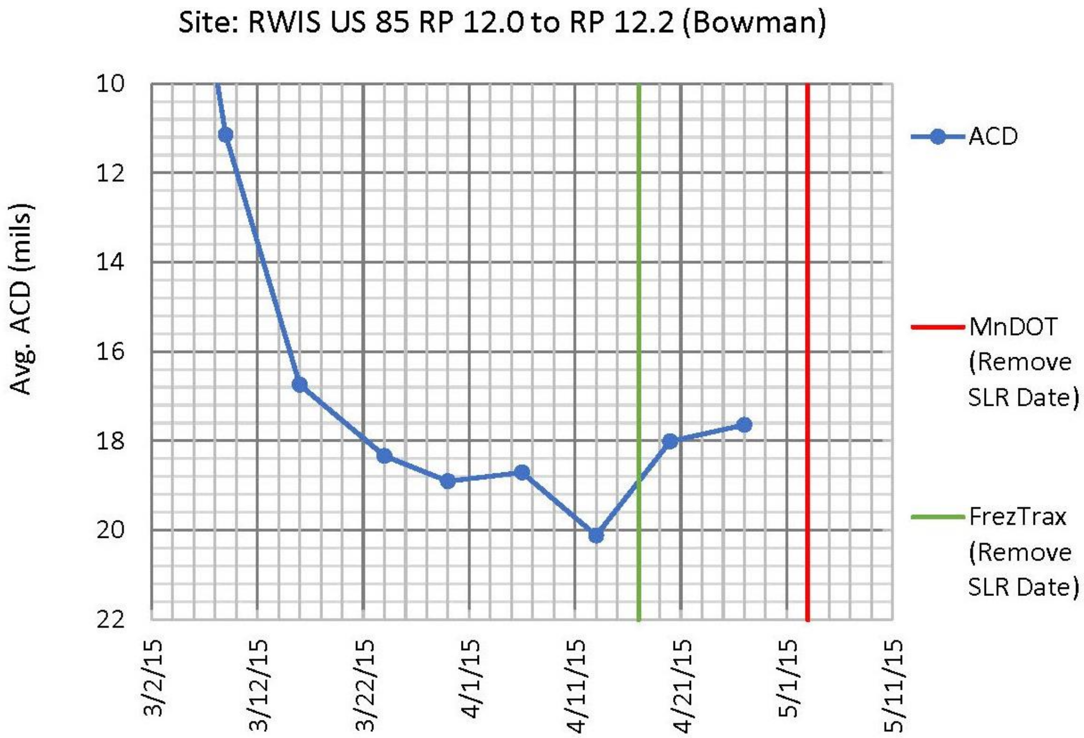


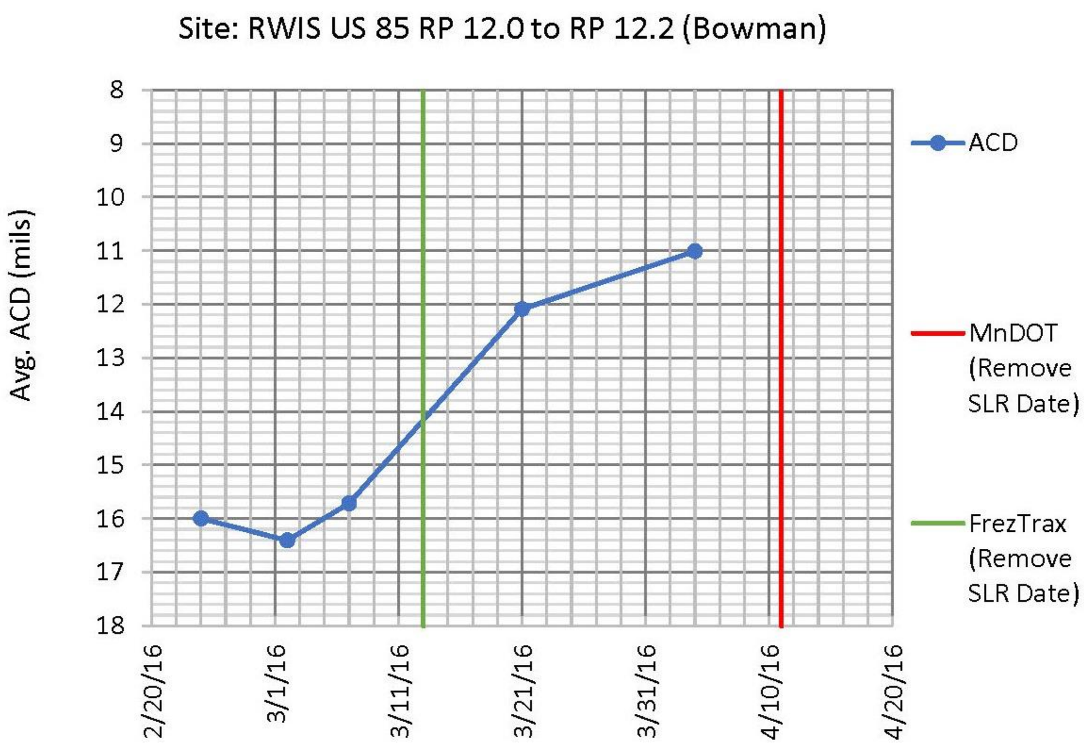
42
37
32
27
22
17
12
Temperature (degrees F)
1/1/20
1/16/20
1/31/20
2/15/20
3/1/20
3/16/20
3/31/20
Temp at 6"
Temp at 12"

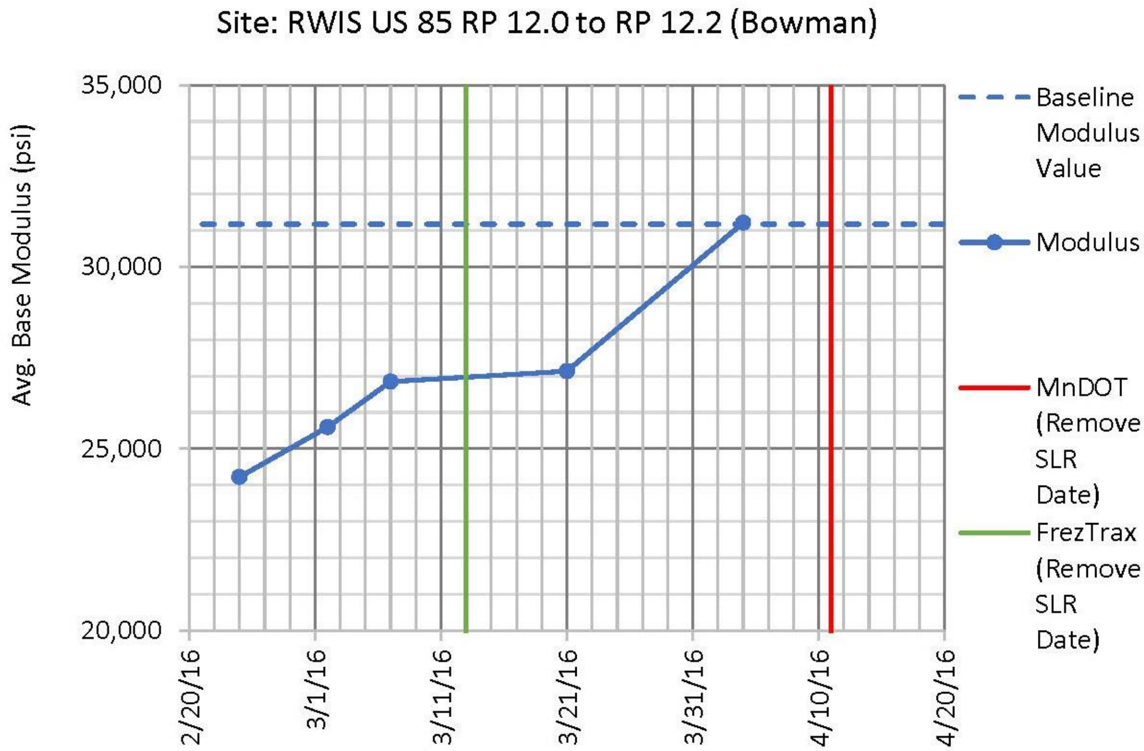


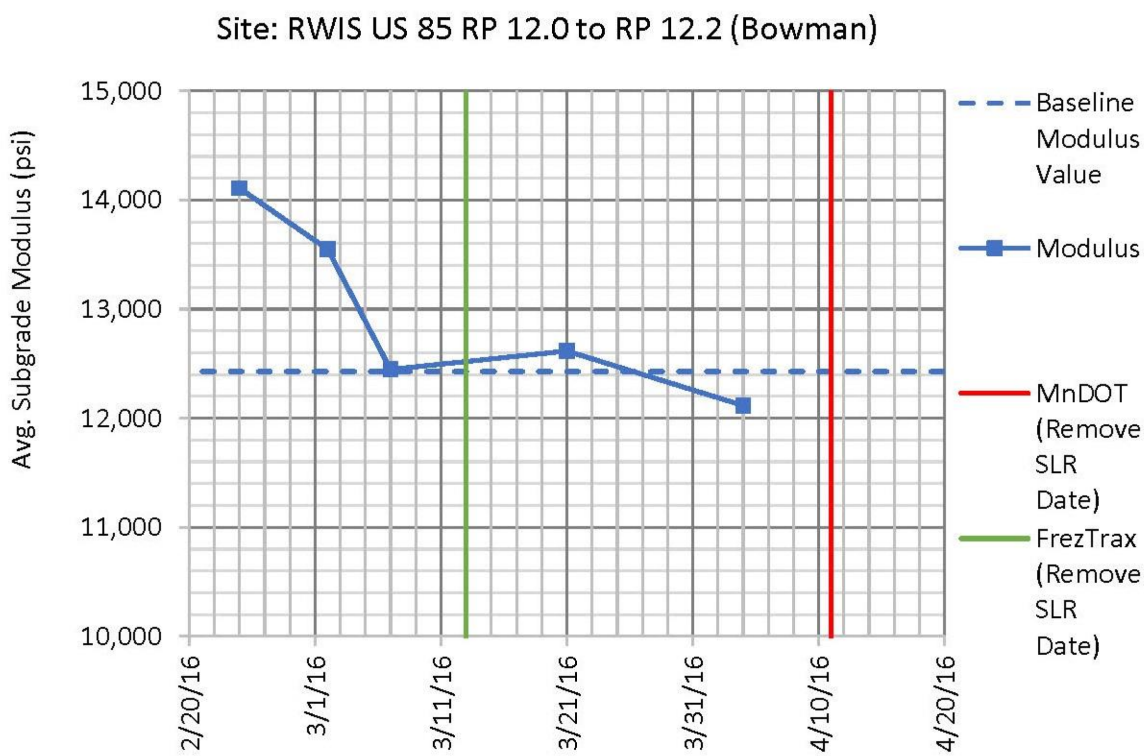
CTI (from NOAA Gridded Data)
CTI (from Air Temp Measured at Site)
100
75
50
25
0
CTI (ºF-days)
TDP Temperature (ºF)
1/1/20
1/11/20
1/21/20
1/31/20
2/10/20
2/20/20
3/1/20
3/11/20
3/21/20
3/31/20

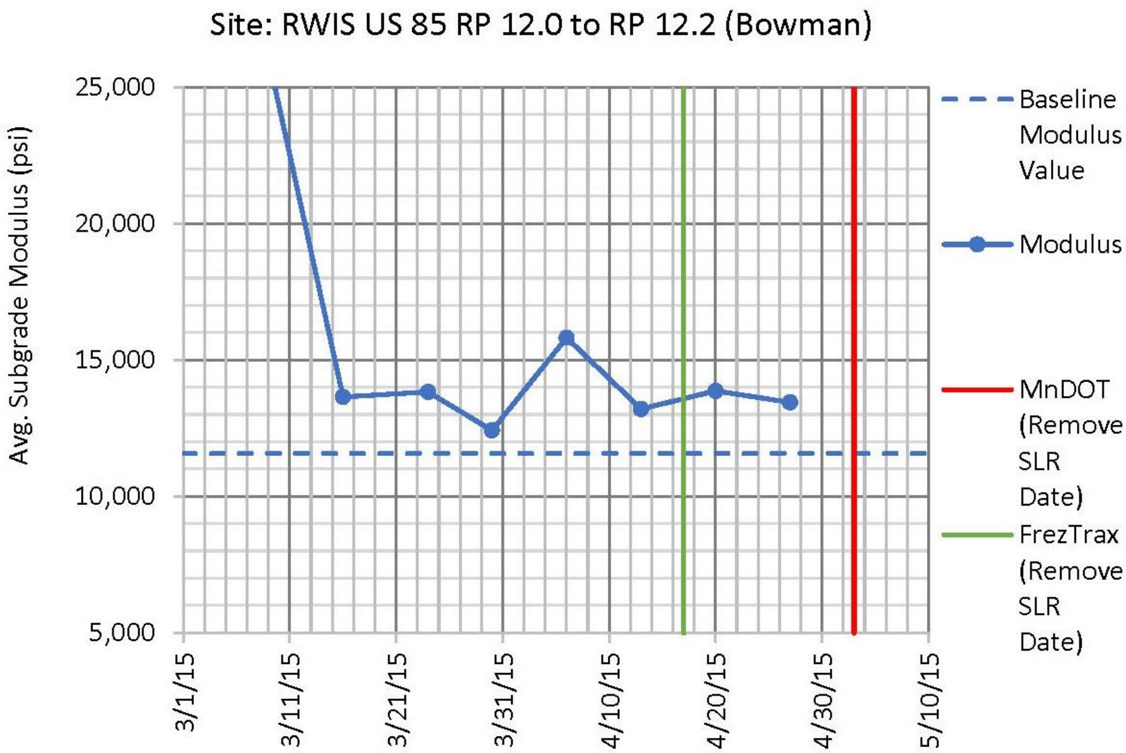
APPENDIX C. SLR POSTING BASED ON DEGREE-DAY THRESHOLD MODELS: MAHONEY ET AL. (1986) AND FREZTRAX



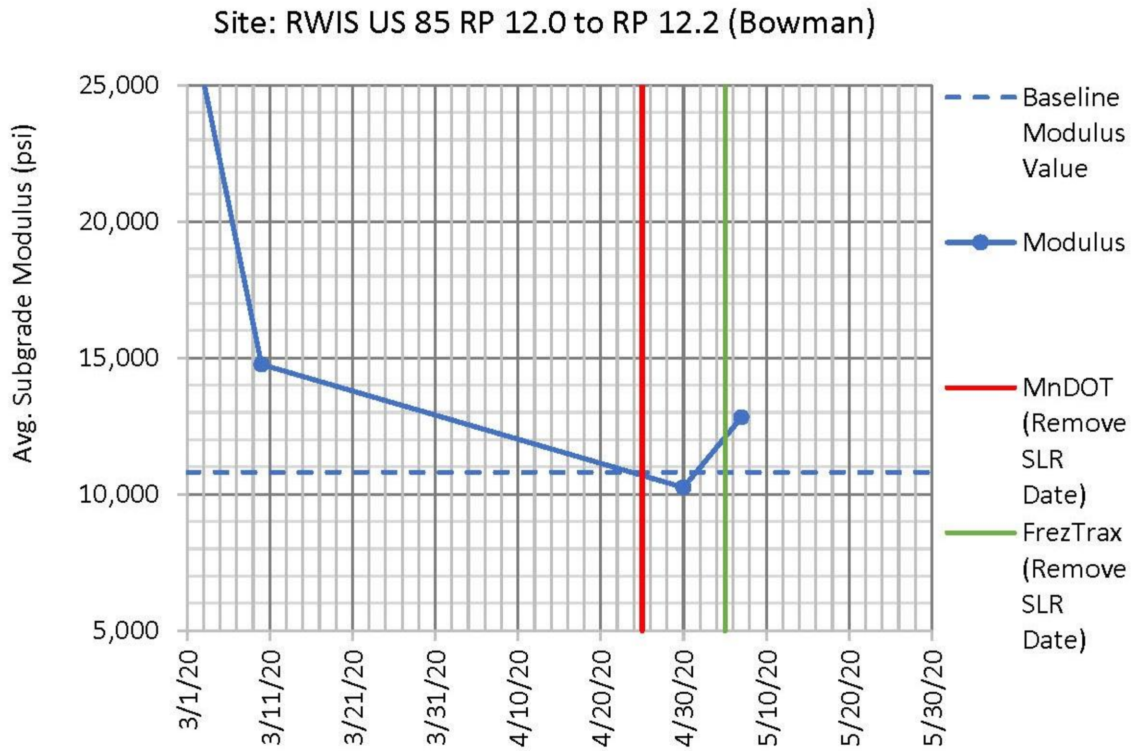



Site: RWIS US 85 RP 12.0 to RP 12.2 (Bowman)
Avg. Base Modulus (psi)
35,000
30,000
25,000
20,000
2/20/16
3/1/16
3/11/16
3/21/16
3/31/16
4/10/16
4/20/16
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)

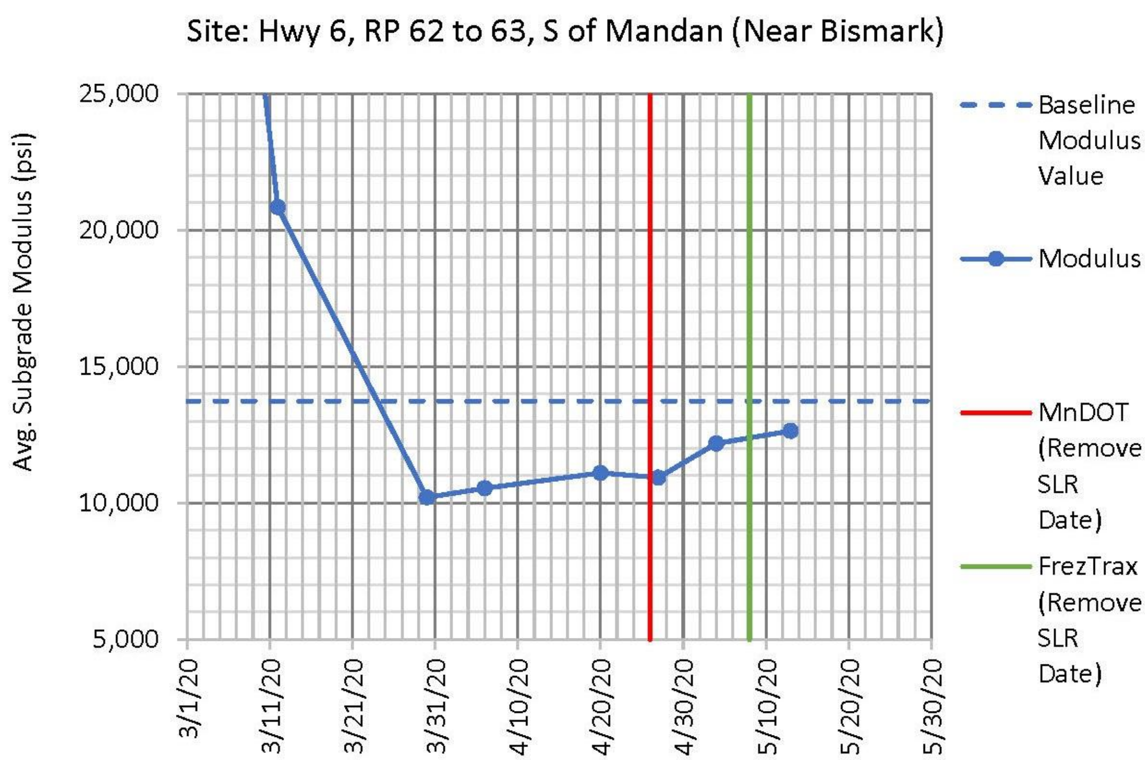

Site: RWIS US 85 RP 12.0 to RP 12.2 (Bowman)
Avg. Subgrade Modulus (psi)
15,000
14,000
13,000
12,000
11,000
10,000
2/20/16
3/1/16
3/11/16
3/21/16
3/31/16
4/10/16
4/20/16
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)



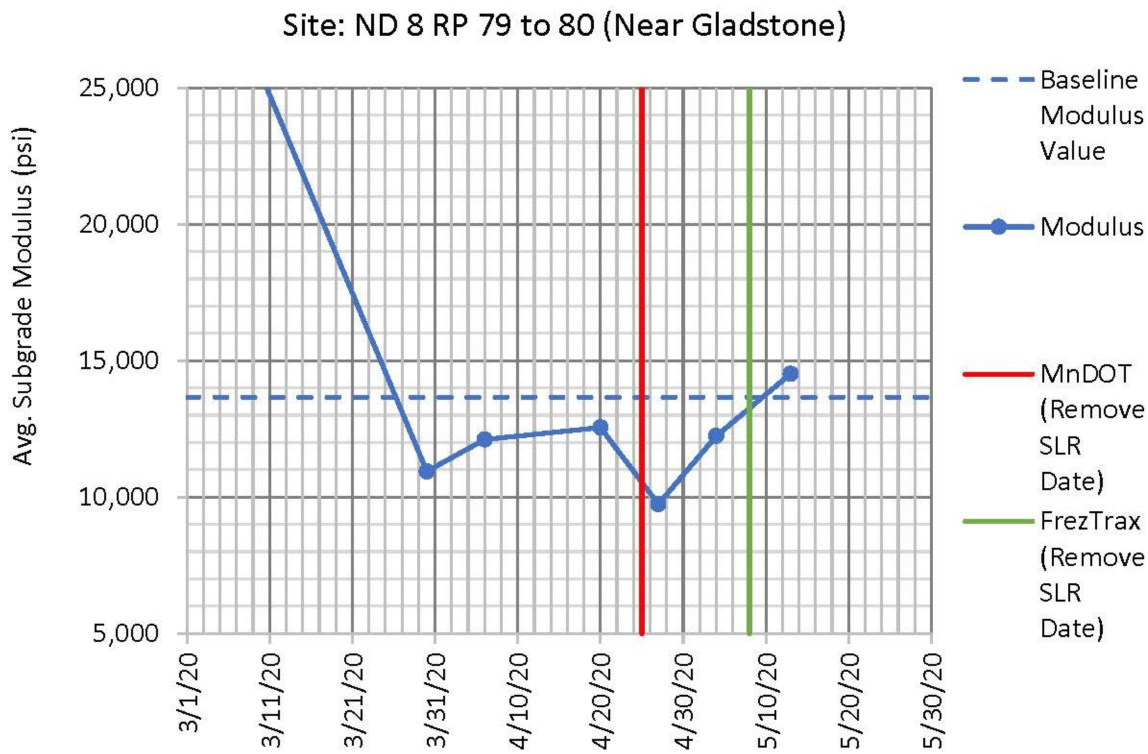
Site: RWIS US 85 RP 12.0 to RP 12.2 (Bowman)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/1/15
3/11/15
3/21/15
3/31/15
4/10/15
4/20/15
4/30/15
5/10/15
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)

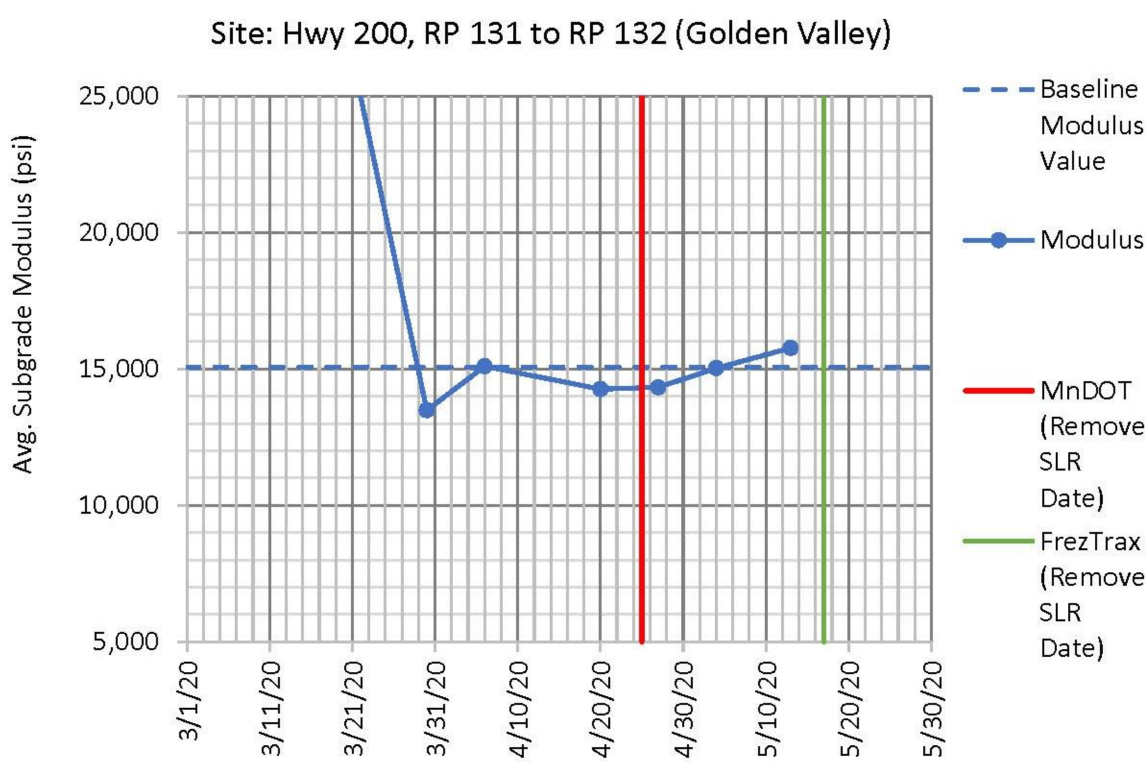


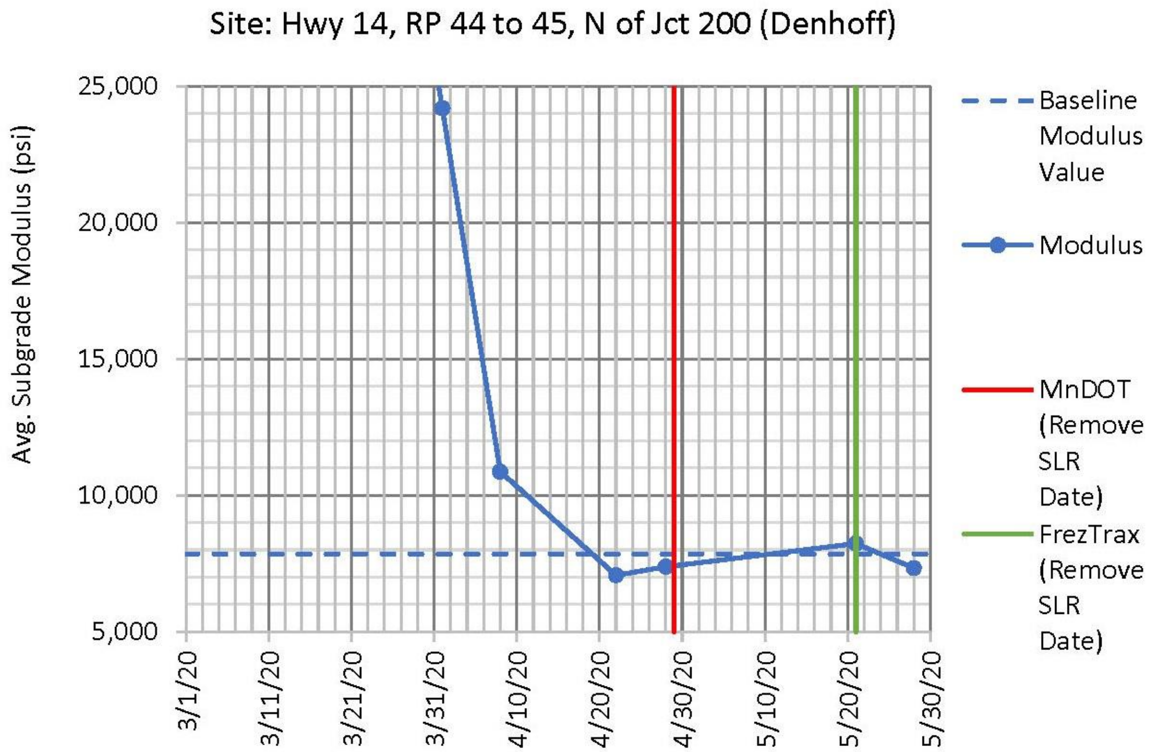
Site: RWIS US 85 RP 12.0 to RP 12.2 (Bowman)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/1/20
3/11/20
3/21/20
3/31/20
4/10/20
4/20/20
4/30/20
5/10/20
5/20/20
5/30/20
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)

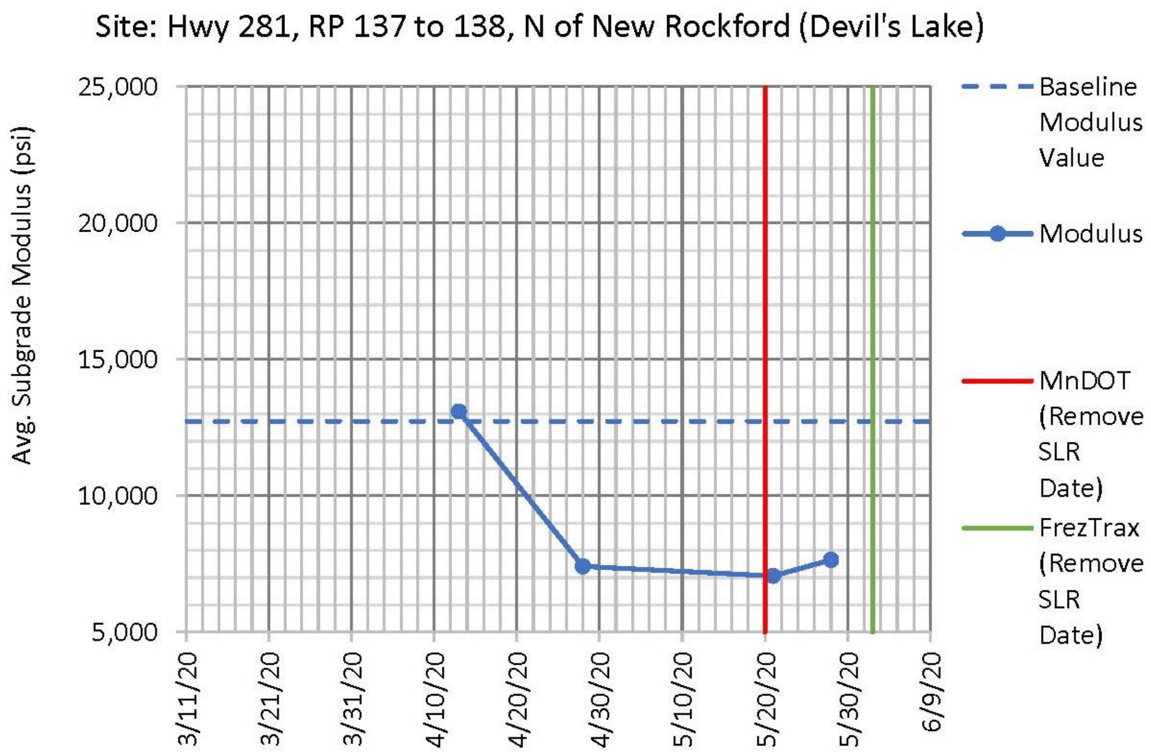


Site: Hwy 6, RP 62 to 63, S of Mandan (Near Bismark)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/1/20
3/11/20
3/21/20
3/31/20
4/10/20
4/20/20
4/30/20
5/10/20
5/20/20
5/30/20
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)


Site: ND 8 RP 79 to 80 (Near Gladstone)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/1/20
3/11/20
3/21/20
3/31/20
4/10/20
4/20/20
4/30/20
5/10/20
5/20/20
5/30/20
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)


Site: Hwy 200, RP 131 to RP 132 (Golden Valley)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/1/20
3/11/20
3/21/20
3/31/20
4/10/20
4/20/20
4/30/20
5/10/20
5/20/20
5/30/20
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)


Site: Hwy 14, RP 44 to 45, N of Jct 200 (Denhoff)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/1/20
3/11/20
3/21/20
3/31/20
4/10/20
4/20/20
4/30/20
5/10/20
5/20/20
5/30/20
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)

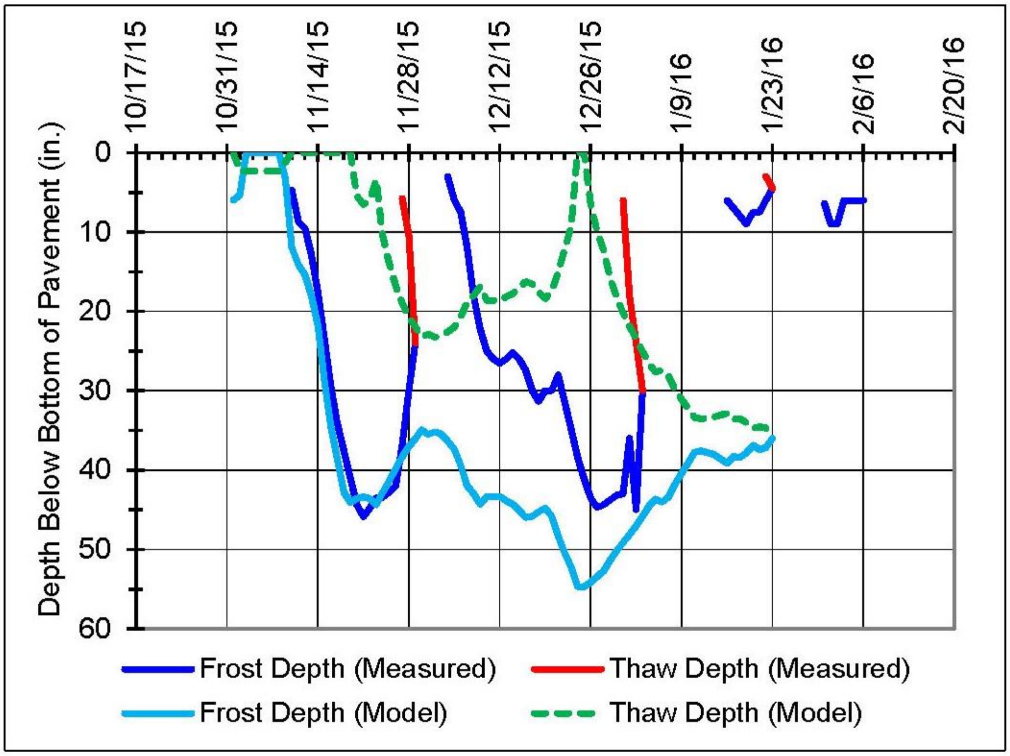

Site: Hwy 281, RP 137 to 138, N of New Rockford (Devil's Lake)
Avg. Subgrade Modulus (psi)
25,000
20,000
15,000
10,000
5,000
3/11/20
3/21/20
3/31/20
4/10/20
4/20/20
4/30/20
5/10/20
5/20/20
5/30/20
6/9/20
Baseline Modulus Value
Modulus
MnDOT (Remove SLR Date)
FrezTrax (Remove SLR Date)

APPENDIX D. FROST AND THAW DEPTH PREDICTION MODELS: MODELS BASED ON REGRESSION ANALYSES (SITE-SPECIFIC CALIBRATION)

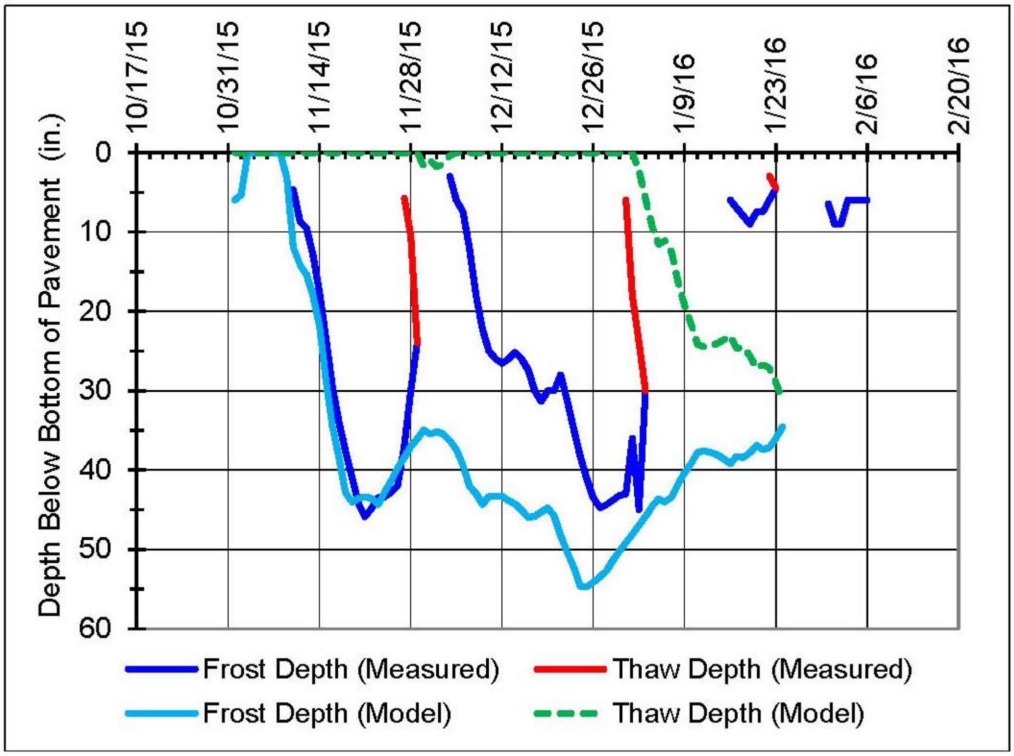
Notes:

1. "Linear Regression (Zero Intercept)" and "Linear Regression (Non-Zero Intercept)" models based upon procedures outlined by Miller et al. (2012[b])
2. "Polynomial Regression" model based upon procedures outlined by Chapin et al. (2013) and Pernia et al. (2014)

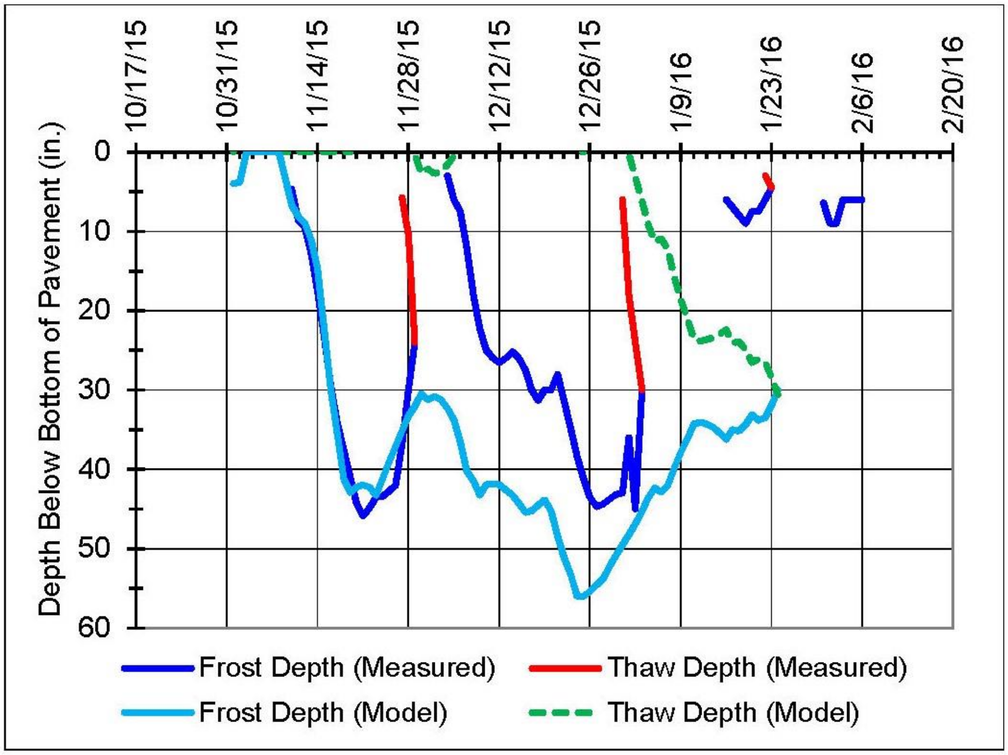
Alaska **Model**: Linear Regression (Zero-Intercept)



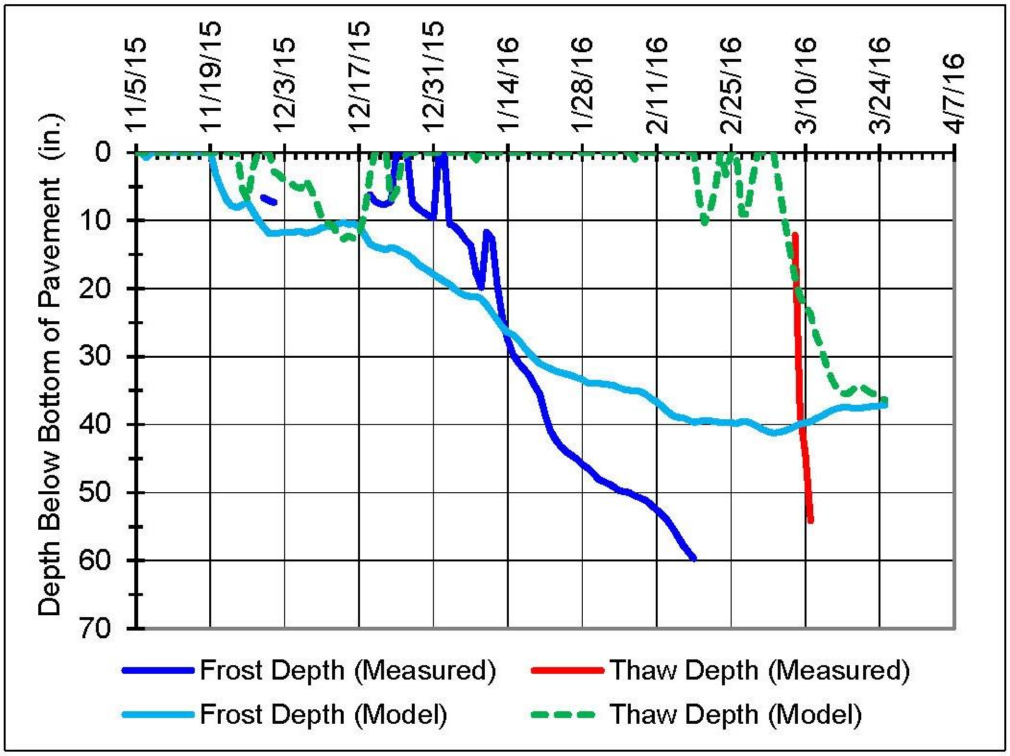
Alaska **Model**: Linear Regression (Non Zero-Intercept)



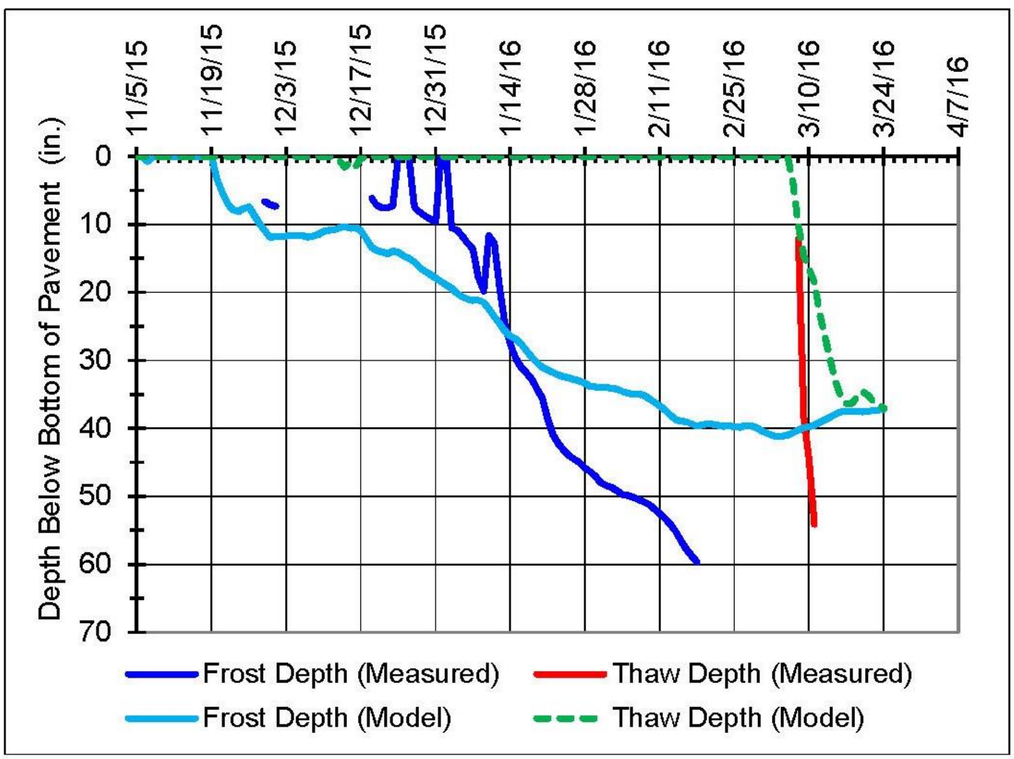
Alaska **Model**: Polynomial Regression



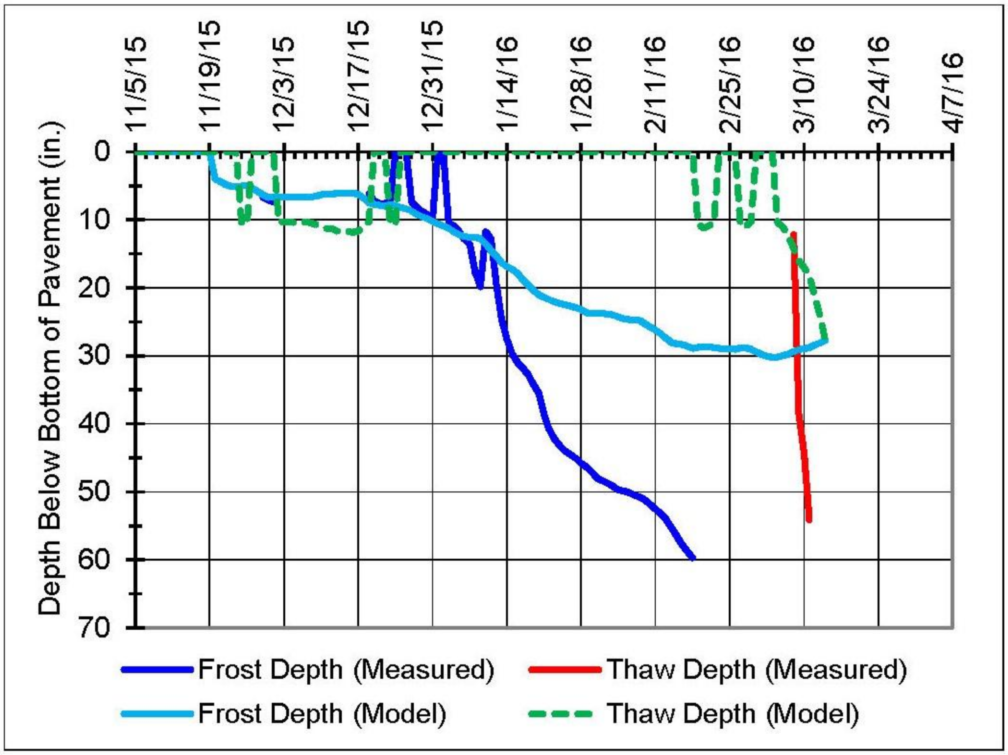
Michigan **Model**: Linear Regression (Zero-Intercept)



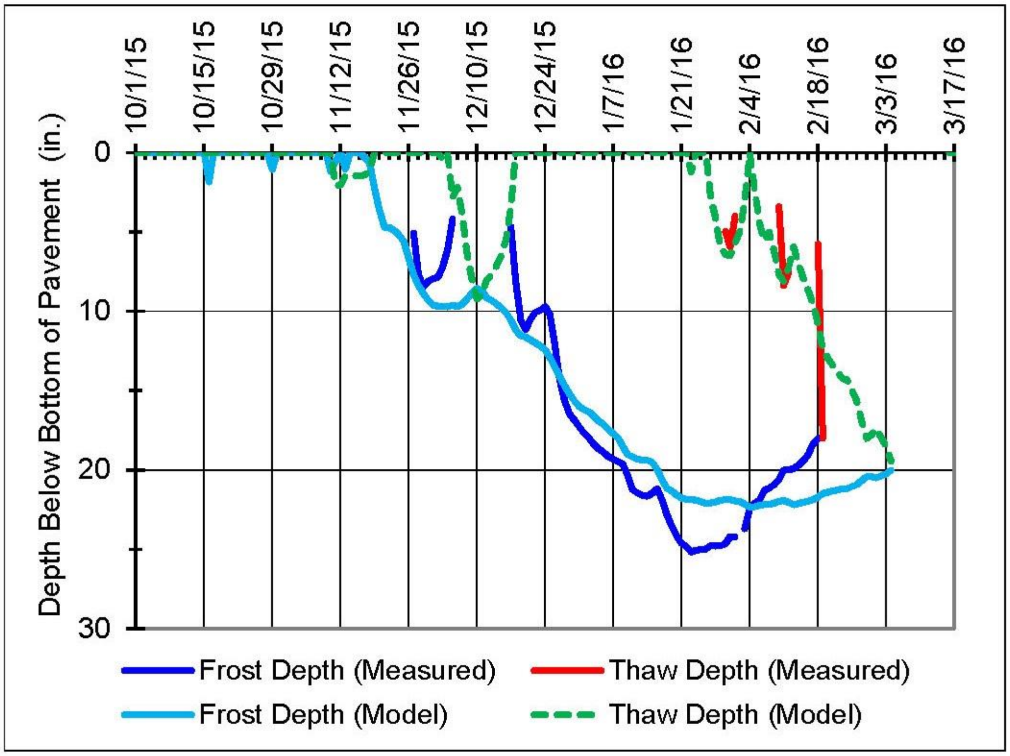
Michigan **Model**: Linear Regression (Non Zero-Intercept)



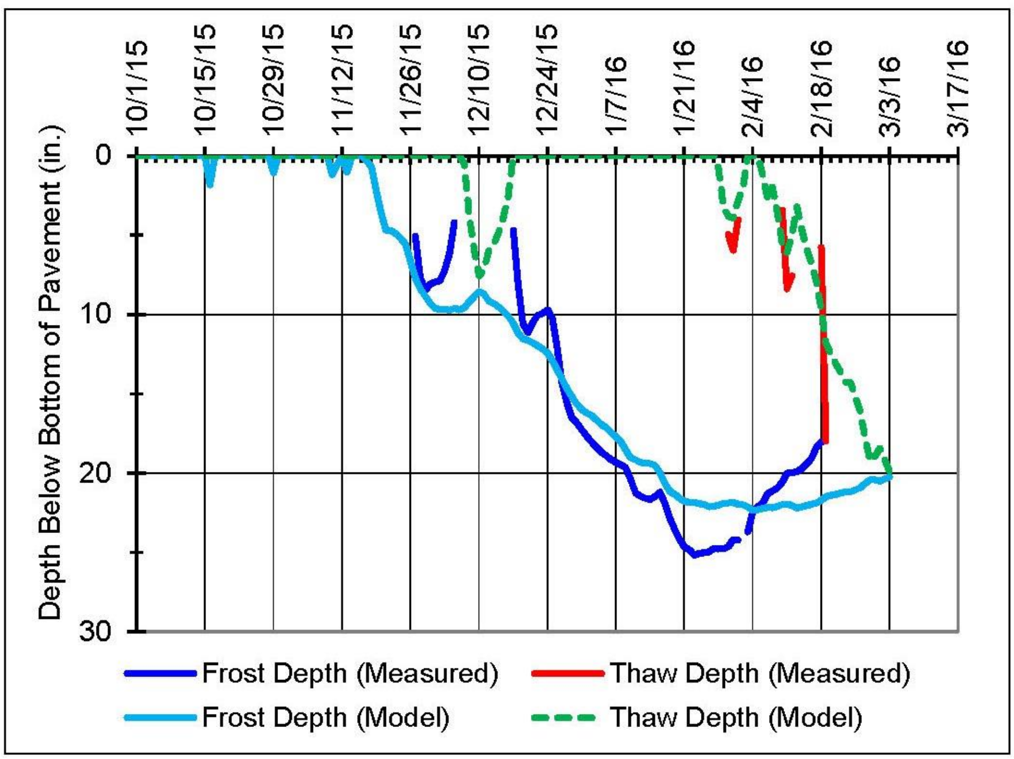
Michigan **Model**: Polynomial Regression



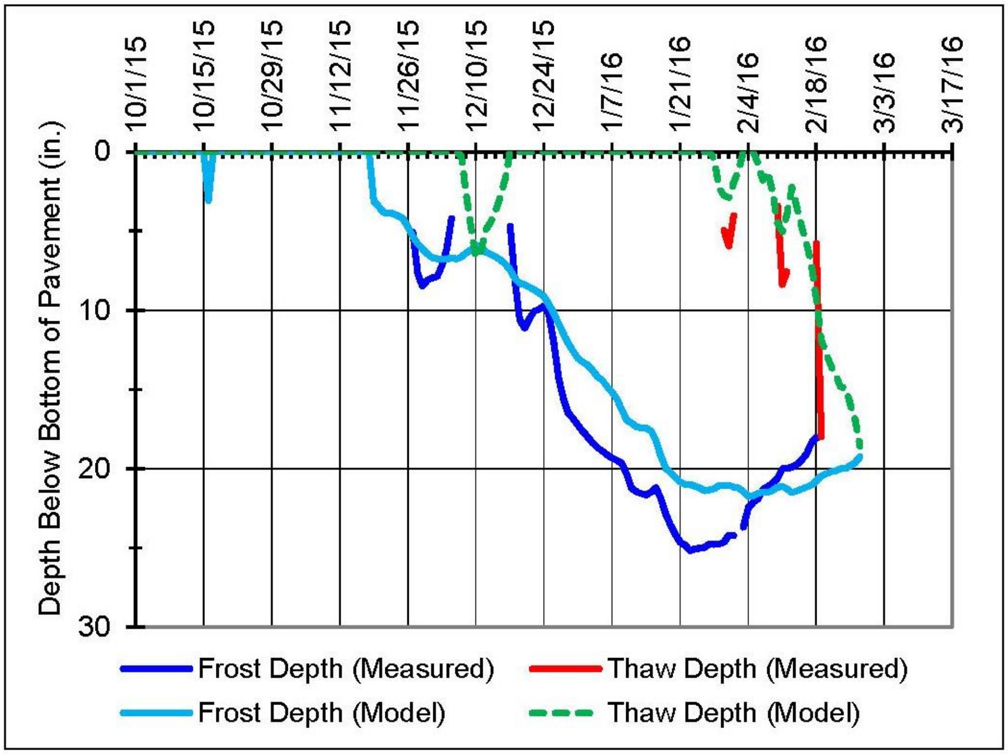
North Dakota **Model**: Linear Regression (Zero-Intercept)



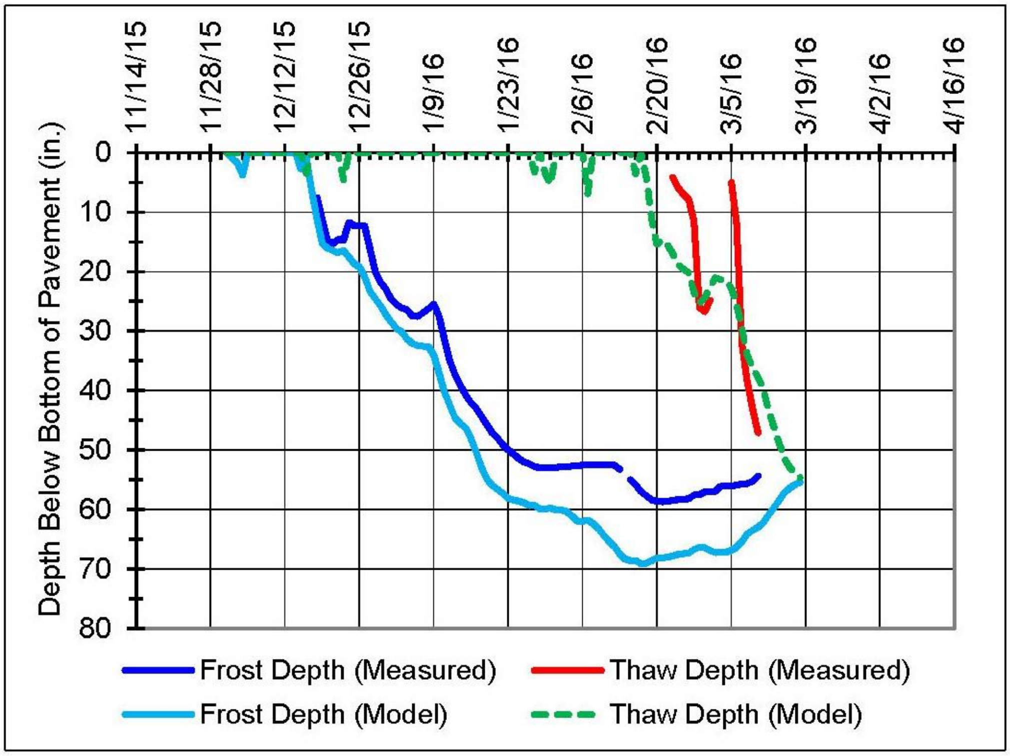
North Dakota **Model**: Linear Regression (Non Zero-Intercept)



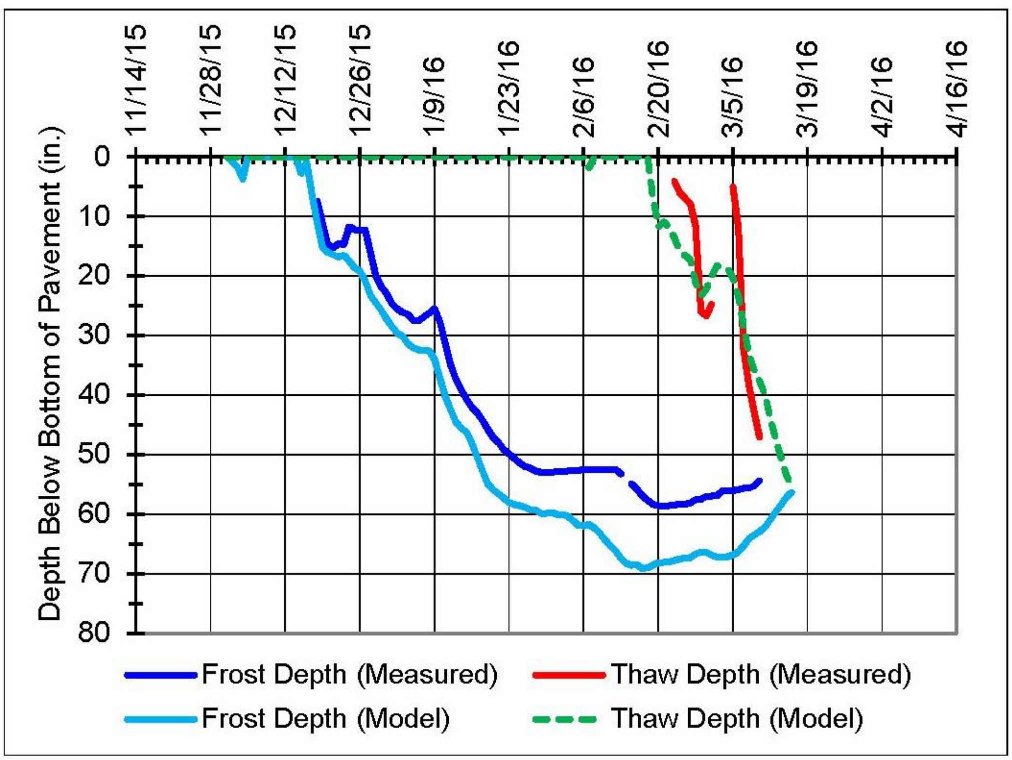
North Dakota **Model**: Polynomial Regression (Non Zero-Intercept)



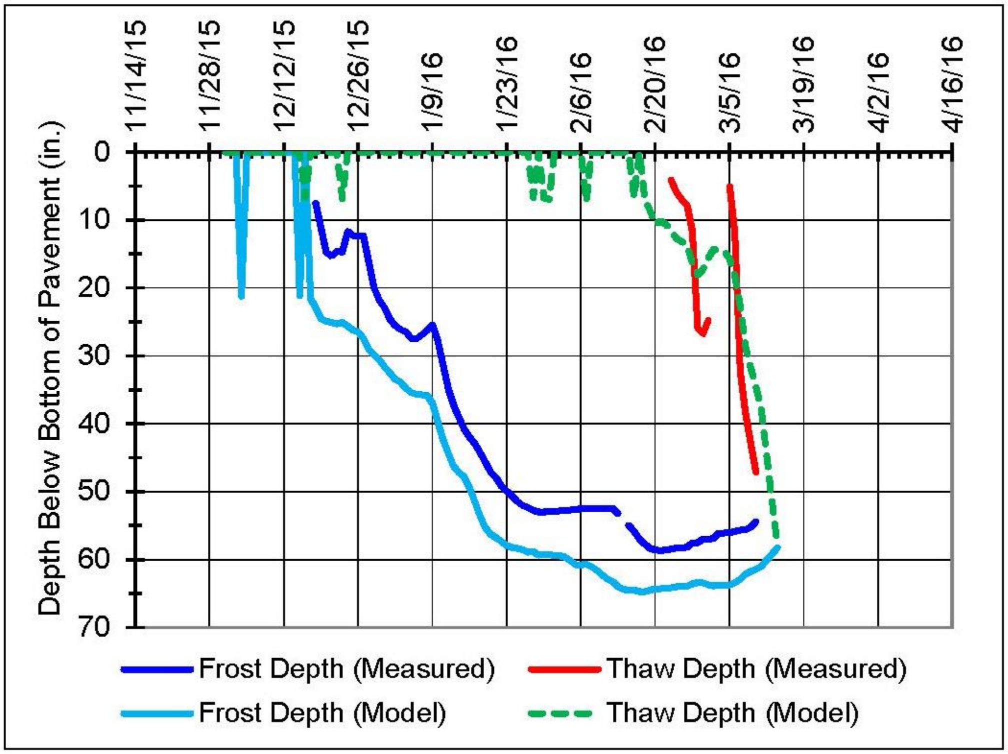
Wisconsin **Model**: Linear Regression (Zero-Intercept)



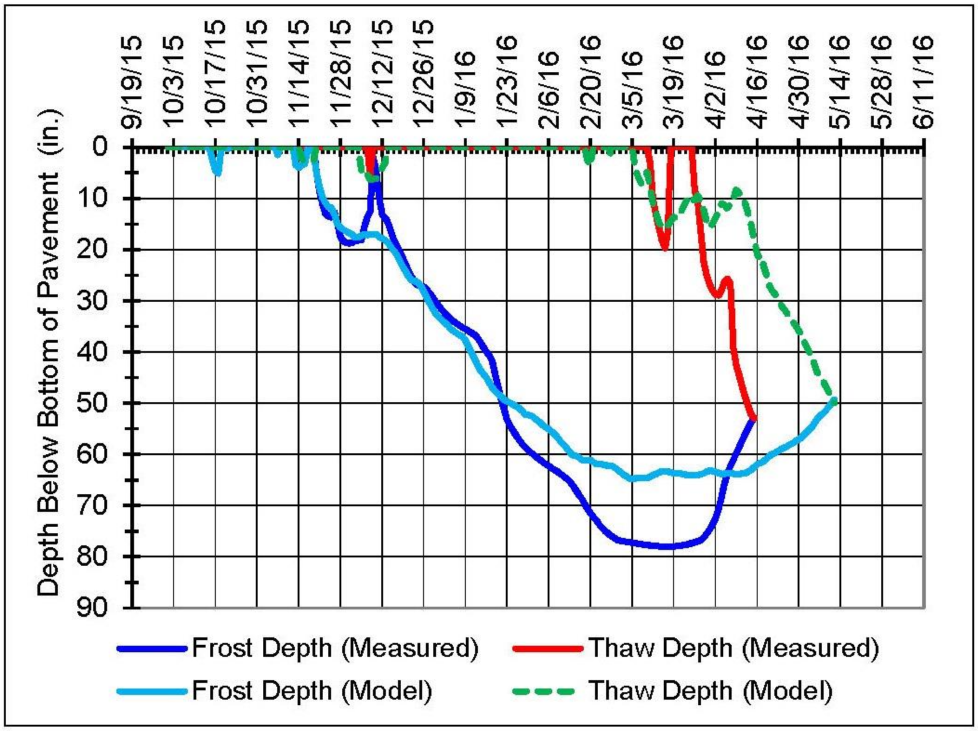
Wisconsin **Model**: Linear Regression (Non Zero-Intercept)



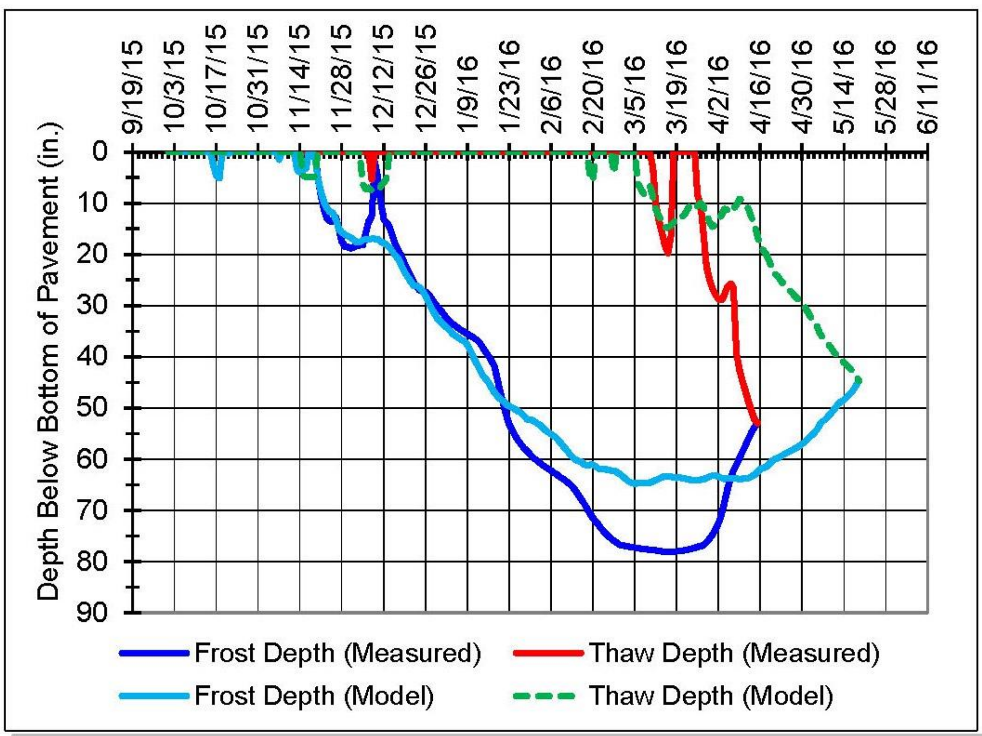
Wisconsin **Model**: Polynomial Regression



Ontario (527) ***Model**: Linear Regression (Zero-Intercept)

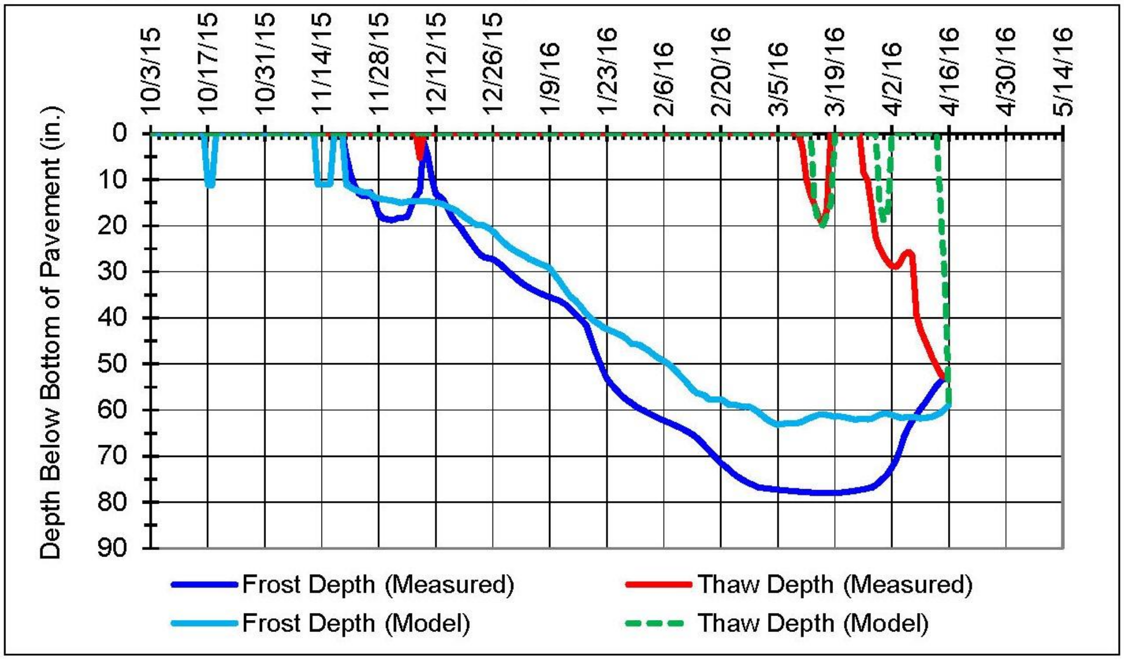


Ontario (527) ***Model**: Linear Regression (Non Zero-Intercept)



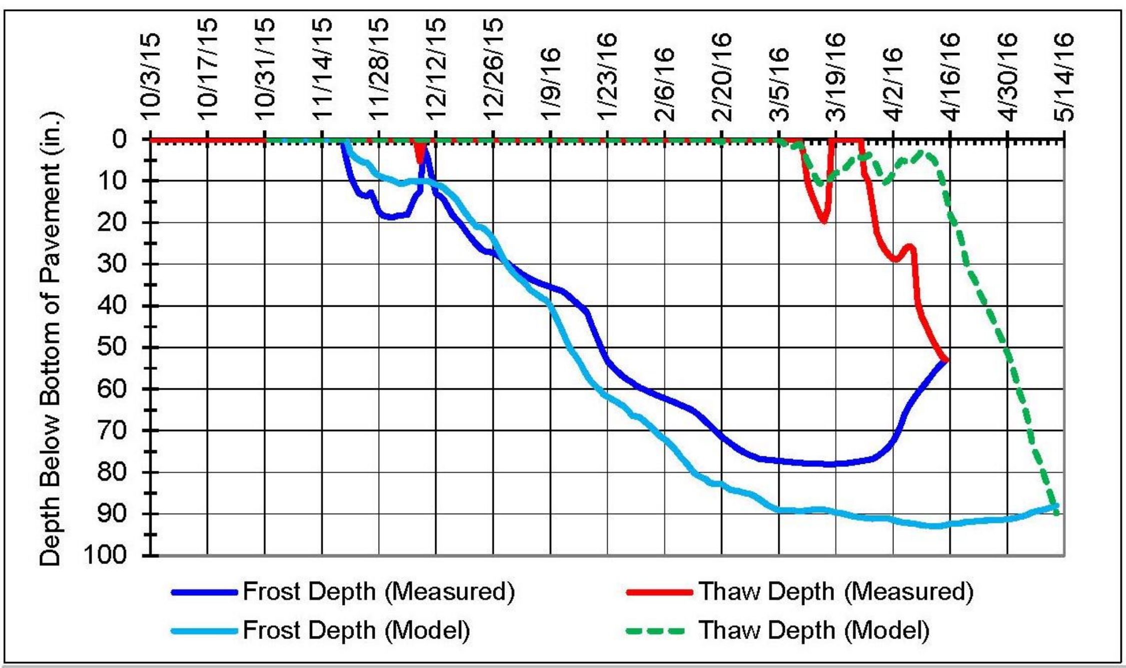
*These (2015-2016) predicted frost & thaw depths were based upon model coefficients determined from one season (2014-2015) of measured frost & thaw depth data.

Ontario (527) *Model: Polynomial Regression



*These predicted frost & thaw depths were based upon model coefficients determined from one season (2014-2015) of measured frost & thaw depth data.

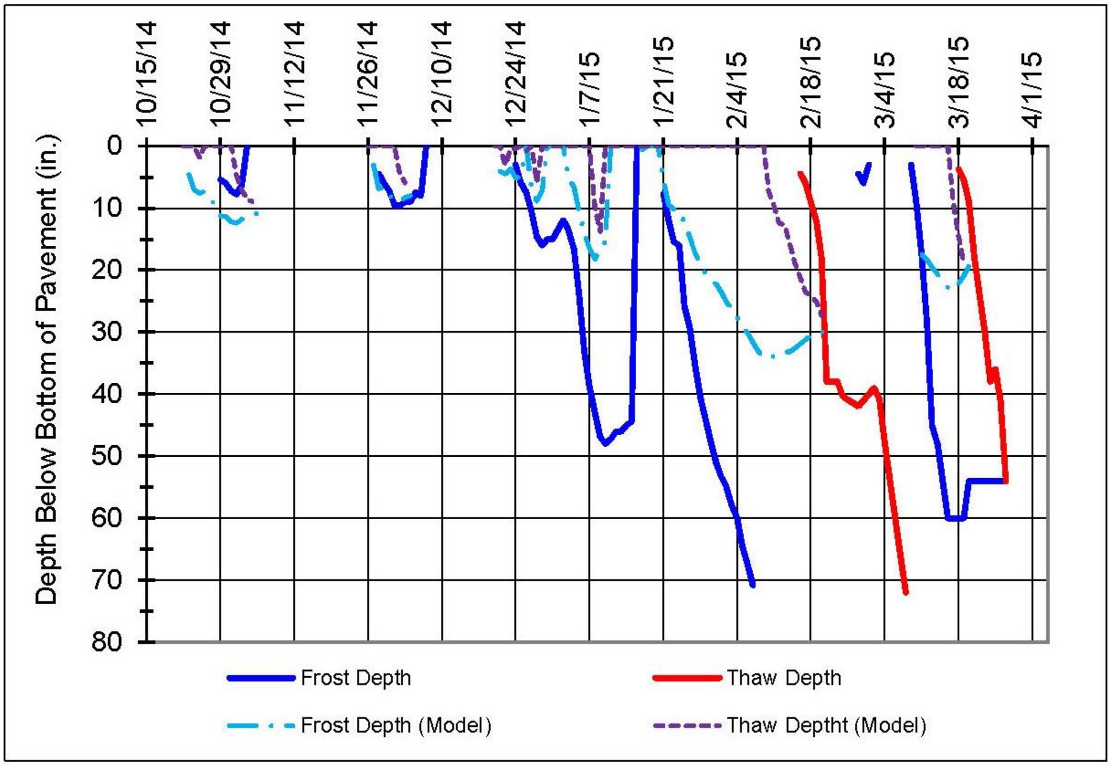
Ontario (527) **Model: Polynomial Regression

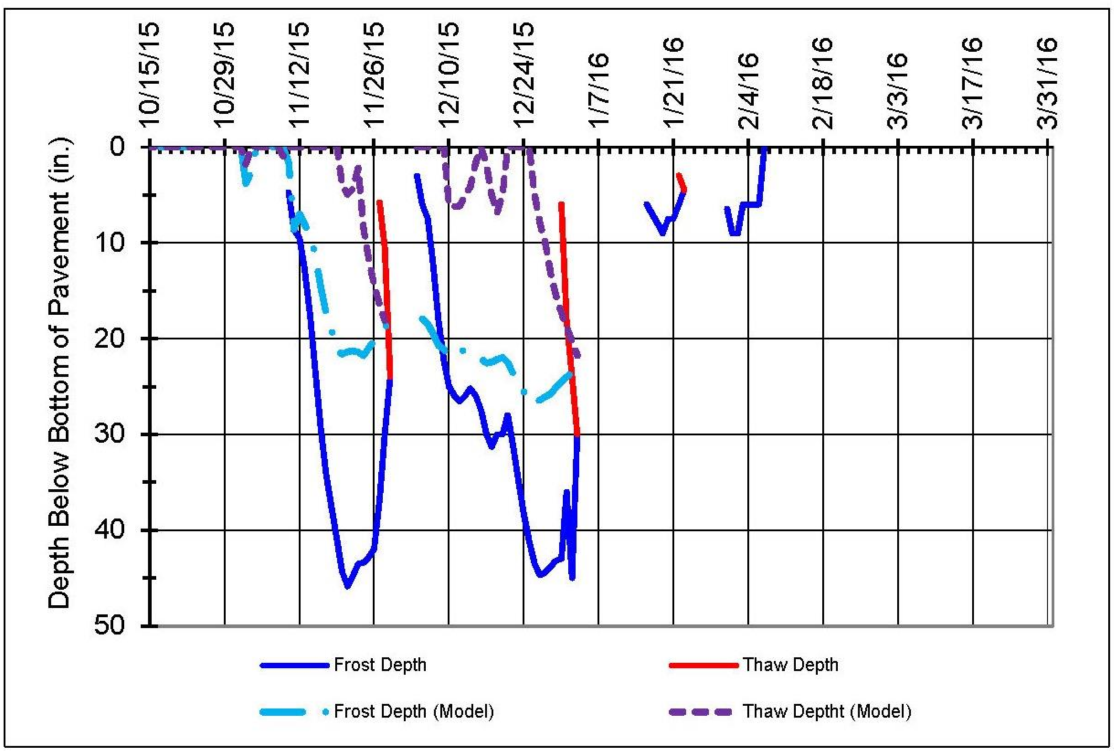


**These predicted frost & thaw depths were based upon model coefficients determined by Pernia (2014) from four seasons of measured frost & thaw depth data (2008-2009 through 2011-2012).

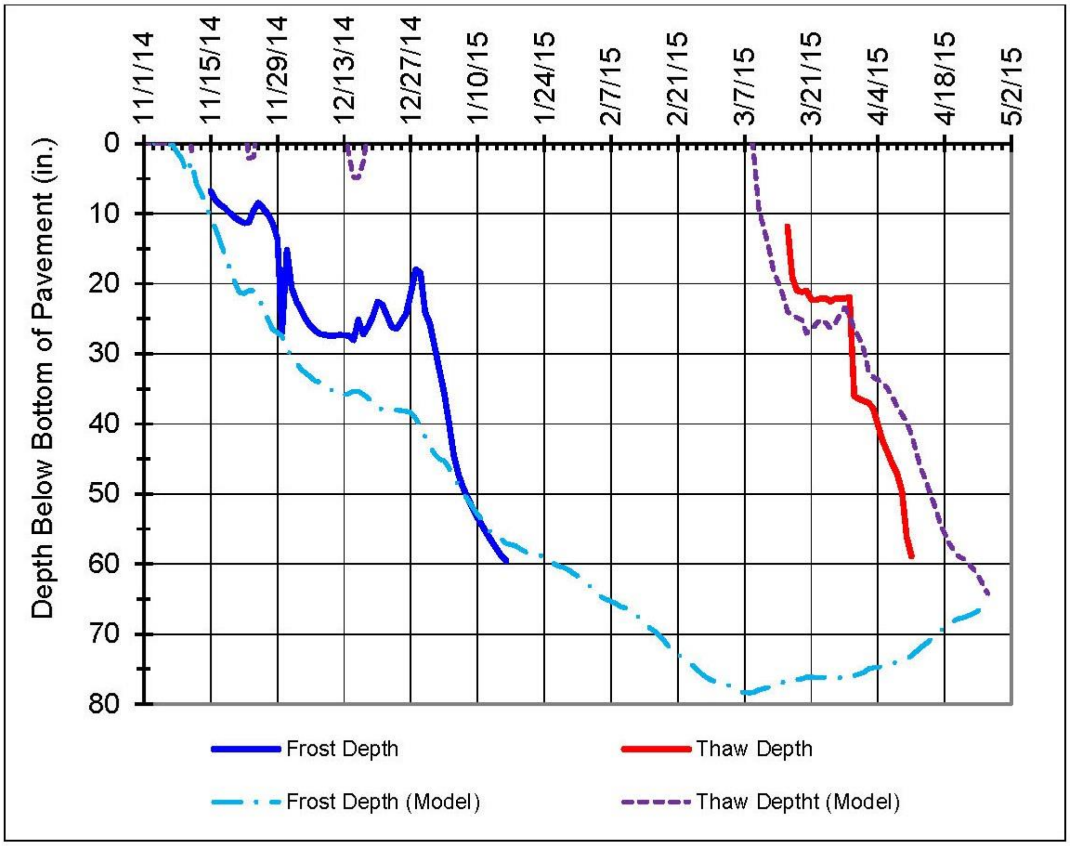
APPENDIX E. FROST AND THAW DEPTH PREDICTION MODELS: MODIFIED MODEL 158 (ORR AND IRWIN 2006, MILLER ET AL. 2015)

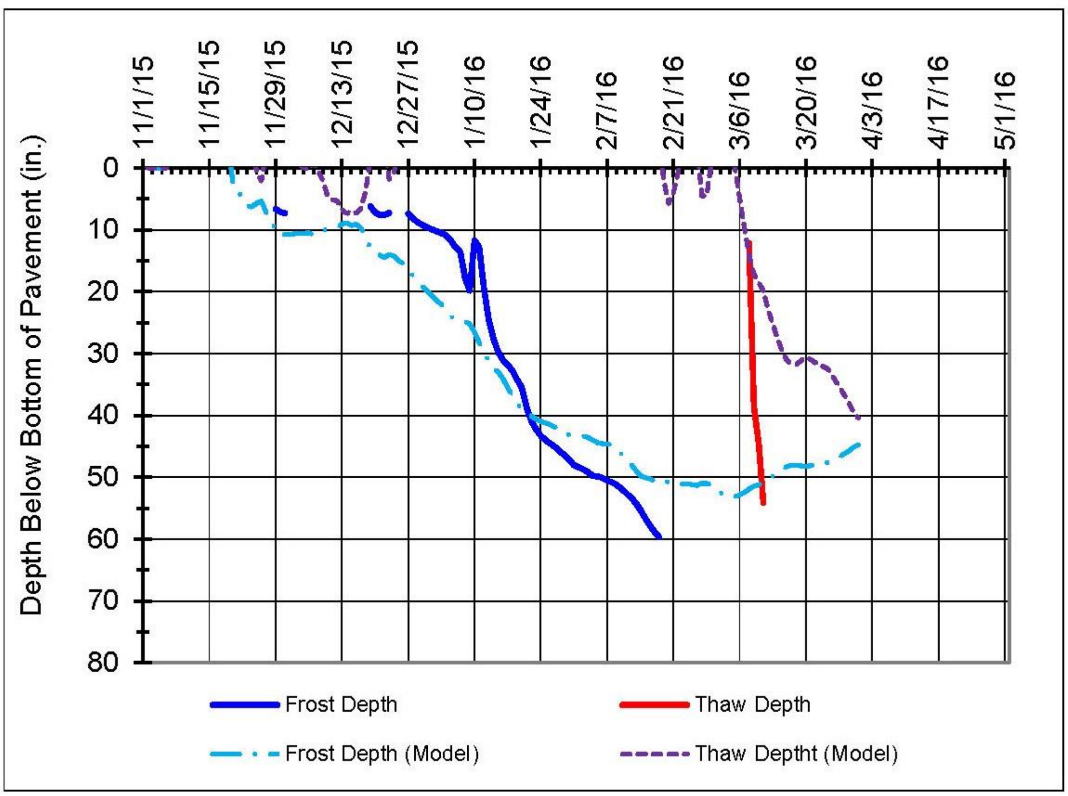
Alaska **Model 158**



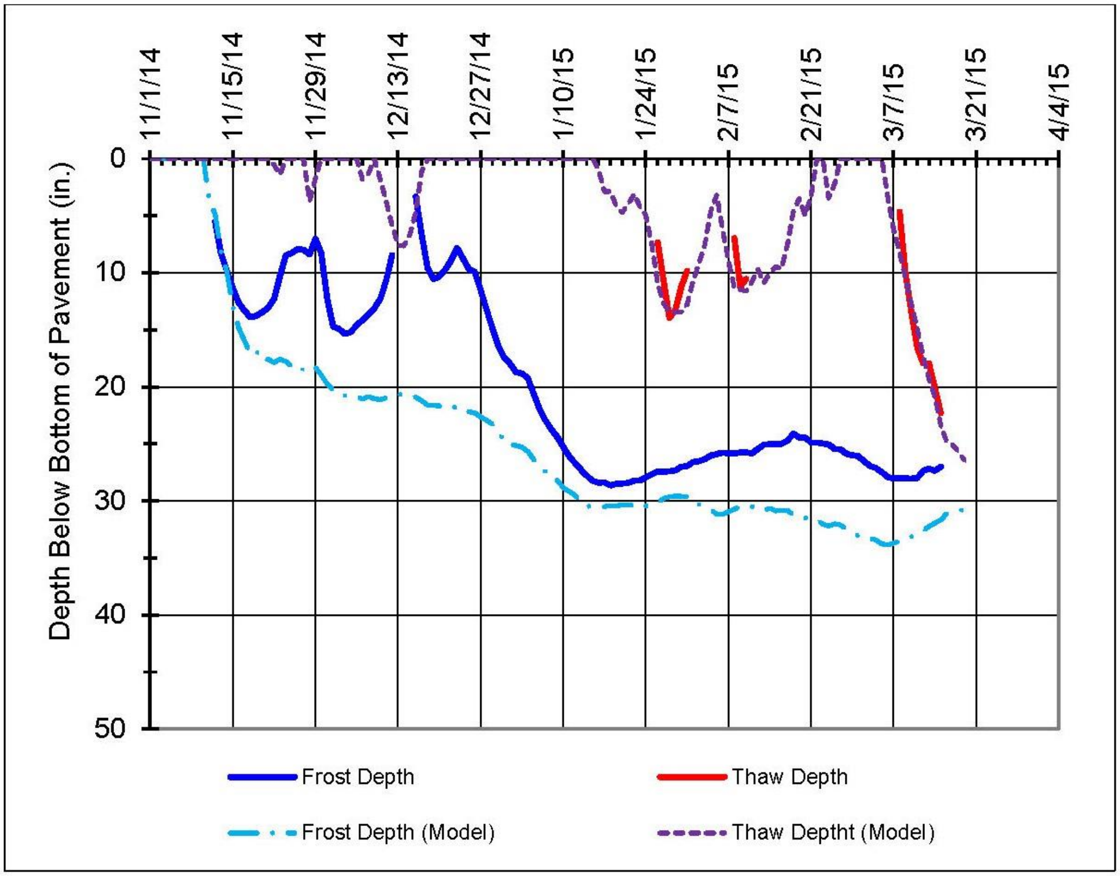


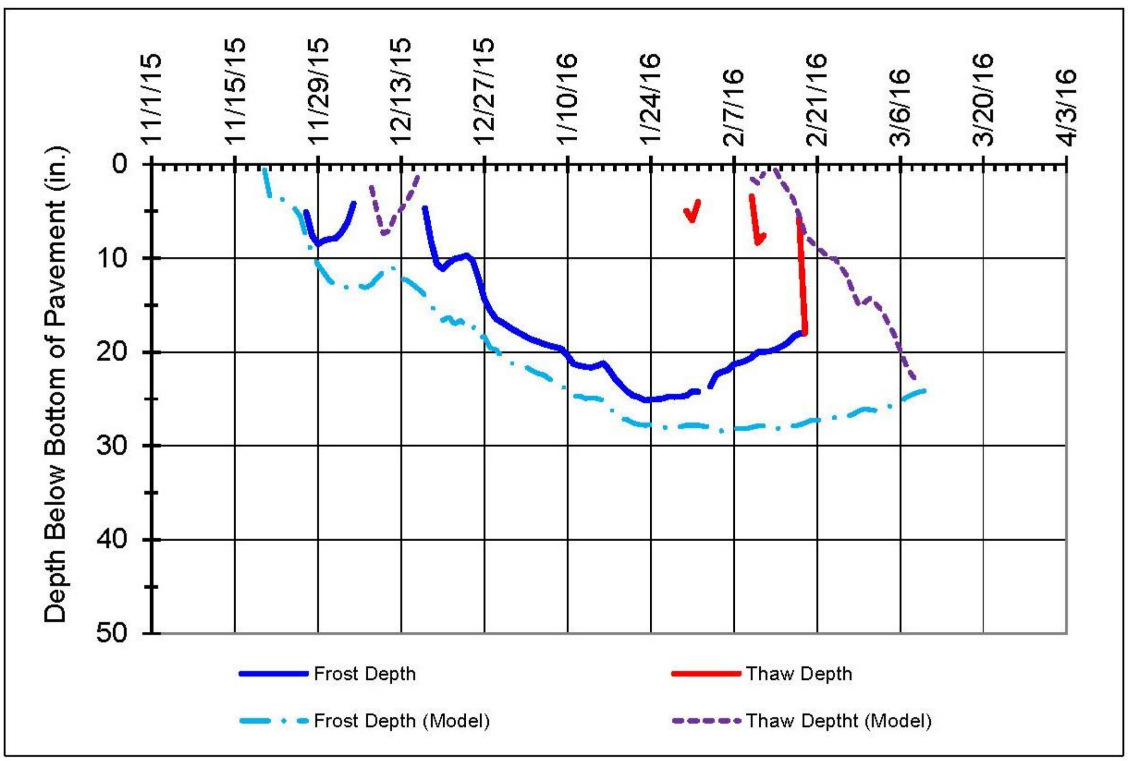
Michigan Model 158



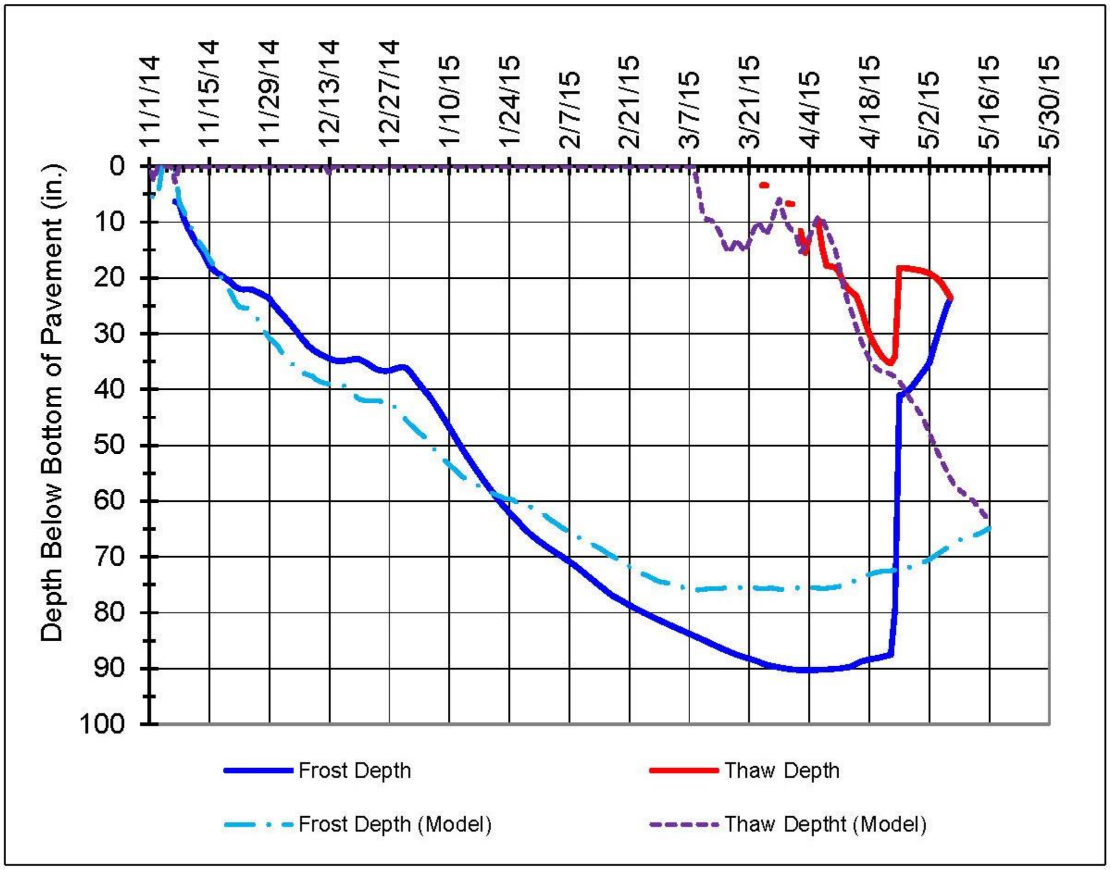


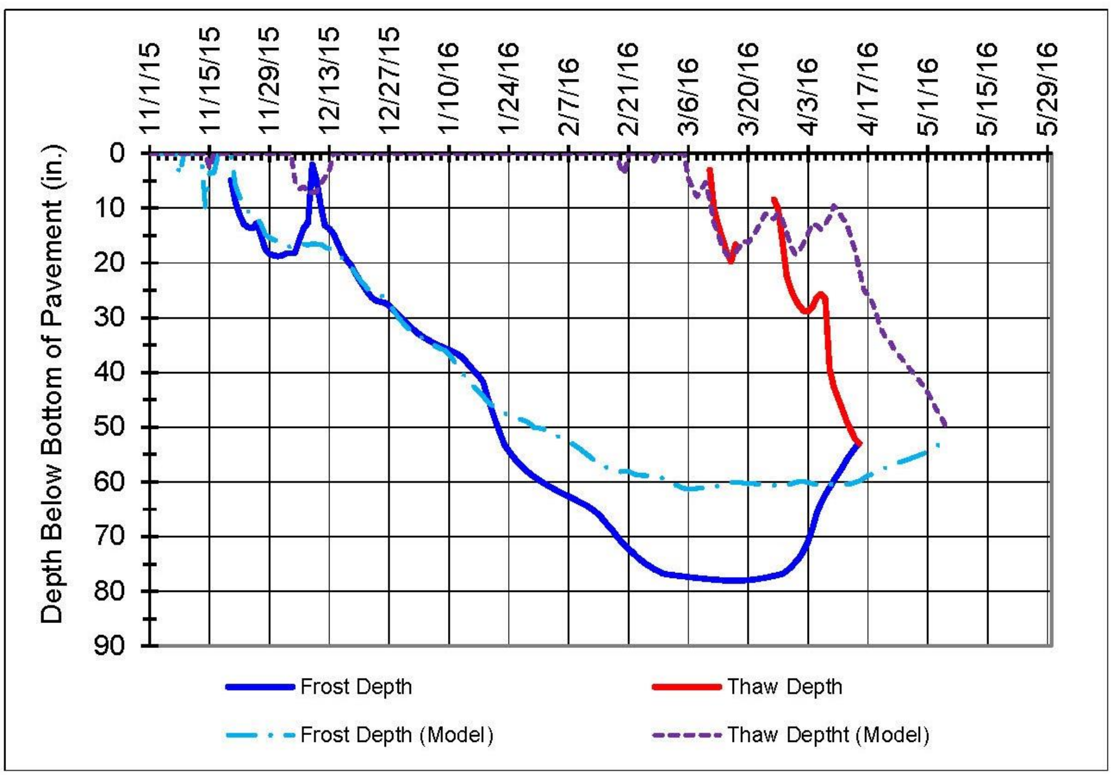
N. Dakota **Model 158**



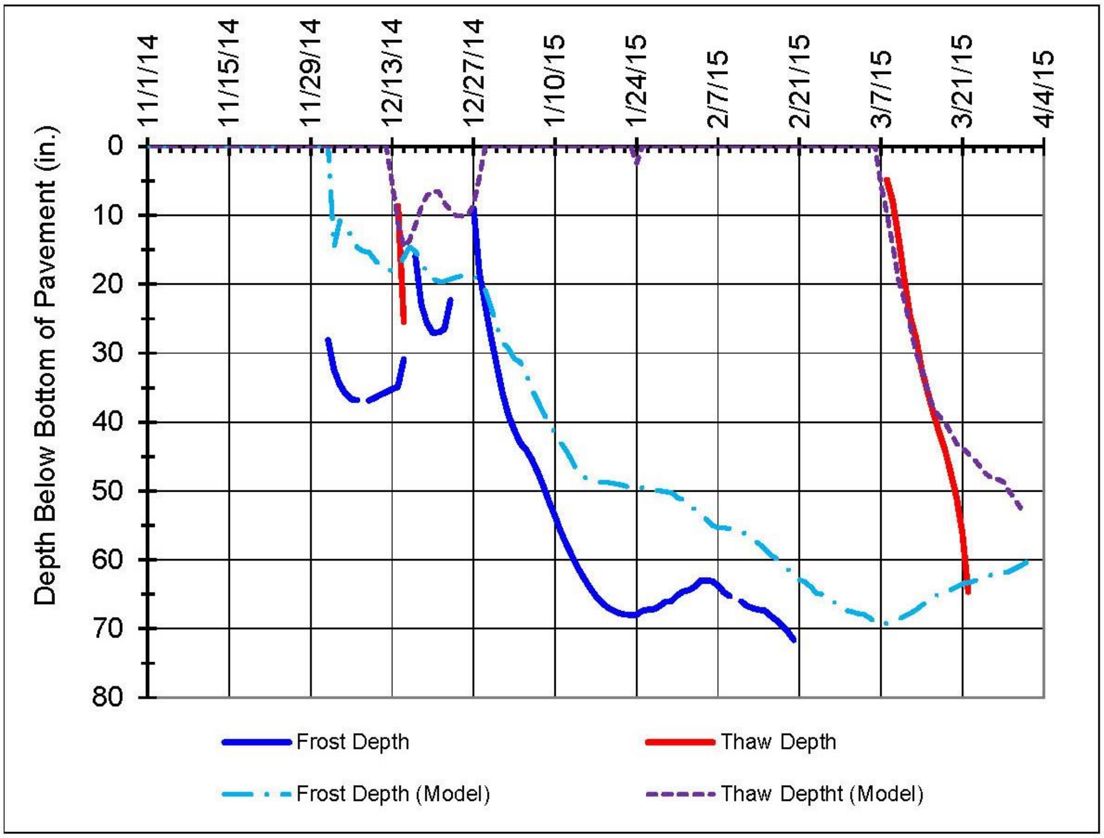


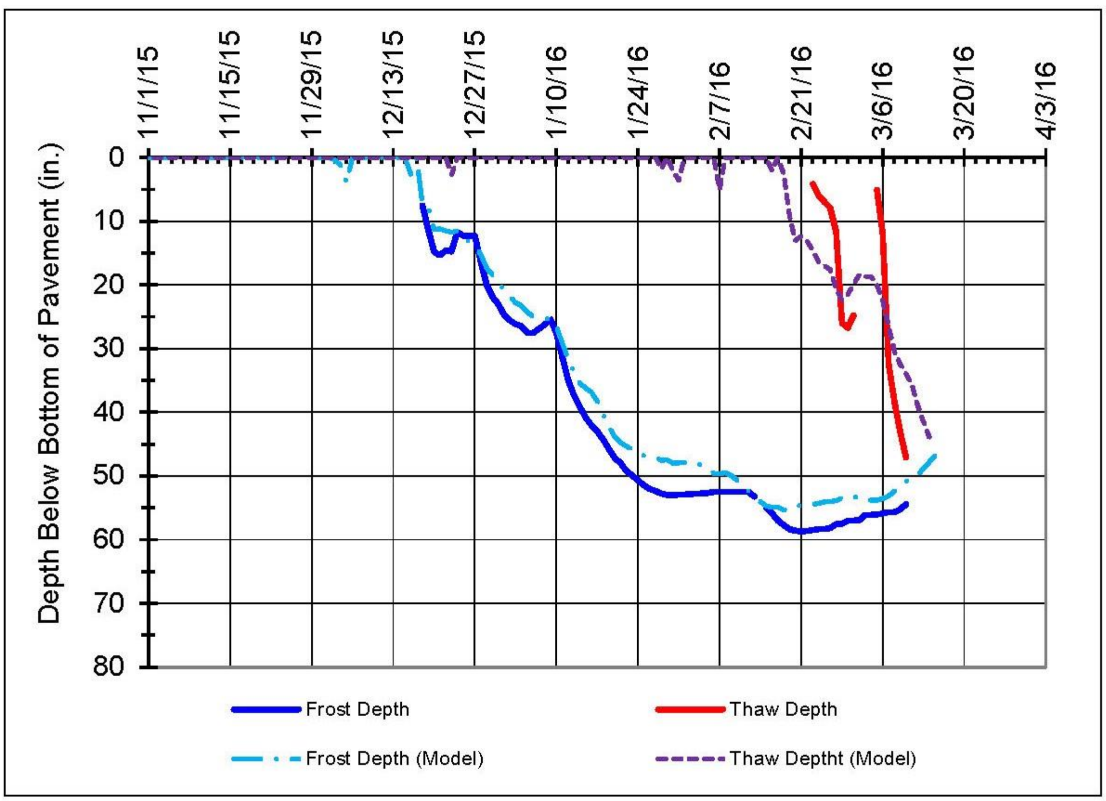
Ontario **Model 158** **Site 527**





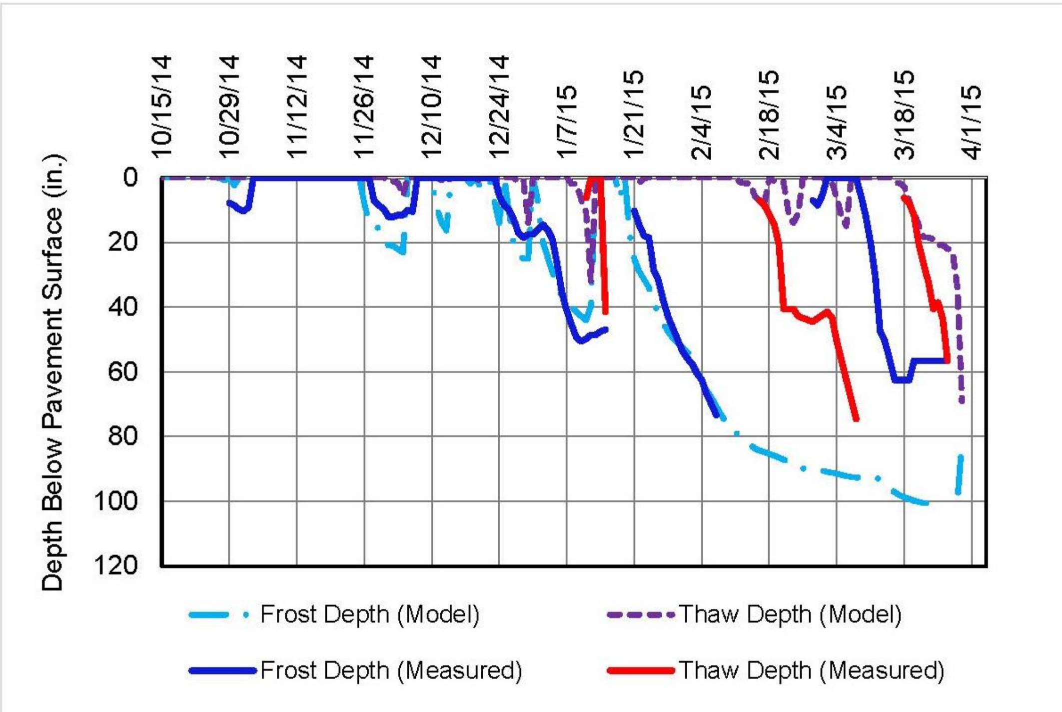
Wisconsin **Model 158**

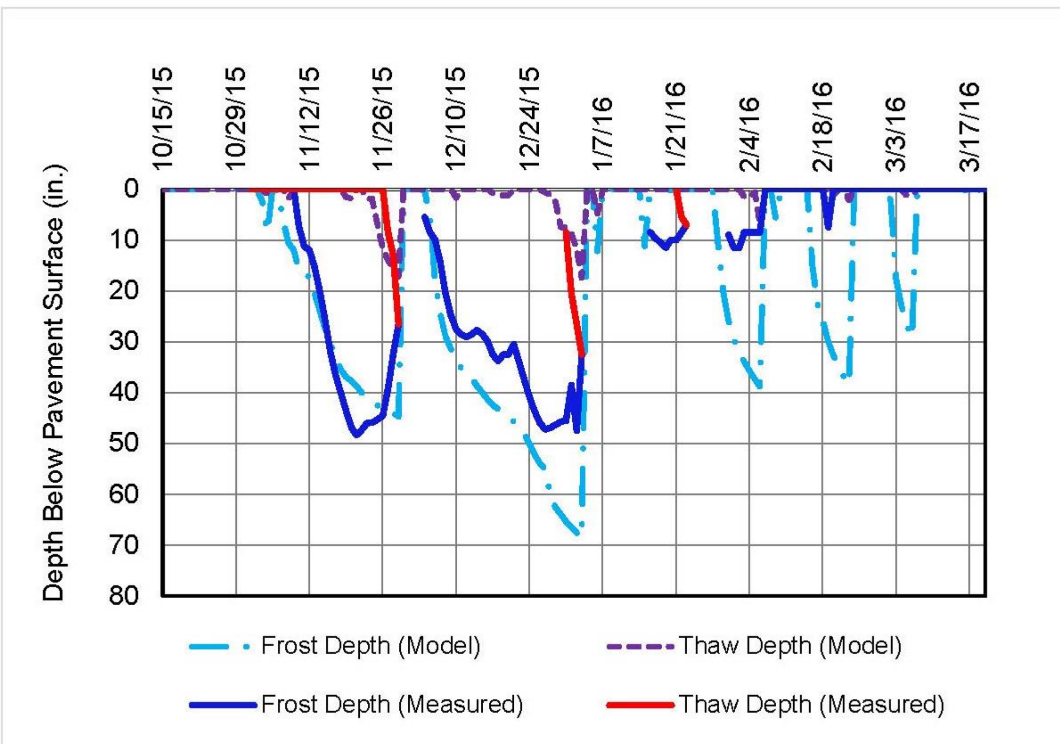




APPENDIX F. FROST AND THAW DEPTH PREDICTION MODELS: ENHANCED INTEGRATED CLIMATIC MODEL RUN VIA AASHTOWARE PAVEMENT ME DESIGN, V2.5

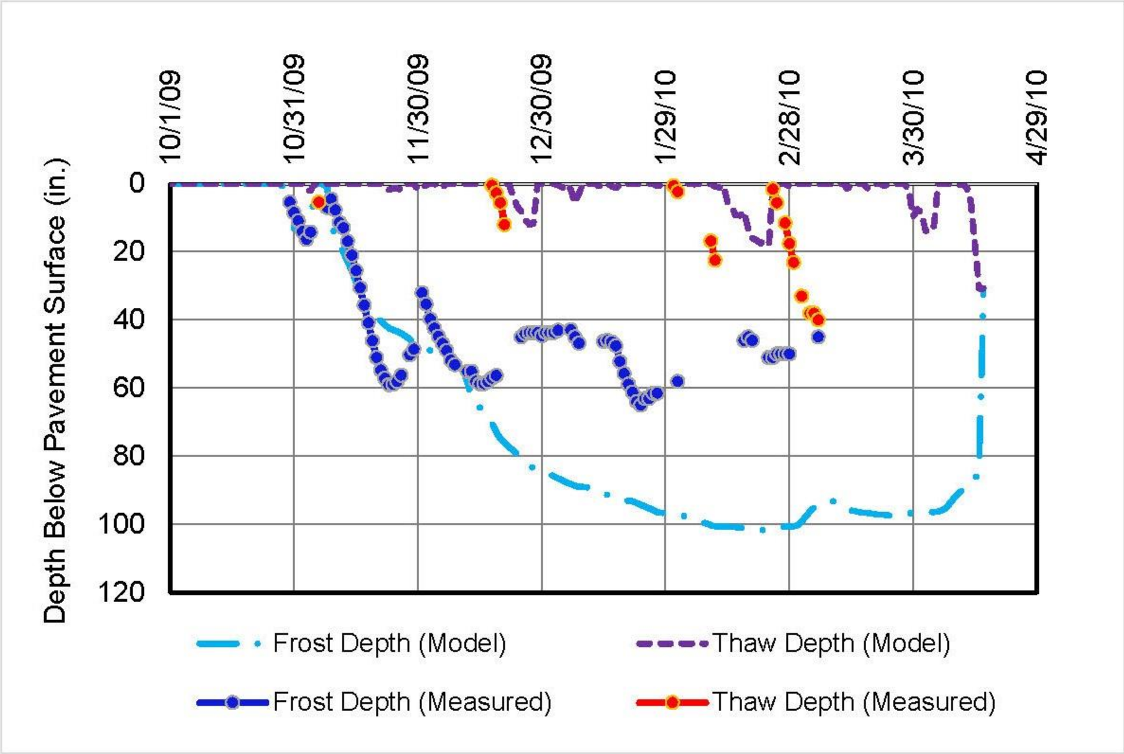
Alaska **Model: EICM (AASHTOWare Pavement ME Design Software)**

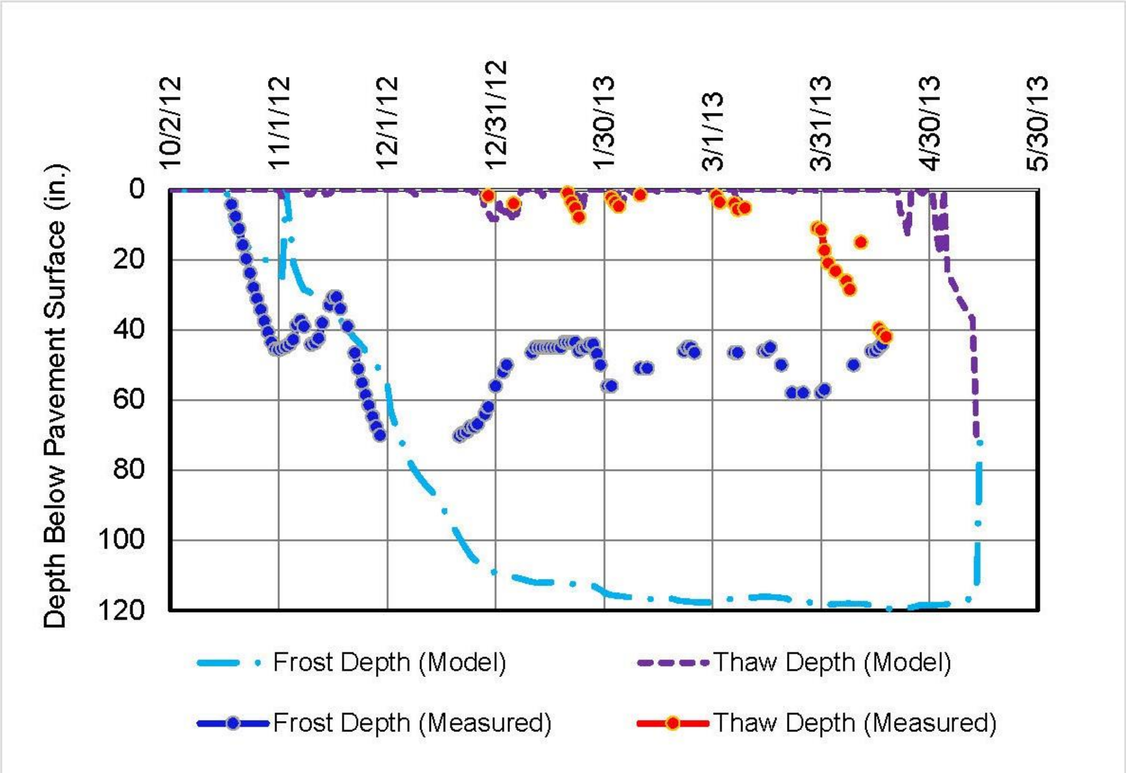




Alaska **Model: EICM (AASHTOWare Pavement ME Design Software)**

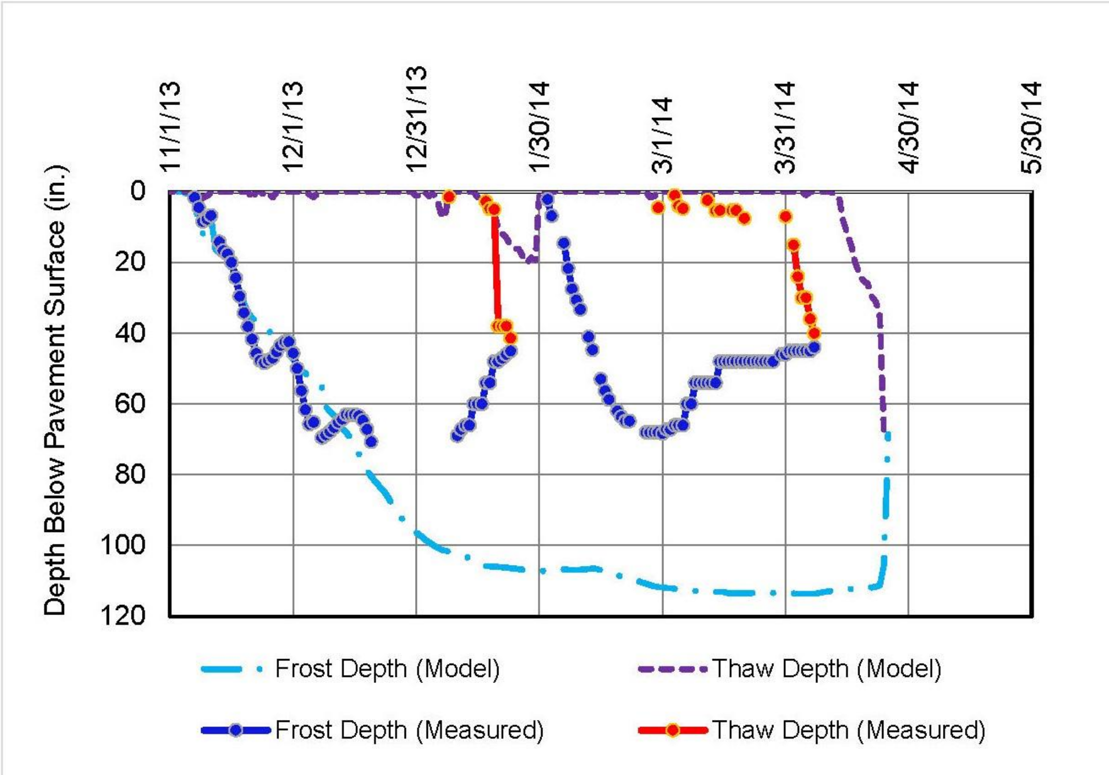
Extra analysis comparing model with measured frost-thaw depths in previous years





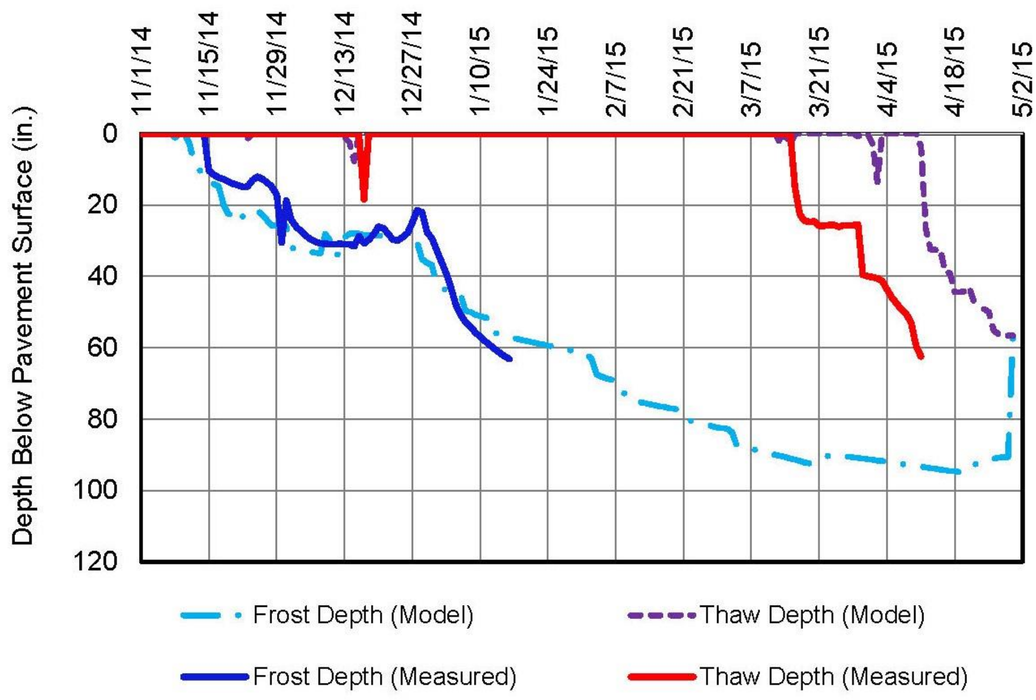
Alaska **Model: EICM (AASHTOWare Pavement ME Design Software)**

Extra analysis comparing model with measured frost-thaw depths in previous years

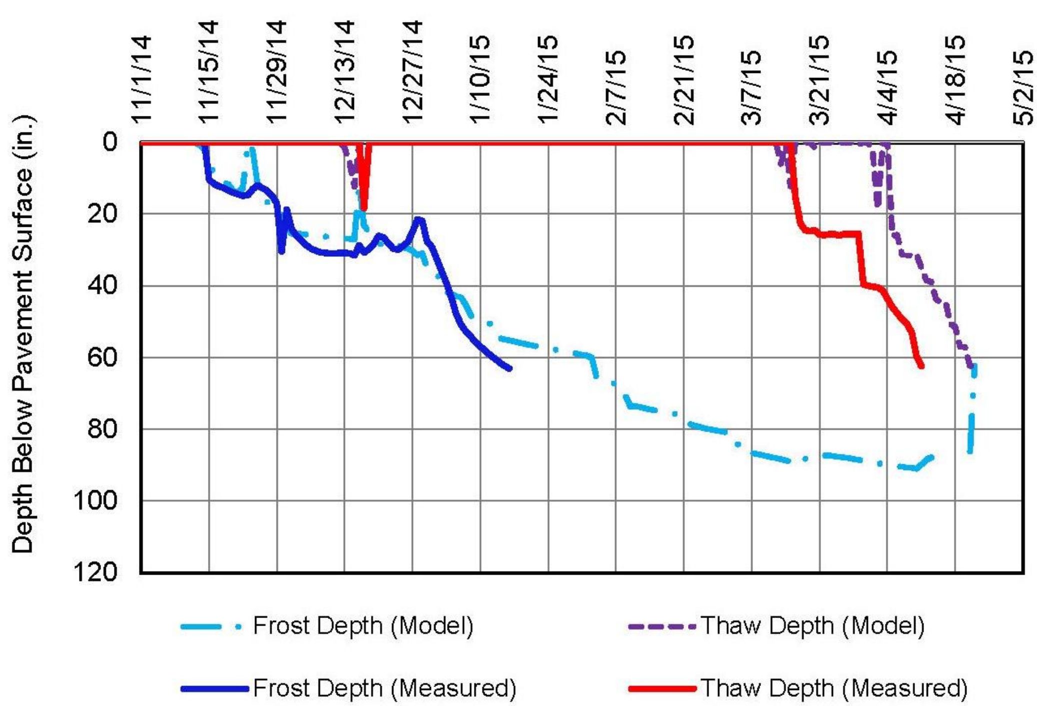


Michigan **Model: EICM (AASHTOWare Pavement ME Design Software)**

Run 3A: Climate Grid North of Site

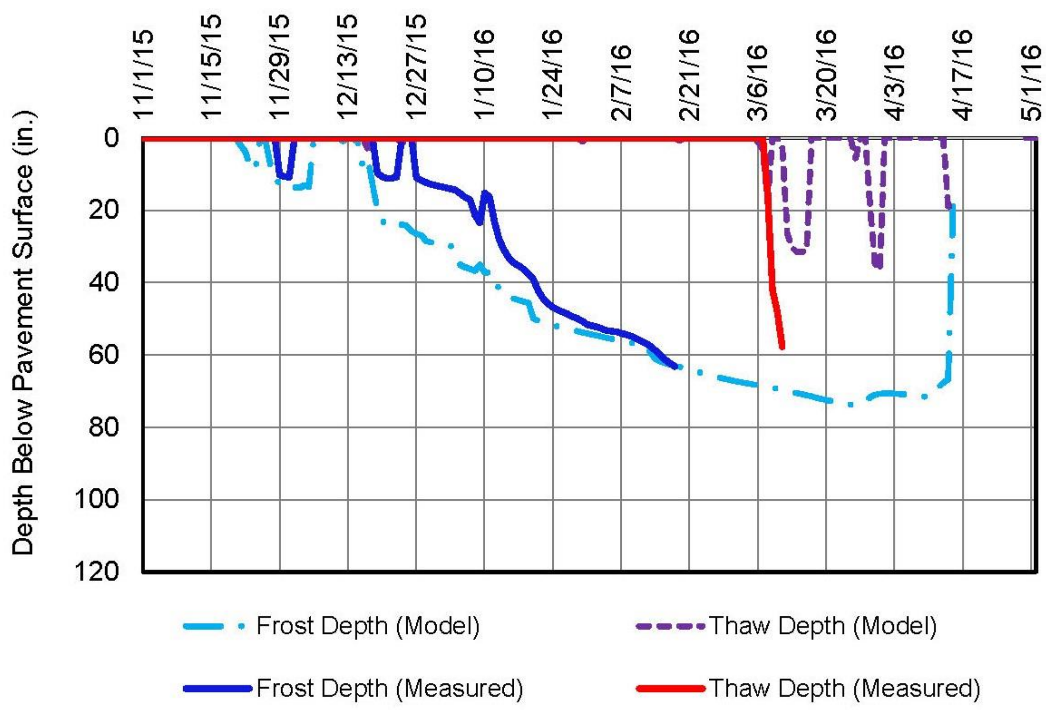


Run 3B: Climate Grid South of Site

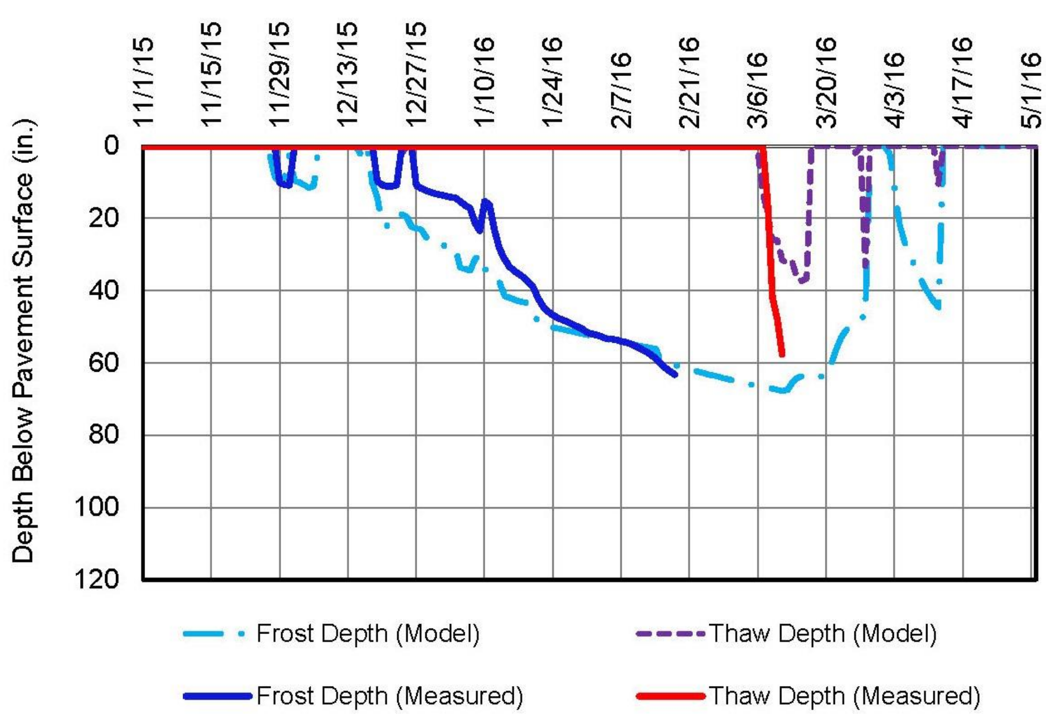


Michigan **Model: EICM (AASHTOWare Pavement ME Design Software)**

Run 3A: Climate Grid North of Site

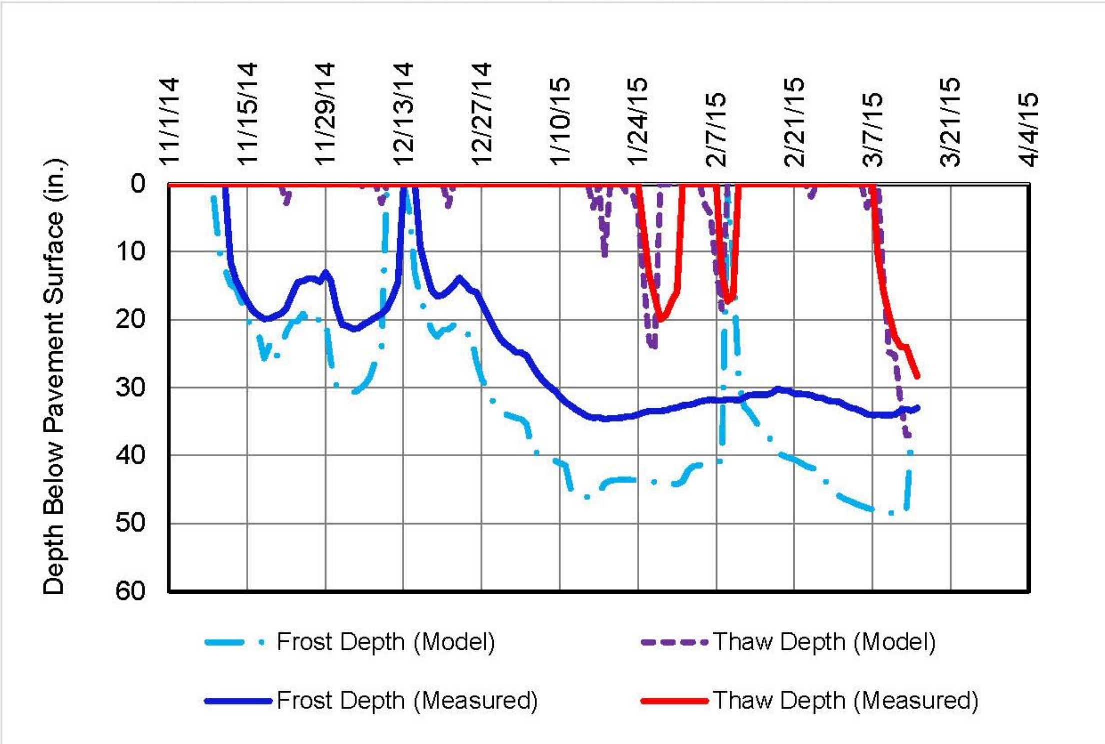


Run 3B: Climate Grid South of Site

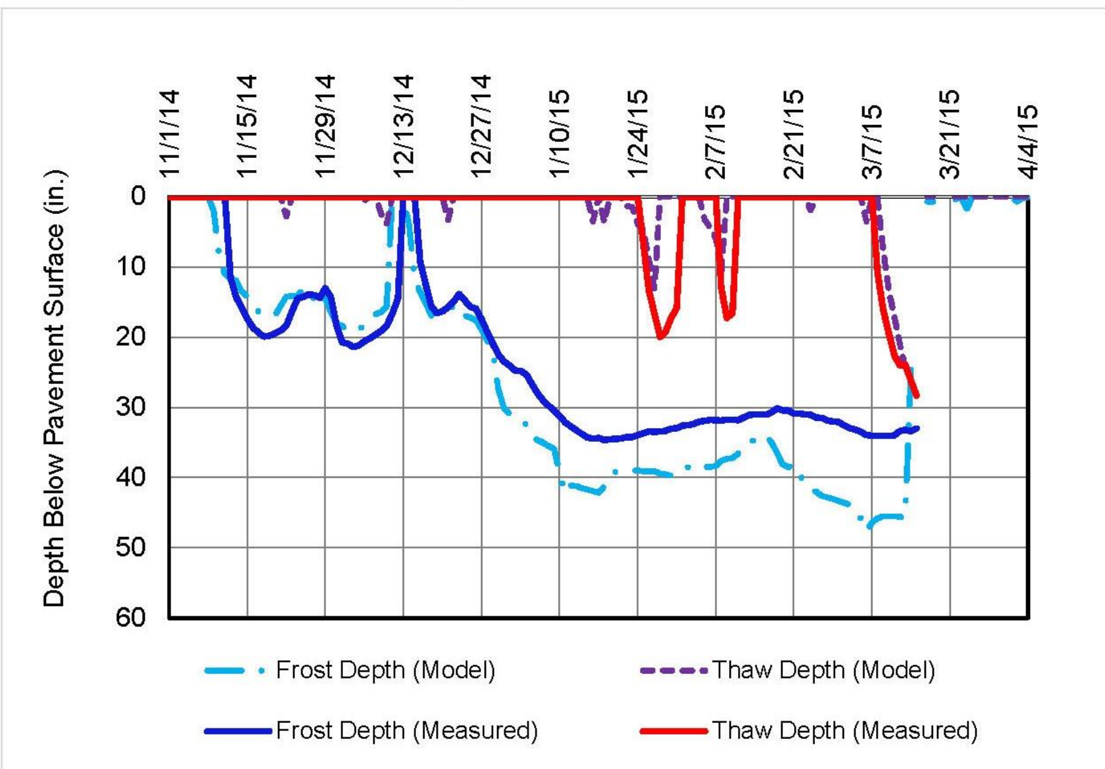


N. Dakota **Model: EICM (AASHTOWare Pavement ME Design Software)**

Run 1B Most reasonable Inputs based on Lab/Measured Soil Properties

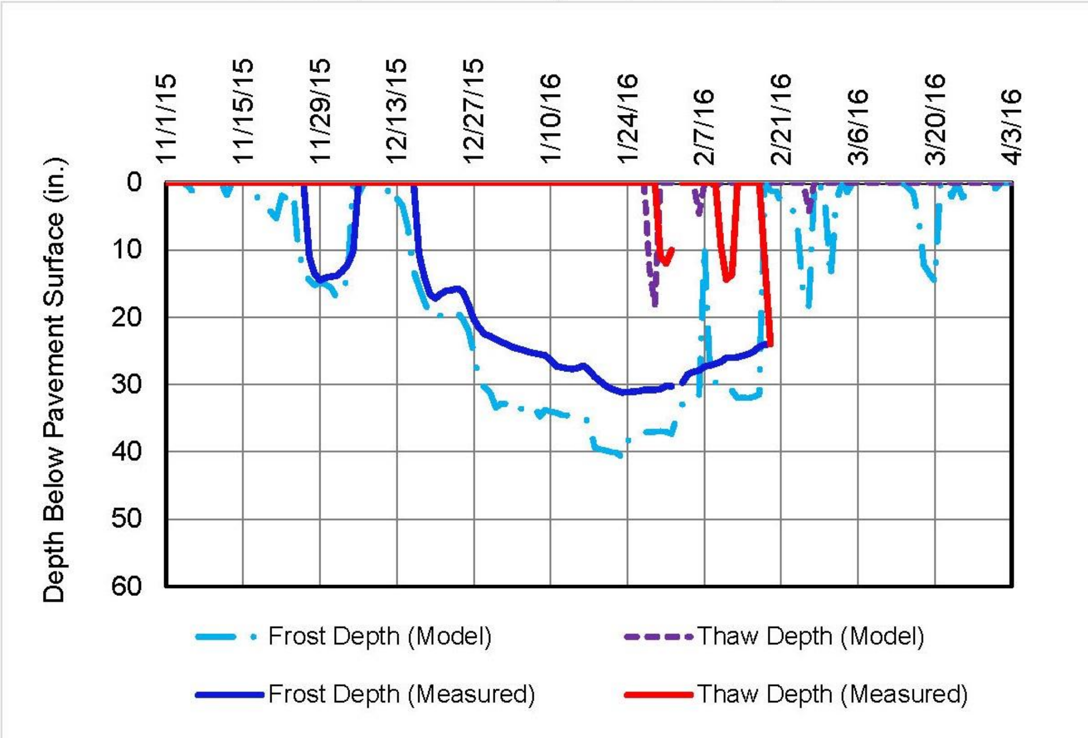


Run 1D Same as 1B, but increased Layer 2 moisture and fines content

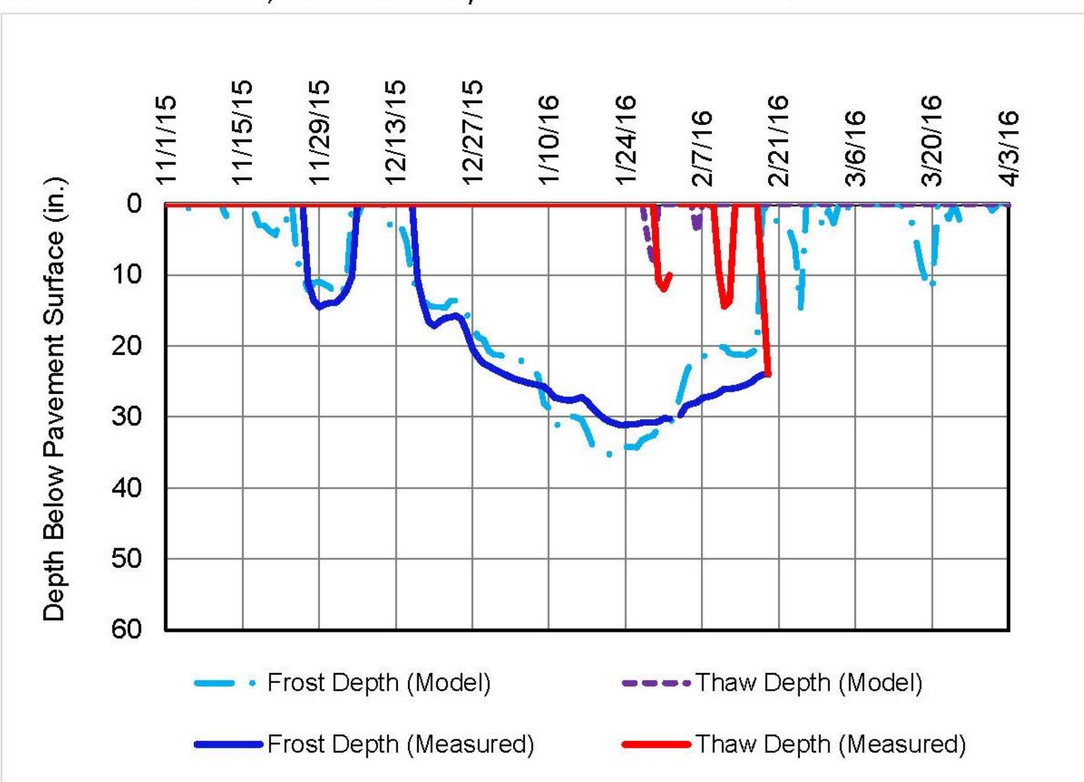


N. Dakota **Model: EICM (AASHTOWare Pavement ME Design Software)**

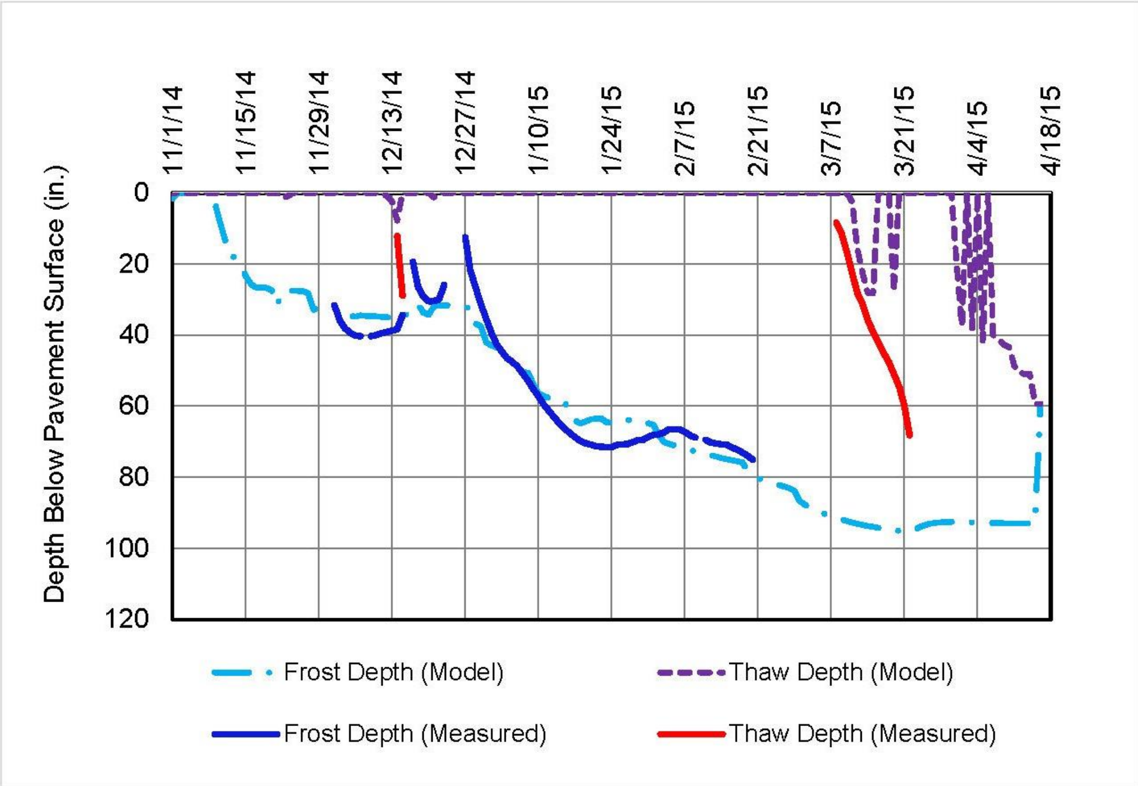
Run 1B Most reasonable Inputs based on Lab/Measured Soil Properties

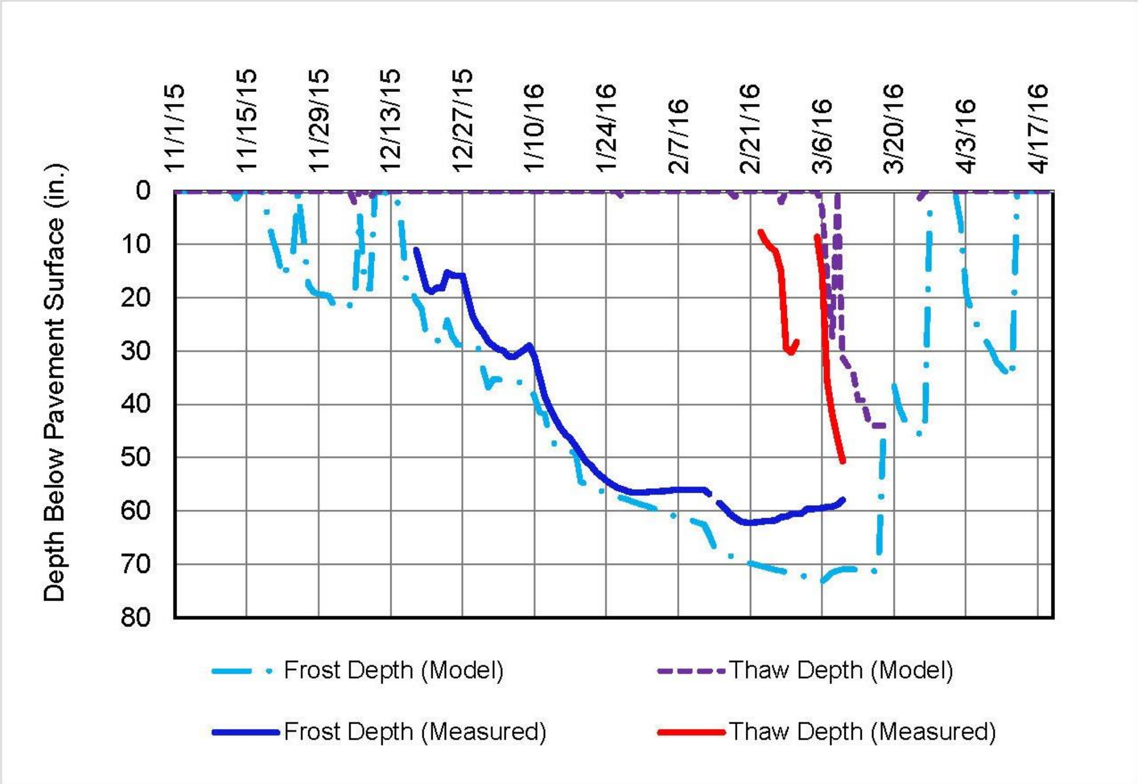


Run 1D Same as 1B, but increased Layer 2 moisture and fines content

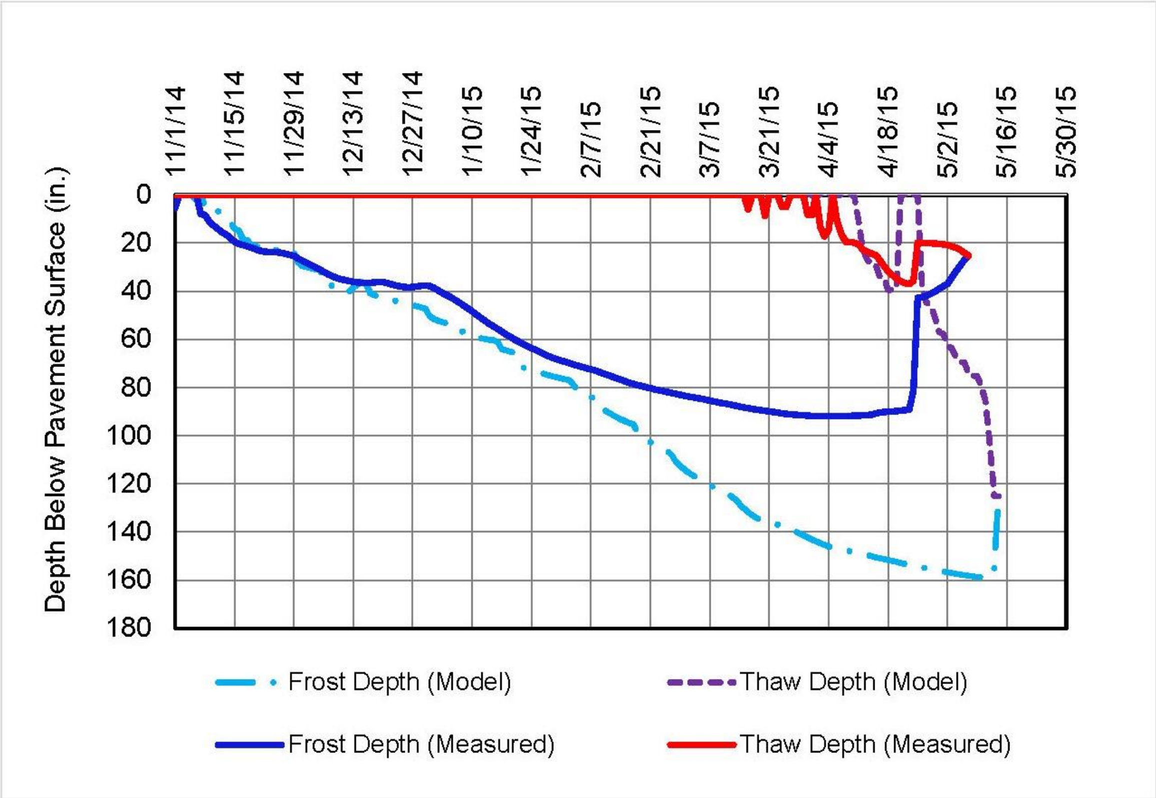


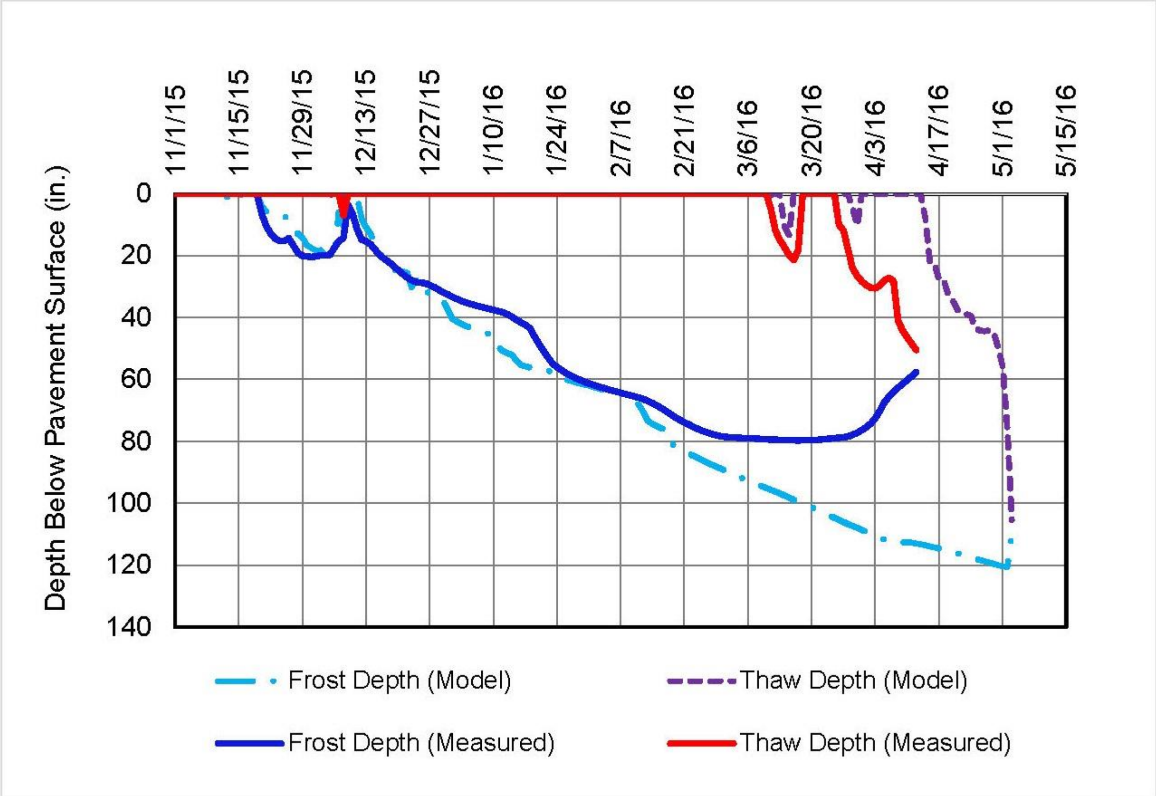
Wisconsin **Model: EICM (AASHTOWare Pavement ME Design Software)**





Ontario Site 527 Model: EICM (AASHTOWare Pavement ME Design Software)





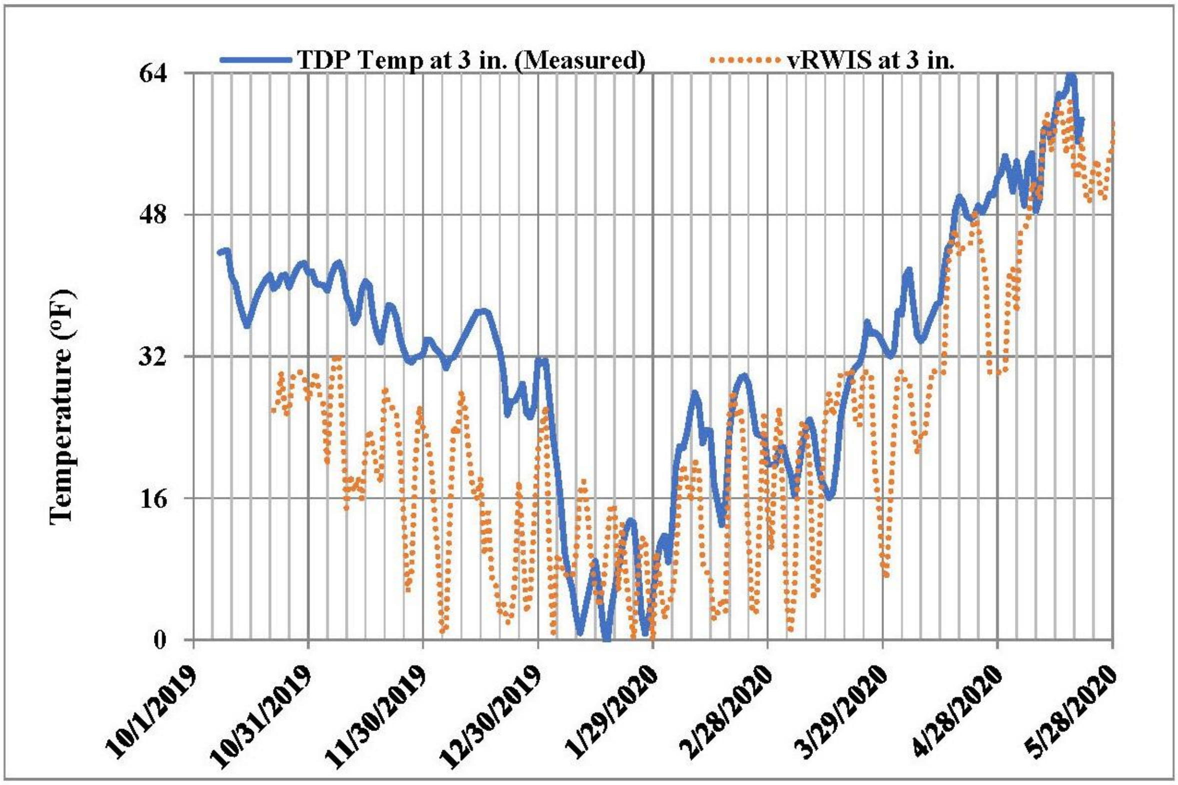
APPENDIX G. FROST AND THAW DEPTH PREDICTION MODELS: ENHANCED INTEGRATED CLIMATIC MODEL RUN USING VRWIS SOFTWARE INTERFACE (SET UP BY APPLIED RESEARCH ASSOCIATES)

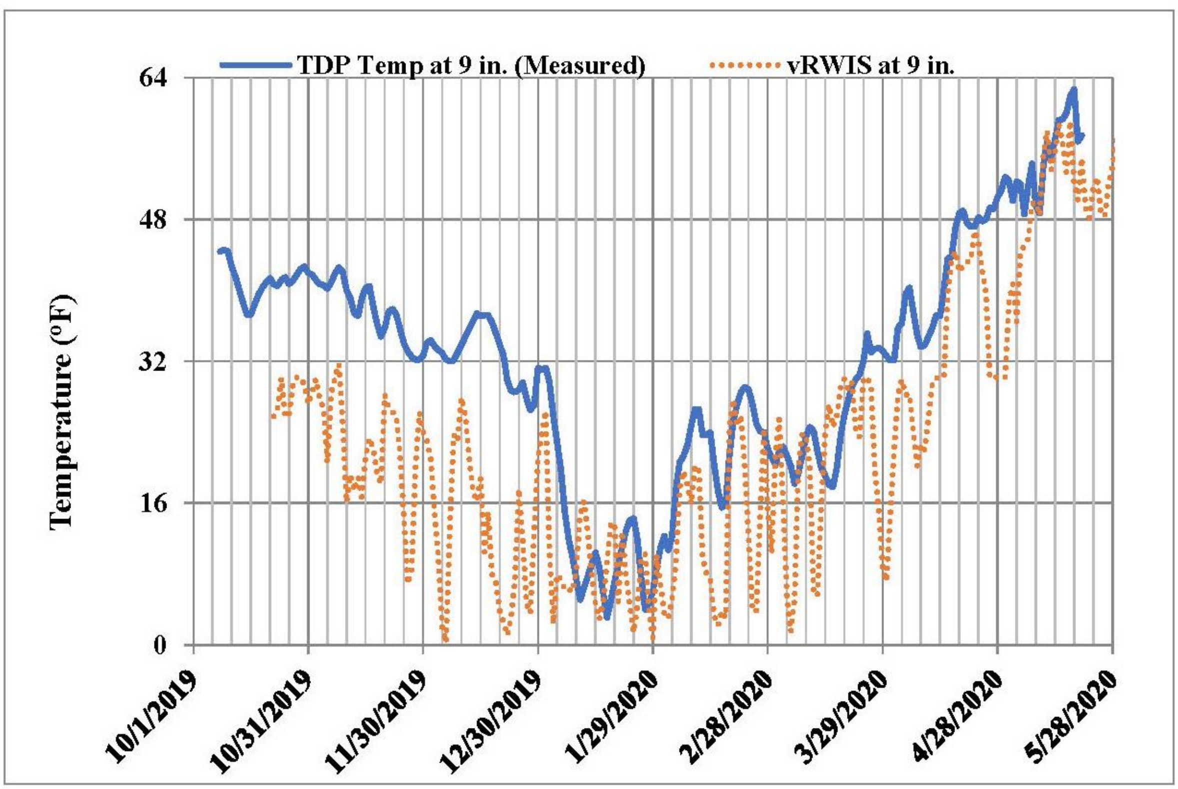
Notes:

1. For each site, a plot is presented comparing frost and thaw depths predicted by the EICM with those based upon measured subsurface temperatures from temperature depth probes (TDPs). The frost and thaw depths are based on interpolation between nodes (EICM) and between adjacent TDP sensors. Daily average values of temperatures were used for both measured and predicted frost and thaw depths.
2. Following the frost and thaw depth plot for each site, we have included several time series plots that compare measured temperatures at a given TDP with EICM-predicted temperatures from a node at a comparable depth or at one node just above and one node just below the TDP depth. In these plots, temperatures are all daily average values, except where noted. In a few plots, temperatures predicted at noontime by the EICM were included (since noontime values are displayed on the Calendar, Chart, and Temperature Profile tabs in the vRWIS software interface). All of the vRWIS node depths listed in these plots are measured from the top of the pavement surface.

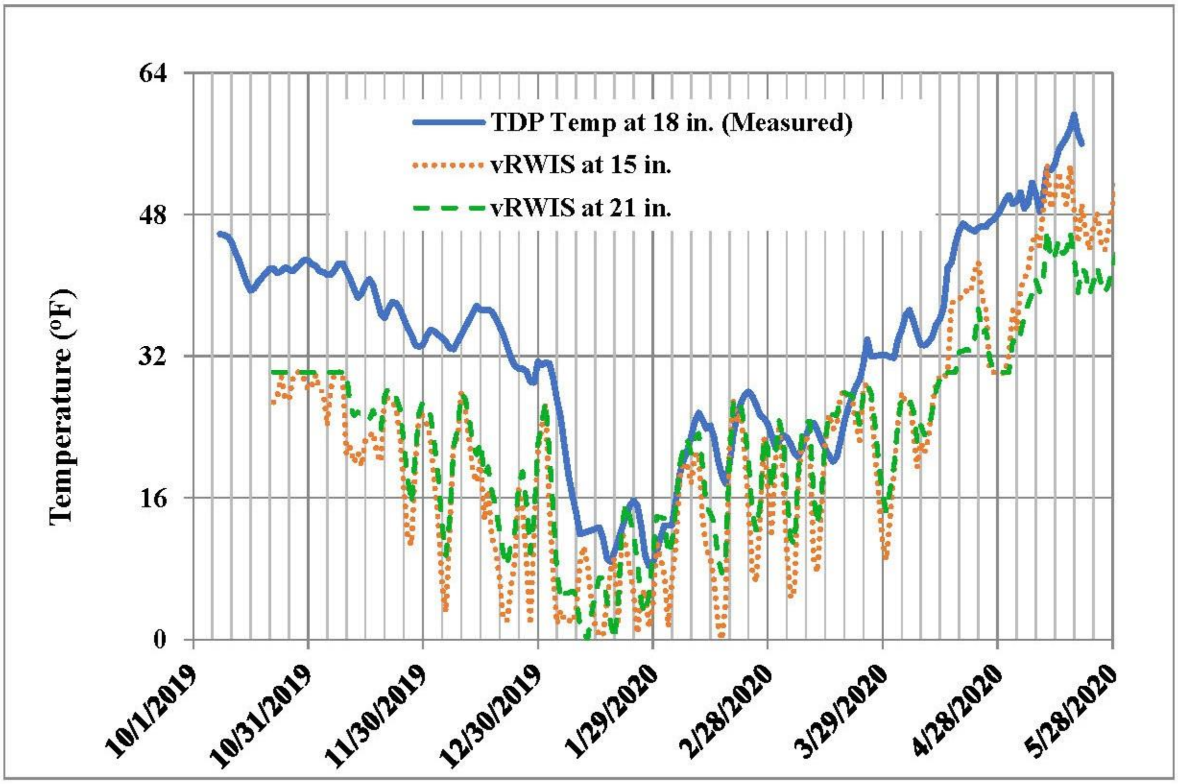
Alaska **Model: EICM (Model Run Using vRWIS Software Interface)**

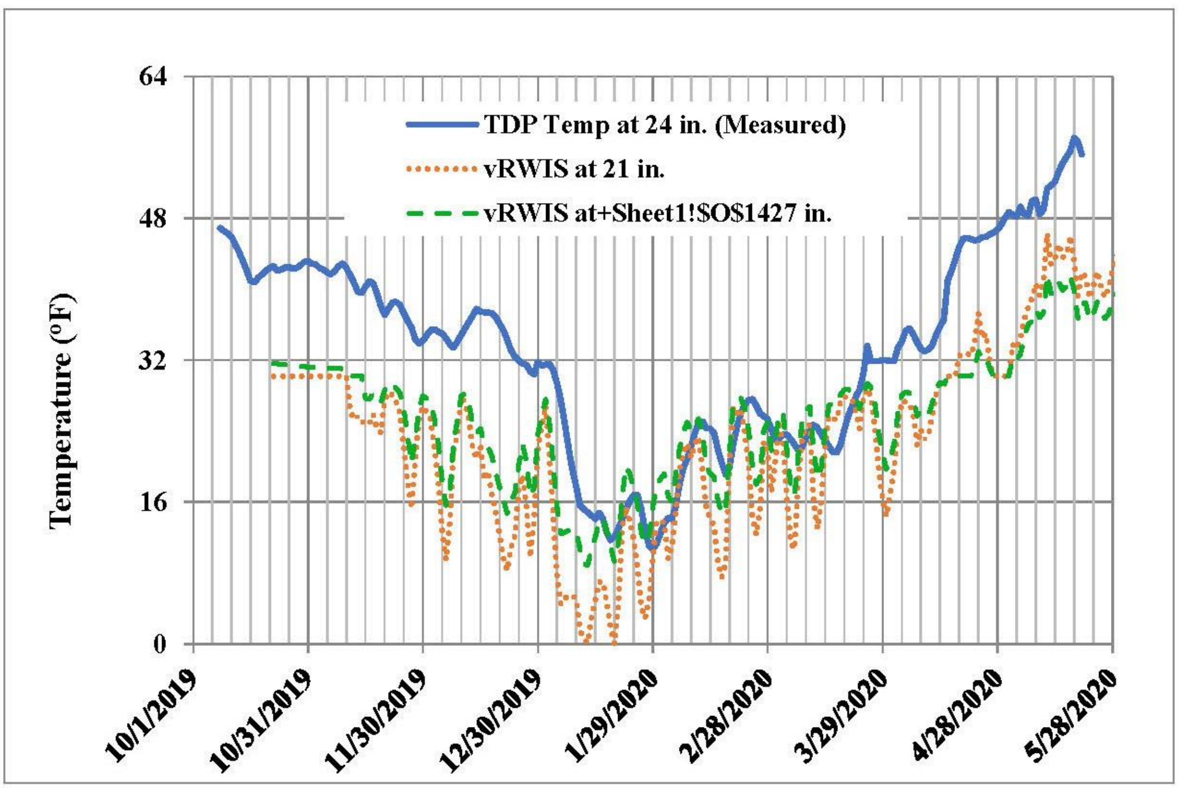
Note: Interpolated frost-thaw depths not provided by ARA for Alaska Site



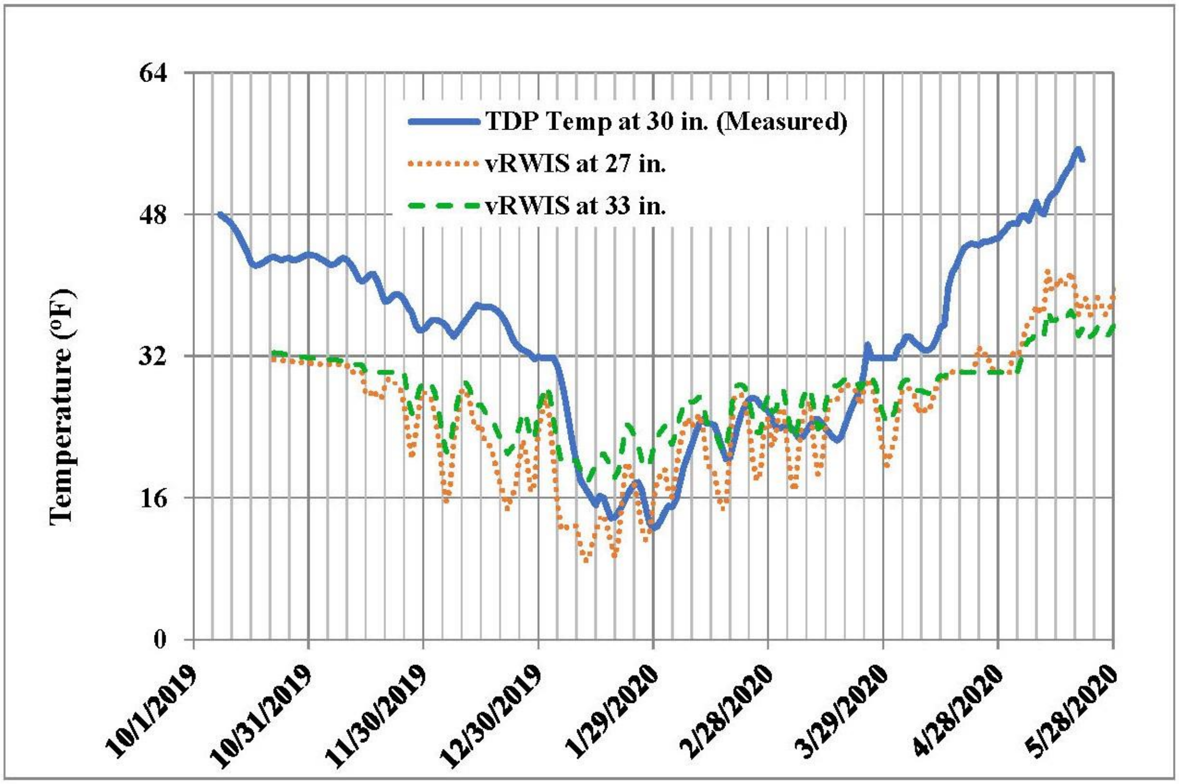


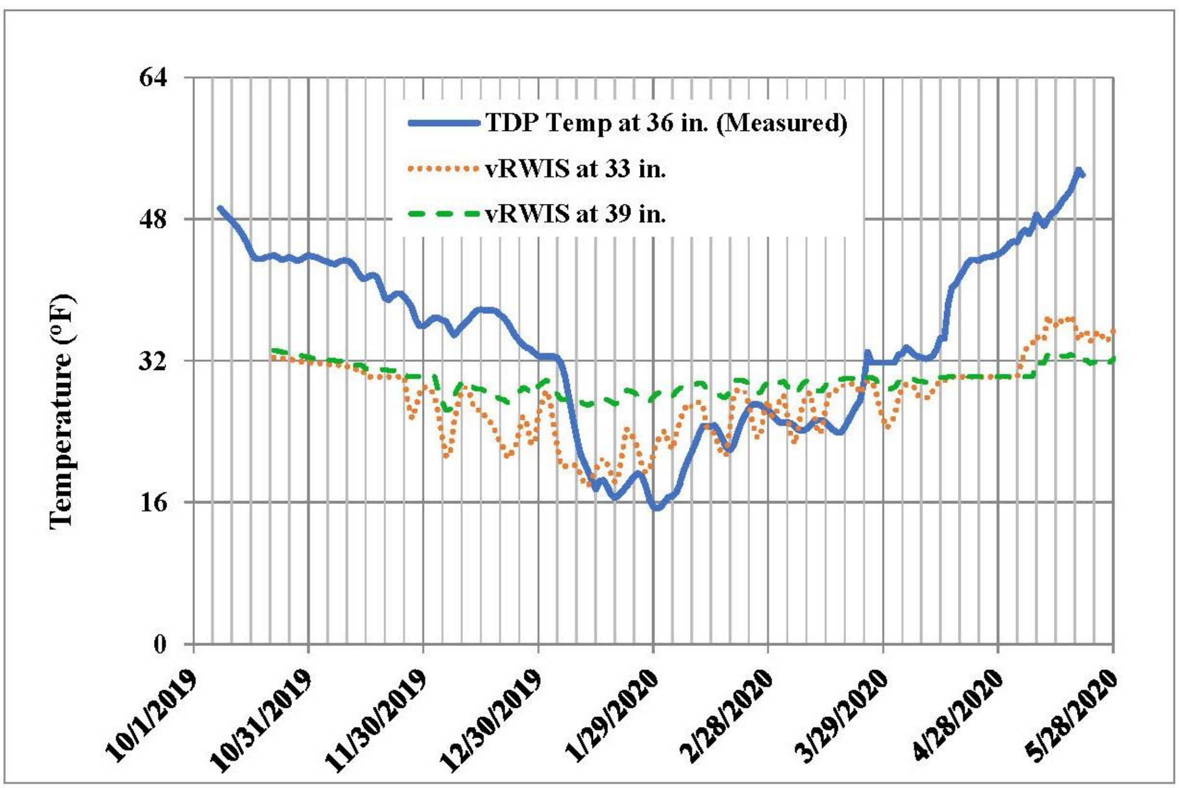
Alaska **Model: EICM (Model Run Using vRWIS Software Interface)**



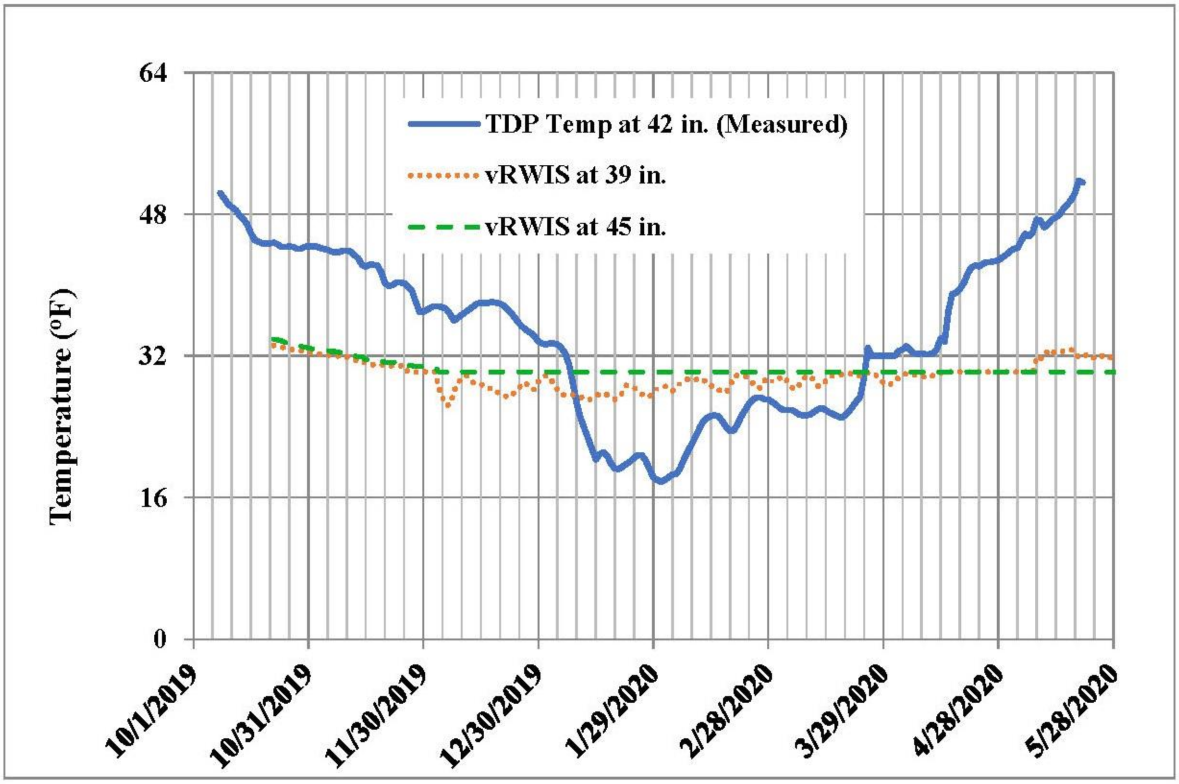


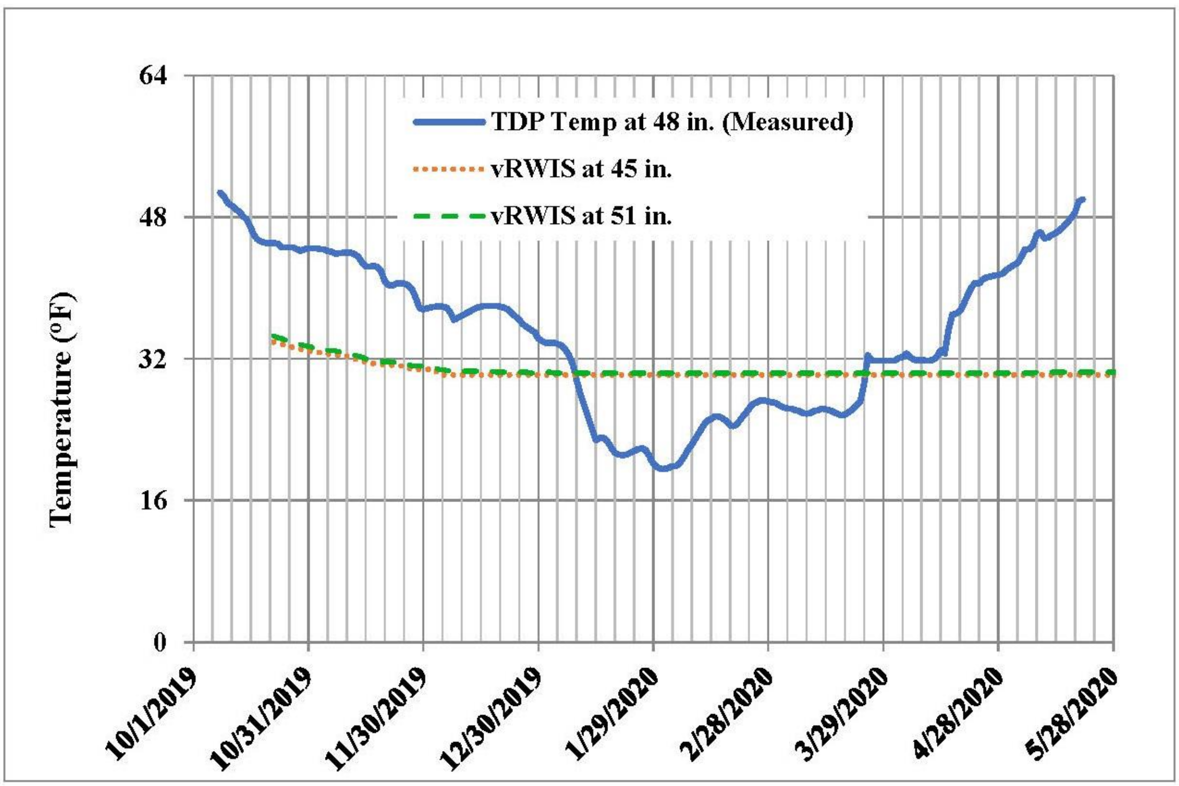
Alaska **Model: EICM (Model Run Using vRWIS Software Interface)**



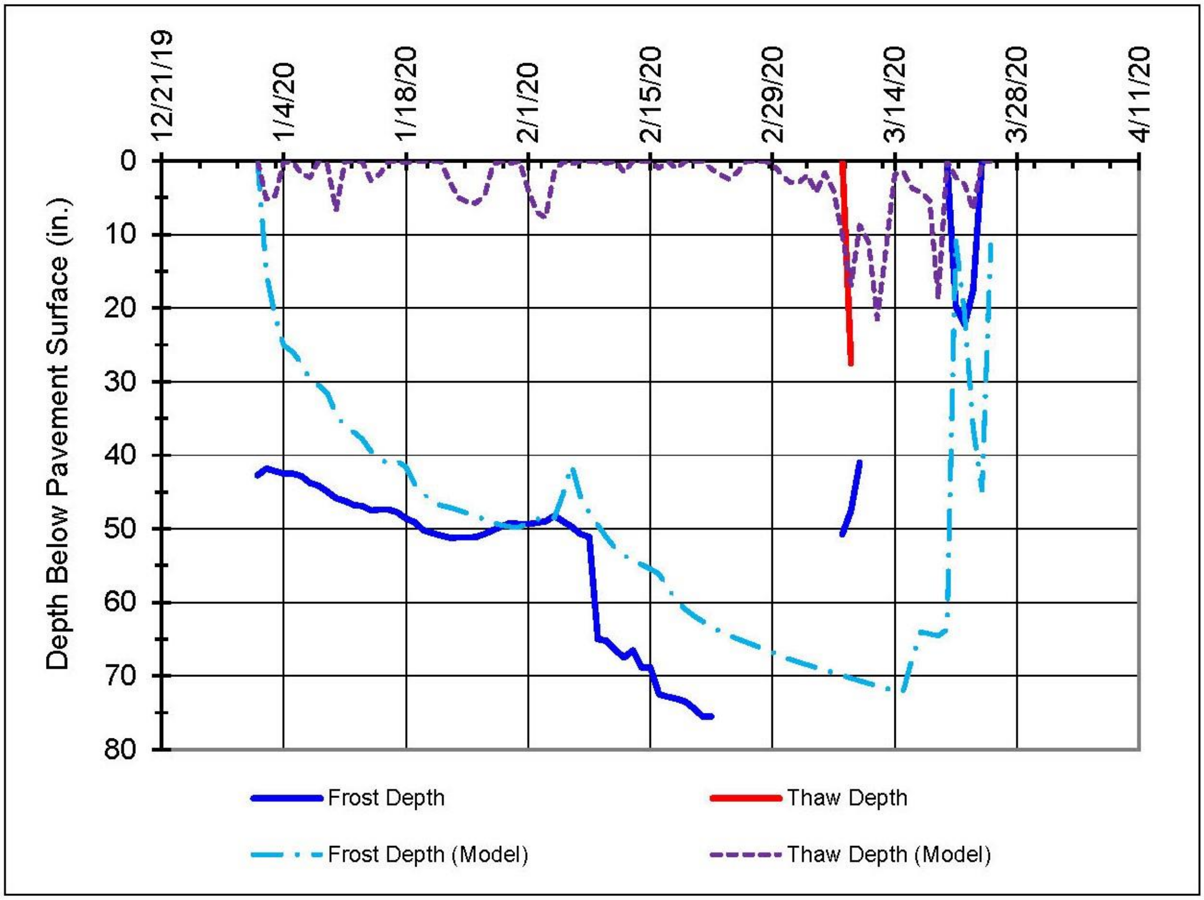


Alaska **Model: EICM (Model Run Using vRWIS Software Interface)**

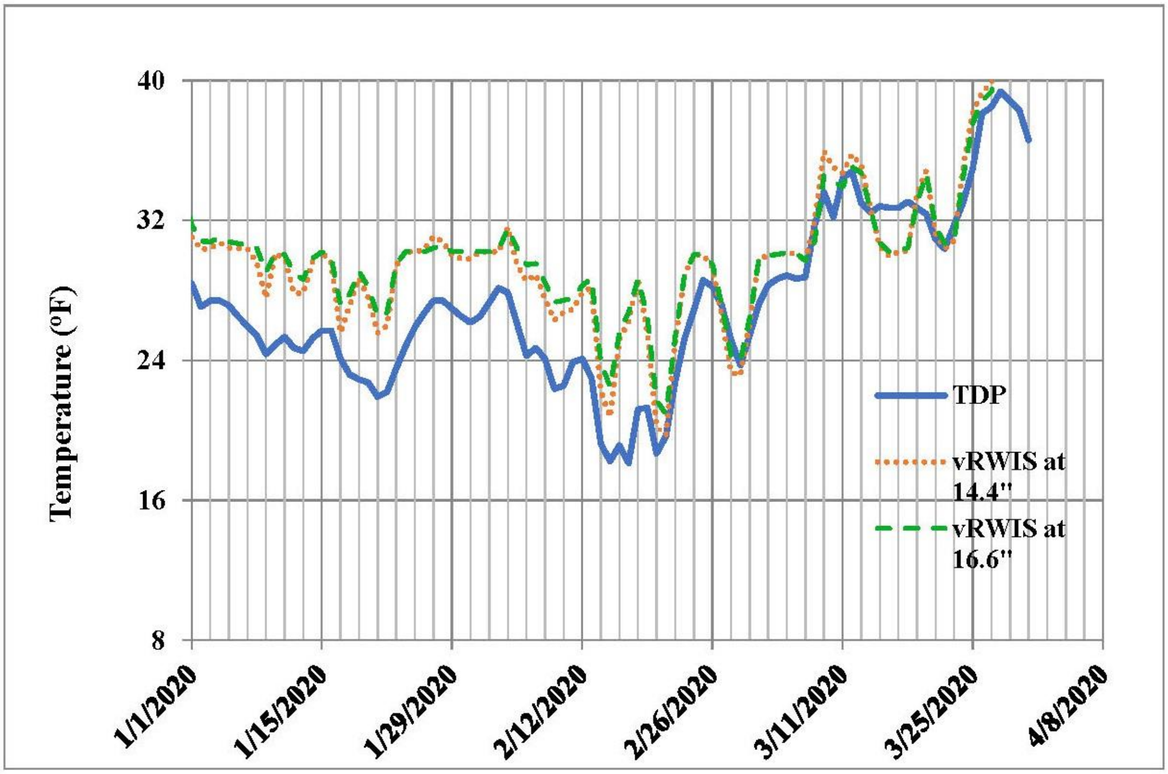




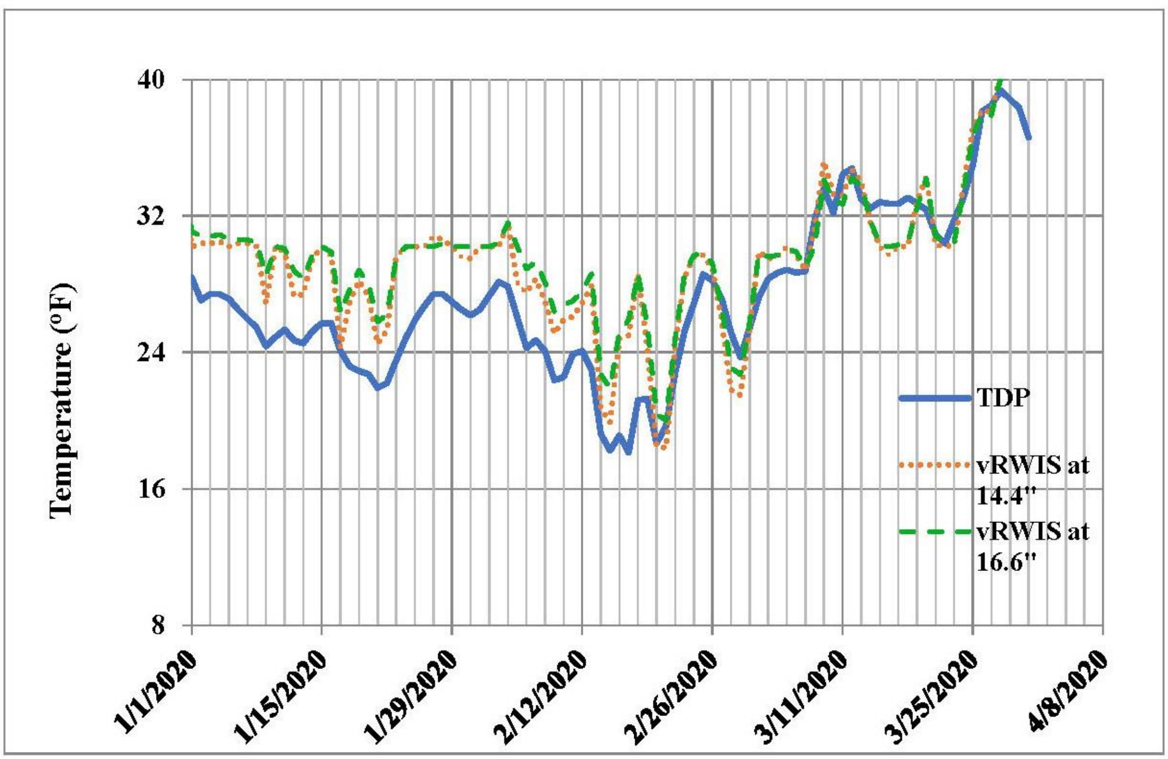
Michigan **Model: EICM (Model Run Using vRWIS Software Interface)**



MIREP_0_3 TDP 15.5" below TOP of Pavement (=12" below BOTTOM of AC Layer)
vRWIS Predicted Daily Average Temperatures

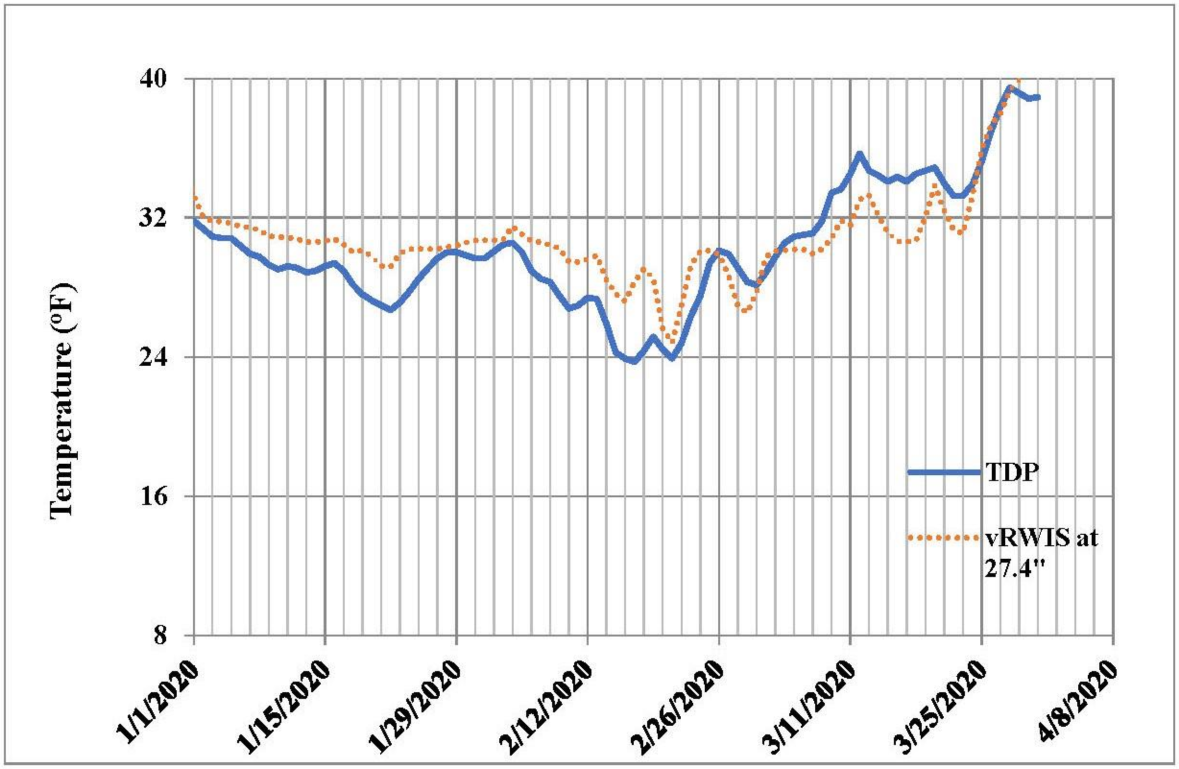


MIREP_0_3 TDP 15.5" below TOP of Pavement (=12" below BOTTOM of AC Layer)
vRWIS Predicted Daily Noon Temperatures

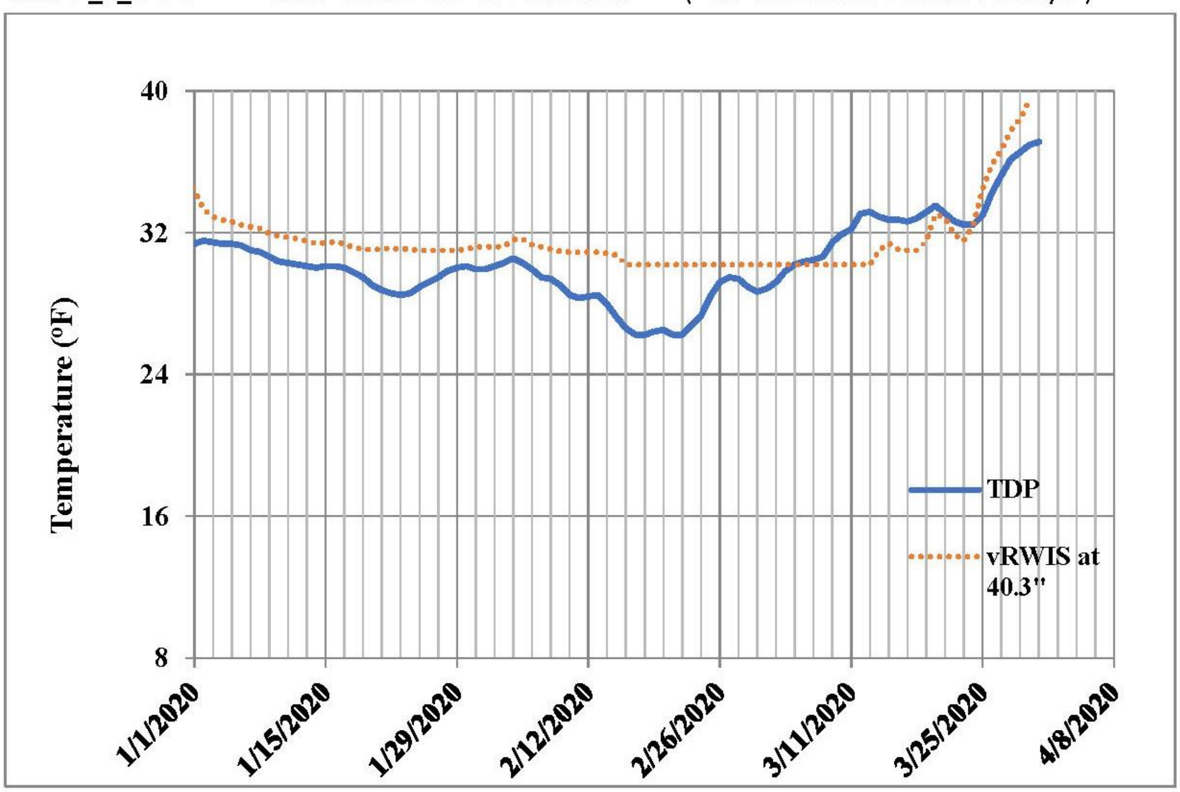


All temperatures on this page are Daily Average Values

MIREP_0_4 TDP 27.5" below TOP of Pavement (=24" below BOTTOM of AC Layer)

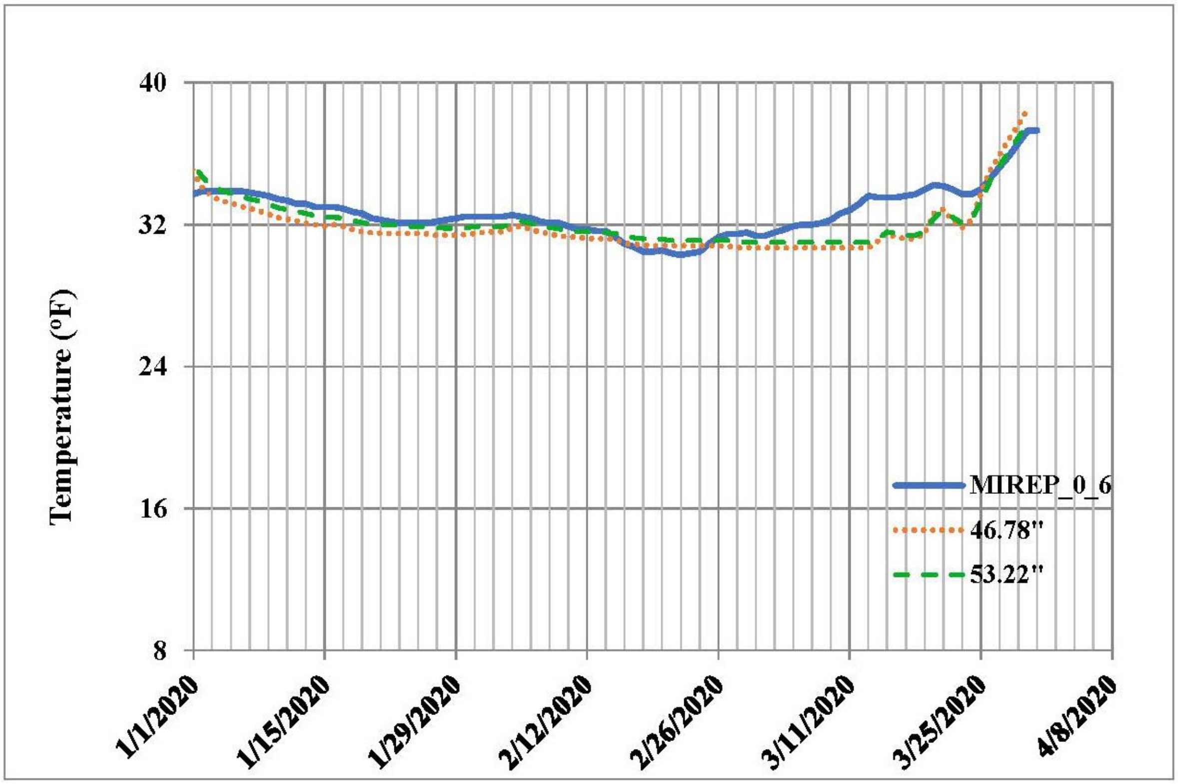


MIREP_0_5 TDP 39.5" below TOP of Pavement (=36" below BOTTOM of AC Layer)

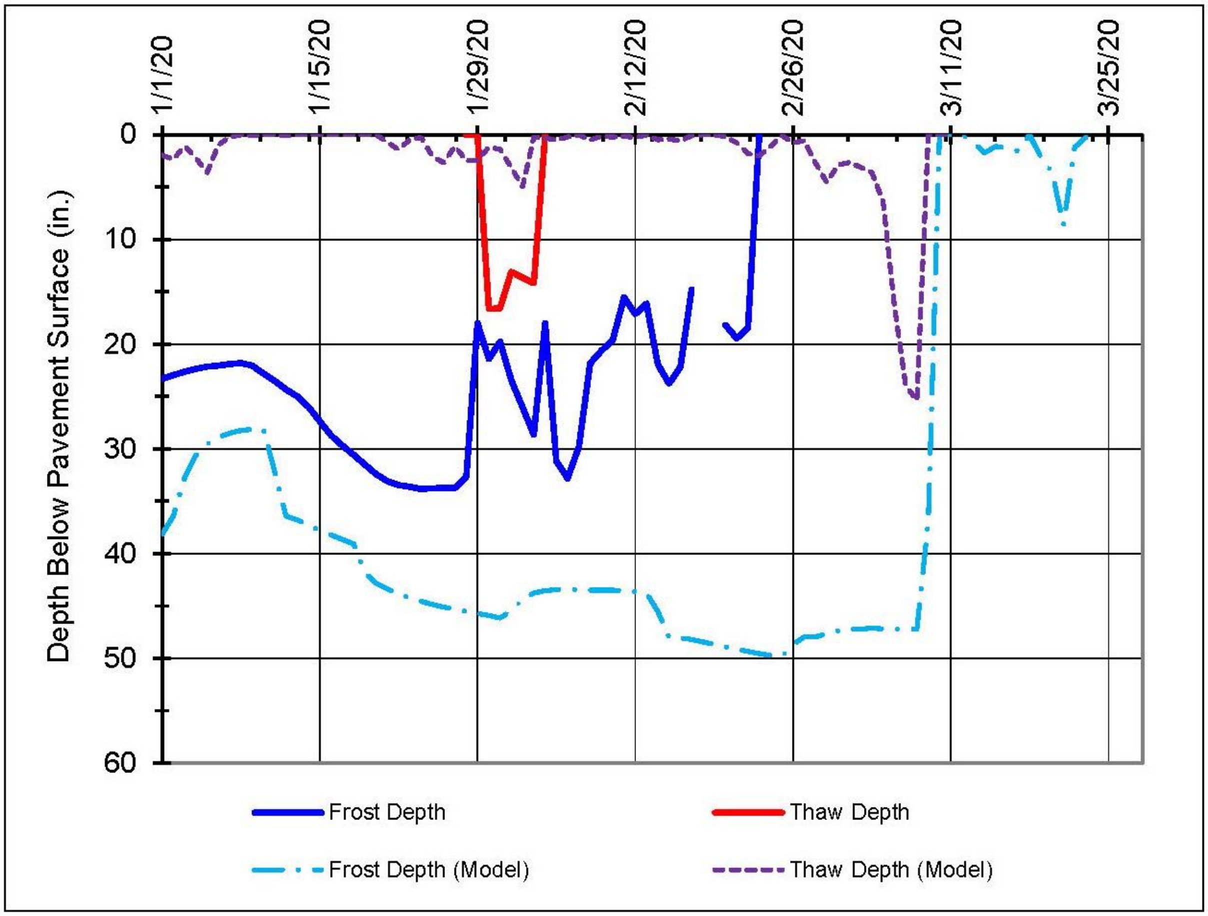


All temperatures on this page are Daily Average Values

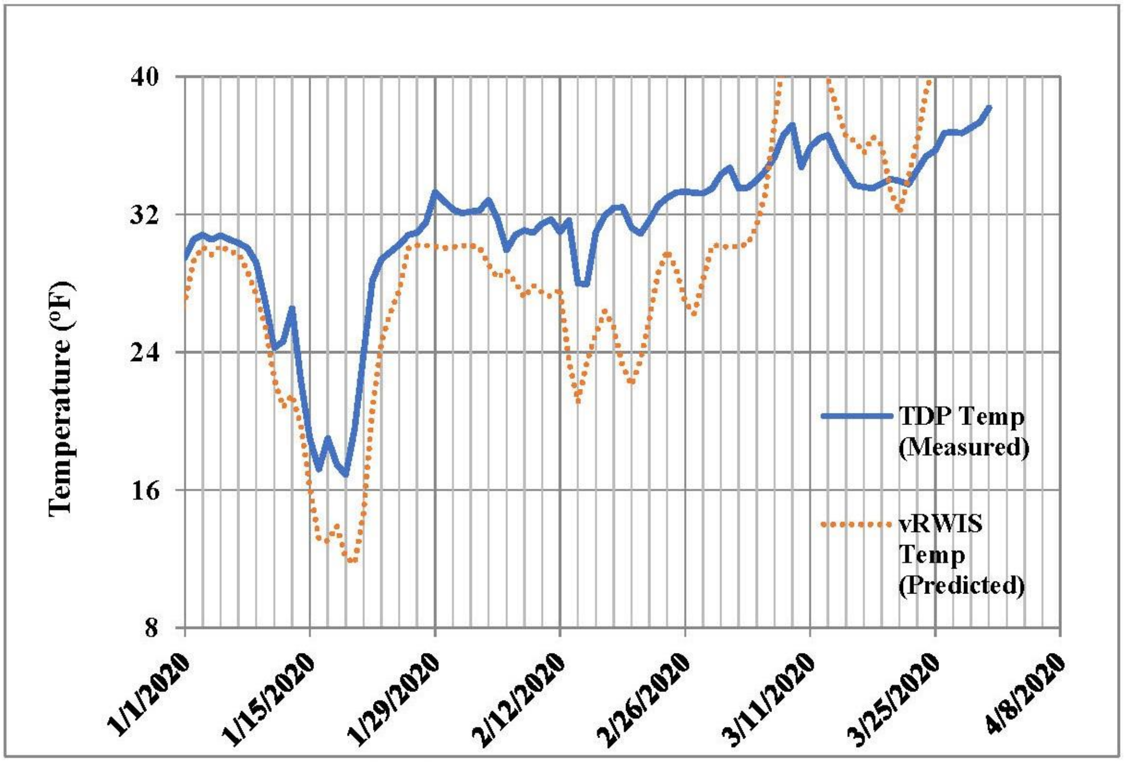
MIREP_0_6 TDP 51.5" below TOP of Pavement (=48" below BOTTOM of AC Layer)



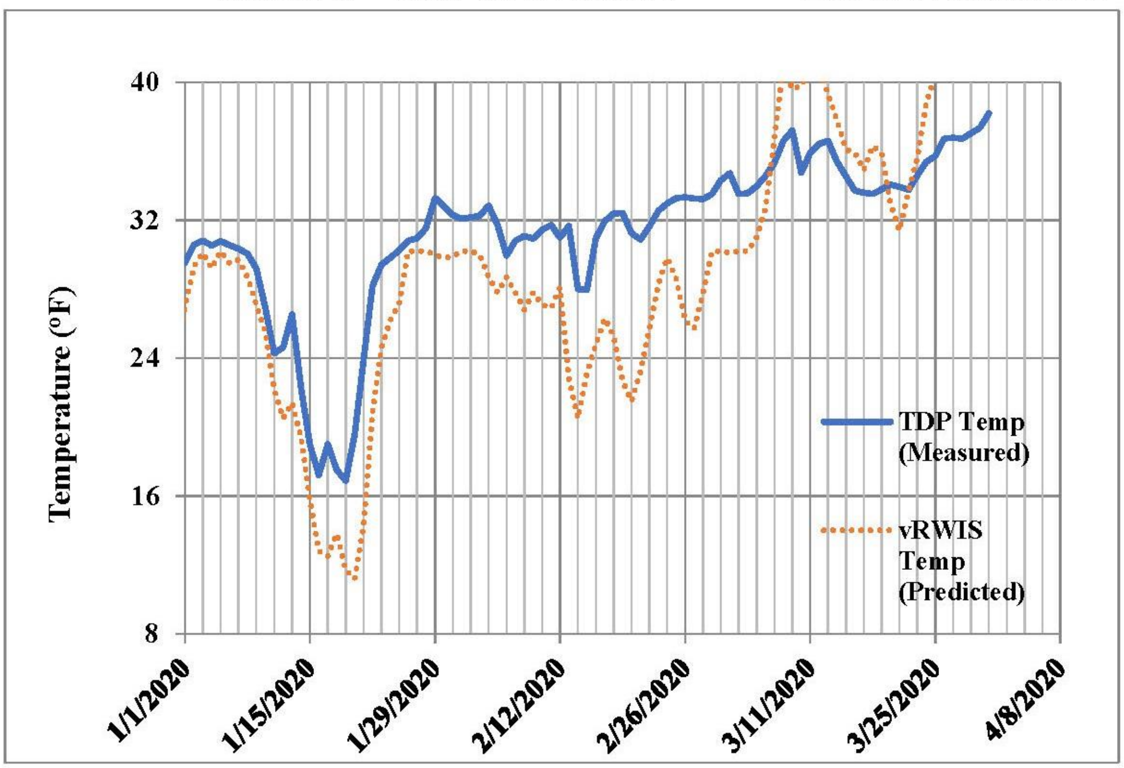
N. Dakota **Model: EICM (Model Run Using vRWIS Software Interface)**



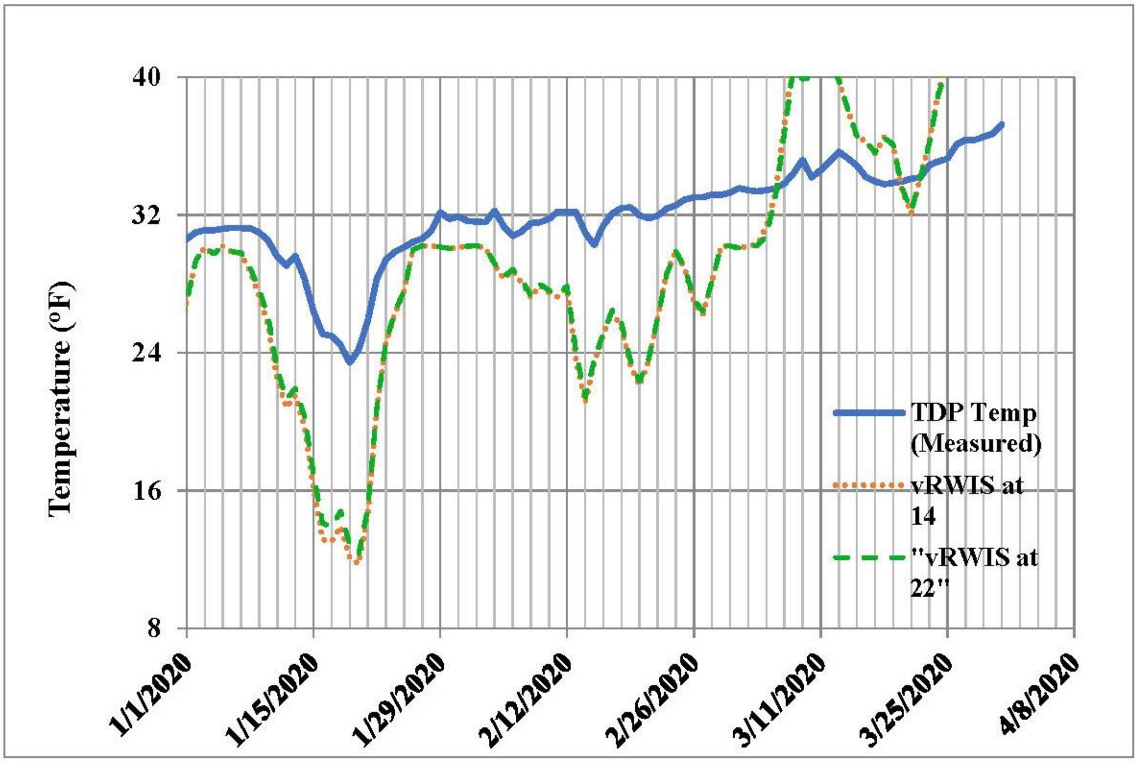
Bowman, ND TDP at 12" Below Top of Pavement Daily Average Temperatures
vRWIS at 14" Below Top of Pavement Daily Average Temperatures



Bowman, ND TDP at 12" Below Top of Pavement Daily Average Temperatures
vRWIS at 14" Below Top of Pavement Daily Noon Temperatures

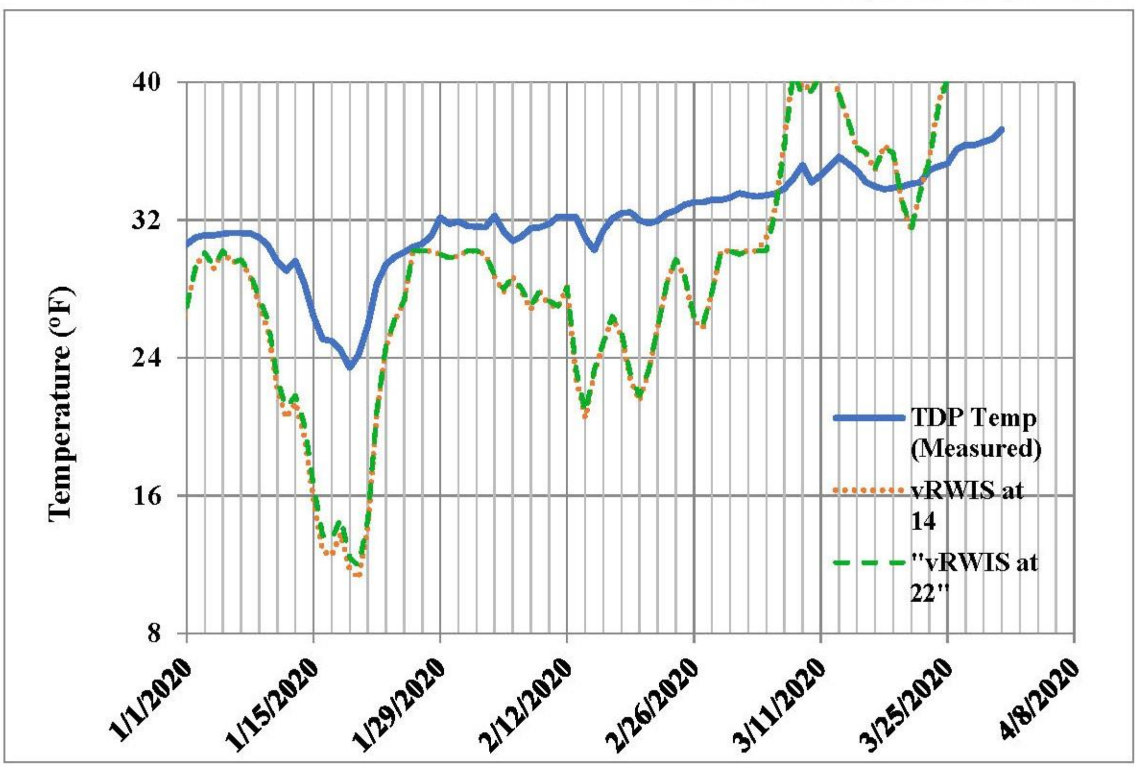


Bowman, ND TDP at 18" Below Top of Pavement Daily Average Temperatures

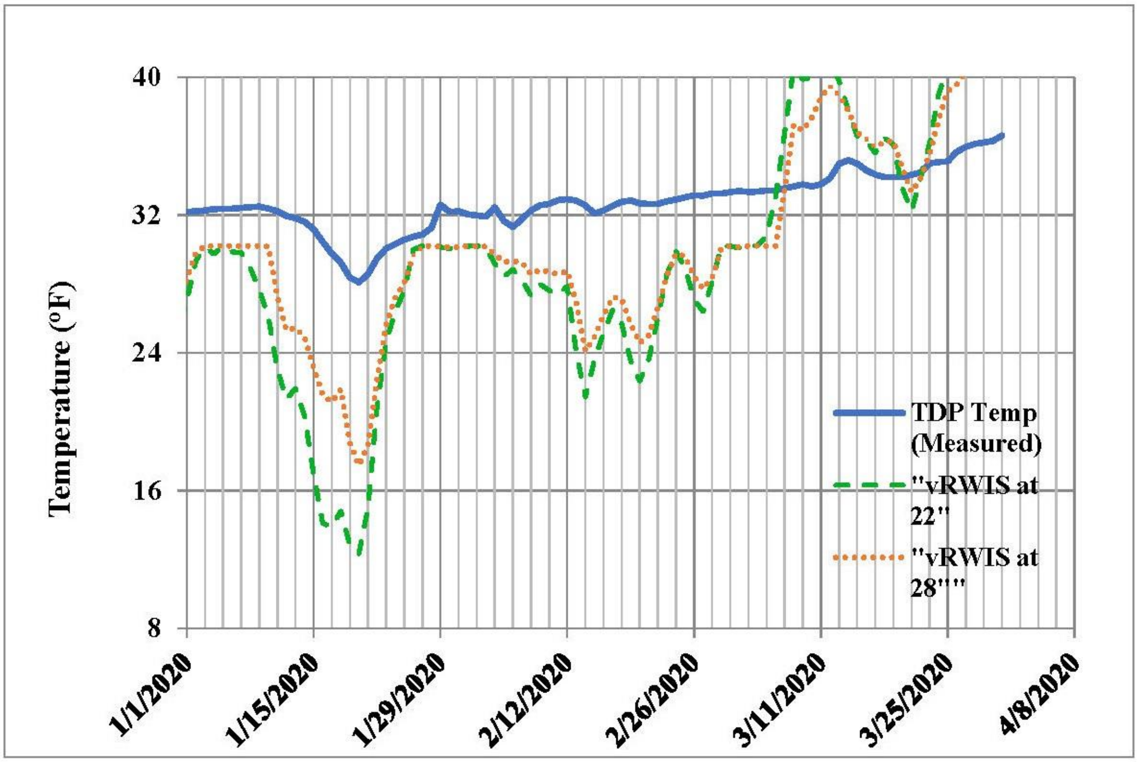


Bowman, ND TDP at 18" Below Top of Pavement Daily Average Temperatures

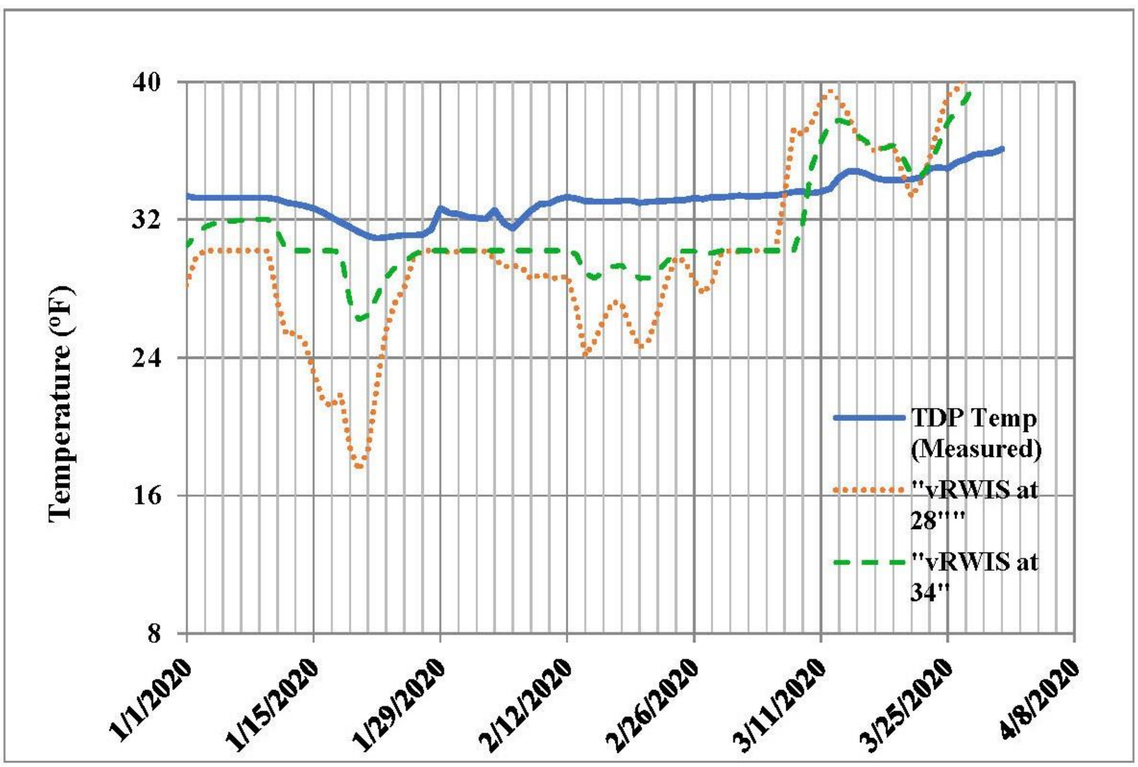
vRWIS Daily Noon Temperatures



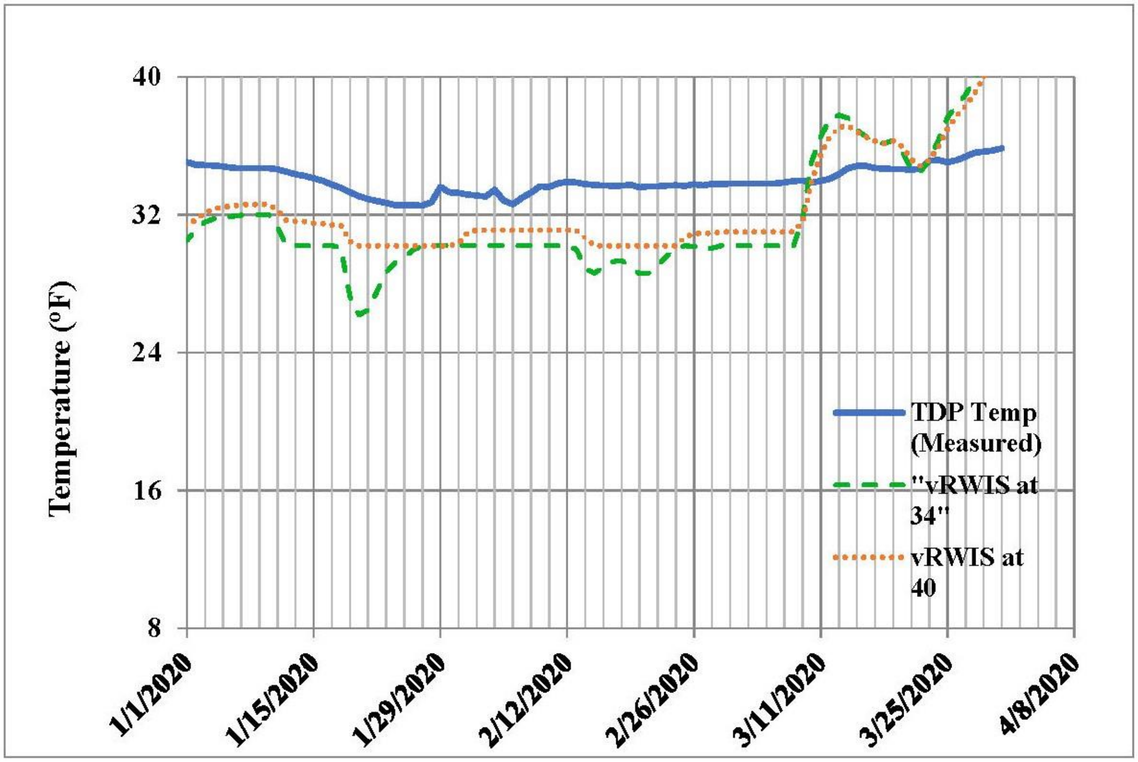
Bowman, ND TDP at 24" Below Top of Pavement Daily Average Temperatures



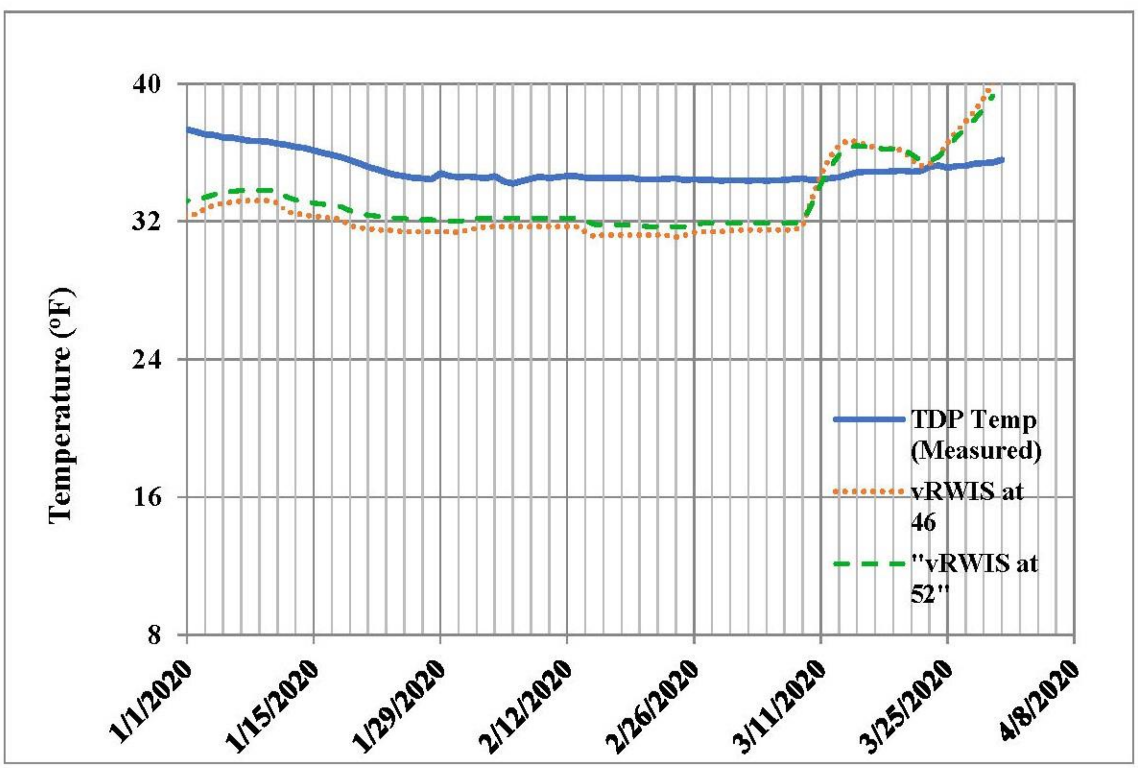
Bowman, ND TDP at 30" Below Top of Pavement Daily Average Temperatures



Bowman, ND TDP at 36" Below Top of Pavement Daily Average Temperatures



Bowman, ND TDP at 48" Below Top of Pavement Daily Average Temperatures



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