Data Collection via CRS&SI Technology to Determine When to Impose SLR

Cooperative Agreement: RITARS-11-H-UMDA

Between

University of Massachusetts Dartmouth & USDOT RITA

Final Report

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Final Report

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GLOSSARY

AJAX – Asynchronous JavaScript and XML
ANDs Lab – Autonomous Networking Dependable Laboratory
CEN – Civil & Environmental Engineering
CIS – Computer & Information Science
CRS&SI – Commercial Remote Sensing and Spatial Information
CRUD – Create, Read, Write and Delete
CTI – Cumulative Thawing Index
DSS – Decision Support System
ECE – Electrical & Computer Engineering
EICM – Enhanced Integrated Climatic Model
FWD – Falling Weight Deflectometer
USDA FS – United States Department of Agriculture Forest Service
GUI – Graphical User Interface
ICCRE – International Conference on Cold Weather Engineering
ITS Lab – Intelligent Transportation Systems Laboratory
ME – Maine
MN – Minnesota MN – Minnesota
MVC – Model View Controller
NHDOT – New Hampshire Department of Transportation
NUWC – Naval Undersea Warfare Center
ORA – Office of Research Administration
PHP – Hypertext Preprocessor
PO – Purchase Order
PSU – Plymouth State University
RA – Research Assistant
RITA – Research and Innovative Technology Administration
RH&T – Relative Humidity & Temperature
RWIS – Regional Weather Information Service
RWM – Road Weather Management
SLR – Seasonal Load Restriction or Spring Load Restriction
SWR – Seasonal Weight Restriction
SLRI – Seasonal Load Restriction Interpolator
TA – Teaching Assistant
TI – Thawing Index
TRB – Transportation Research Board
UMassD – University of Massachusetts Dartmouth; UMass Dartmouth
WAMS – Workshop on Applied Modeling and Simulation

EXECUTIVE SUMMARY

The research team and its partners have completed the project objectives to deploy Commercial Remote Sensing and Spatial Information, CRS&SI, technology and to launch a website, DSS-SLR, to display information or data retrieved via satellite. The DSS-SLR website's *Manual and Tutorial* is provided separately in conjunction with this final report. This manual also includes an *Implementation Guide.*

In order to ensure progress, the UMass Dartmouth research team held meetings and made phone calls within the research group and with our partners and advisory board members during the entire duration of the project. Partners now include technical contacts at Hoskin Scientific Limited, Douglas Calvert, Onset Computer Corporation, Plymouth State University partners and partners with Upward Innovations and DataGarrison, Tom Stalcup. A list of all project partners and advisory board members is provided in appendix-I. All partners were invited to the project final meeting.

With the deployment of the two CRS&SI technology stations, the deployment of the one cellular transmitted station, and the creation of the DSS-SLR website completed, the team focused on debugging the scripts' codes and on the validation of the website's functionality during the last extension period of the project. The scripts automatically import the data from two providers, DataGarrison (for the satellite sites) and Hobolink (for the cellular site) to the UMass Dartmouth data center. This website, named the Decision Support System for Seasonal Load Restrictions, or DSS-SLR, has a extensive GUI that displays in real time, the data in both tabular as well as graphical form. These can be accessed by logging onto the *New England's - Seasonal Load Restrictions* website stationed at UMass Dartmouth, http://ne-slr.umassd.edu. Username and Password are guest and guest. The site has been tested with both Firefox, Google Chrome and Internet Explorer browsers. Two accounts with DataGarrison provide coverage for the use of satellite transmission to and from our two CRS&SI satellite sites. In addition, for the cellular transmission site, two hobolinks subscriptions are in place. Raw data collected by the satellite transmission stations can be viewed at https://datagarrison.com/ and logging in with the password 'data'. The two usernames are 300234010074300 and 300234011200430. Raw data coming from the cellular site located at Madision, ME, can be viewed at http://www.Hobolink.com using the username "research" and password "umassd."

In order to track the bugs in the system, a bug-tracking system for the DSS-SLR with specific logins will continue to be useful. Its location is http://ne-slr.umassd.edu/redmine. To add a new bug, users clicked on 'New Issue' and entered a title with description. The 'Target Version' had to be set as well as the 'Assigned To fields'. Also, if users want to add a note to any of the sites' database, historic, current or in the future, it is possible to add information on that particular site's information page using the 'Note' feature. PSU's RWIS database at http://vortex.plymouth.edu/nh_rwis.html, both historic and current data is included in the website's database. Again, the DSS-SLR website displays this data both in tabular and graphical form. Historic data was also gathered from other locations, other than PSU's RWIS, and is available on the DSS-SLR. All data collection

location sites are displayed in a list on the homepage by the category of the state in which the site is located. There is also a map display of the site locations. Currently, NH and VT data collection location sites are available.

Coding the first version of the SLR Interpolation application, or the SLRI tool, was one of the last task activities to be completed during the extension period of this project and is installed onto the DSS-SLR. Debugging and validation were also completed on the SLRI during this last period. This tool is integrated with the database in the DSS-SLR and finds the average daily temperatures at subsurface locations, and then interpolates to determine the depth at which the subsurface temperature is 32 degrees Fahrenheit or 0 degrees Centigrade. Frost-thaw plots are then generated. These graphs plot over time, the subsurface depth at which the subsurface temperature is 32 degrees Fahrenheit or 0 degrees Centigrade. This graphing capability is in addition to the plots of the incoming raw data over time mentioned previously. These frost-thaw plots are only available for locations that have multiple underground temperature sensors so that depth beneath the surface at which the temperature is approximated as 32 degrees Fahrenheit can be estimated. These plots are used by our State DOT partners to determine when to restrict trucks from passage on roadways and when to lift these restrictions.

For the validation process of the SLRI scripts and code and for the validation of the SLRI's integration with the database, frost-thaw plots were manually generated weekly for the winter months 2012-13, the second winter of this project. The team compared the manually generated plots to the DSS-SLR's output. To generate the manually generated plots, the raw data was downloaded from the DataGarrison provider for the two test sites at Mariaville, ME, and Warren Flats, NH. Plots were also generated with raw data downloaded from our Hobolink provider, for the third test site at Madison, ME. After manually interpolation of the subsurface temperatures, frost-thaw plots were manually generated and compared to the output of the DSS-SLR's. These plots were shared with our partners and State DOTs for their use during the winter 2012-13.

For research purposes, a relatively simplistic frost-thaw index prediction model was also installed onto the DSS-SLR and validation is also complete. The model uses air temperature data downloaded by the DSS-SLR from WeatherUnderground to predict subsurface depths at which the temperature is estimated to be 32 degrees Fahrenheit. This website is located at www.wunderground.com. A report ranking all the predictive models that were under consideration for deployment onto the DSS-SLR was provided to the US DOT in the last (eighth) quarterly report, but is also provided again in appendix-VIII of this final report. It includes a discussion of the selected top ranking Predictive Model identified as appropriate for implementation onto the DSS-SLR. In addition, a comparison study of the Predictive Model's output with the SLRI's real data plots was completed.

Finally, comparing the frost-thaw plots for the sunny versus the shady locations in the two sites in Maine show significant differences. There were significant differences in frost-thaw patterns, especially at the Madison site. There was about a 4 to 5 week delay in the end-of-thaw-date at the shady site versus the sunny site. This drastically affects when the SLR should be removed.

Dissemination of the project's progress and findings occurred throughout the tenure of the project development. A list of publications is provided in appendix-IV of this final report. Furthermore, DOT representatives, the project Advisory Board and Team members attended a final dissemination/training project meeting, August 22, 2013. A training tutorial was presented as well as a project flowchart which focused on all aspects of the project. A snapshot of the project flowchart and its components are provided in appendix-III of this final report. It can also be accessed at the prezi.com website http://prezi.com/53zyouvf_uq5/?utm_campaign=share&utm_medium=copy.

Help with this site is as follows:

1. In order to see it full screen, Left-click full screen box (bottom right corner)
2. In order to zoom in or out,
   a. you can use the mouse-scroll-wheel
   b. or you can bring mouse to right-edge of your monitor screen and you'll see + and - to scroll
3. Move around in the flow chart when you left-click and drag.
4. escape key will get you out of full screen.
5. In order to see the slide show, use the right and left arrow at the bottom of the screen.

PROJECT CHRONICLE OF WORK EFFORT & ACTIVITIES

An Advisory Board comprising of industry, government and academic experts was established during the first weeks of the project. During the two years, members were added as needed. The Board provided guidance, suggestions and overview on the overall direction of the project. All members were present at the kick-off meeting either via conference call or in person. The Project Manager identified FHWA Jennifer Nicks as a USDOT representative on the Advisory Board. A listing of the Board members is provided in a comprehensive list of project participants in appendix-I of this final report.

A day-long kick-off meeting was organized for August 19, 2011, beginning at 9:00 a.m. and ending at 2:30 p.m. - lunch was provided. All members of the UMD research team (four faculty members and four graduate students) attended as well project-subcontractors, representatives from the NH DOT, ME DOT, and FS, and all members of the project's Advisory Board. Three outside teams joined the meeting via conference calling. The program manager, Caesar Singh, and his team called in from Washington DC. One of the consultants, Richard Berg, called in from NH. And Dale Peabody and his ME DOT staff also conference called into the meeting from the Maine DOT office. Everyone else attended in person. A conference calling phone was arranged before-hand so that all attendees could hear one another whether they were attending in person or attending via phone.

The meeting location was on the University Campus in the Board of Trustees Room of the Foster Administration Building.

After introductions, the focus of the meeting was driven by several briefings of the project's objectives and deliverables. Power point presentations were generated and presented by all four of the UMD research team faculty members. After the briefings, questions were raised and the integration-flow-chart was exhibited for all to see and study. In the afternoon, more questions were raised and discussions took place. The emphasis was on the logistics of integration of the four areas of expertise (computer science, electrical engineering, civil engineering and transportation engineering) and how that would lead this interdisciplinary team toward the accomplishment of the project's goals. Also, a confirmation of the roles of each of the partners within the integration flow-chart strategy took place.

Finally, a discussion took place over the constraints on the project's timeline; in particular, weather in New England begins relatively quickly and the project's start date was delayed by 7 months. This could limit data collection during the 2011-2012 winter months.

A conference call was conducted on September 28, 2011, 10 a.m., to discuss the identification of the test site locations, one in NH and one in ME. All advisory board members and subcontractor consultants were invited. Participants included the UMD research team, representatives from state DOTs NH and ME, our subcontractors and our Advisory Board members from the USDA FS and NUWC.

In addition, the UMass Dartmouth faculty members, a research team of four, met weekly on Mondays at 10:30 a.m. Students met together with the PI, weekly each Monday at 12:00 p.m. but also individually with their own advisors. And, the computer group met Tuesdays at 1:00 p.m. In addition, there were several meetings between individual students.

The task to establishment a SLR Test-bed, to be located on campus, equipped with CRS&SI technology, began with much discussion that included our consultants and included travel to NH by Heather Miller. This resulted in the purchase orders (PO) of two satellite weather stations from Hoskin Scientific Limited, located in Canada. The stations included subsurface temperature sensors as well as weather sensors above ground. A complete description of the two weather systems and their components is provided in appendix-VII in the *Description and Application Manual for the SolarStream Iridium Satellite Road Weather Monitoring System.* Two other quotes were acquired, one from Sutron and one from Campbell Inc.

In addition, discussion that began at the kick-off meeting continued, concerning the placement of the underground sensors and whether it is necessary to actually place them underground on the campus test site prior to their relocation to the NH test site. It was decided that assemblage and testing of the equipment and generating the necessary programs on the DSS-SLR server to connect and receive sensor data could be accomplished while the equipment lied above ground. Therefore, the testbed was established above ground.

It was also decided that DataGarrison would be the collector or provider used for the satellite transmission of the data. Hoskin Scientific Limited contact, Doug Calvert, agreed to determine the cost options available for the particular weather station system in the purchase order. In addition, a user or instruction manual would be included in the purchase. A systems integration package and fee would be covered by one of the subcontractors to this project, Ken Kestler.

The establishment of a project website and the DSS-SLR began immediately. Ramprasad Balasubramanian, and his student along with Marguerite Zarrillo and her student held weekly meeting at 1:00 p.m. on Tuesdays. Two computers in the ITS Laboratory in the Physics Department were initially dedicated to the development, then later moved to to Dr. Balasubramanian's computer laboratory. Once functional, the DSS-SLR was moved to its final location within the security protected UMD Data Center.

A listing of the parameters or data collected by the weather station was generated by Heather Miller and the consultants. It was used in the initial design of the database of the DSS-SLR and revised several times. The list appears in appendix-V of this final report. In addition, a listing of the software modules required by the project was generated by Ramprasad Balasubramanian and is listed in appendix-VI of this final report.

Discussions concerning the number of times per day that data should be downloaded into the DSS-SLR lead to a tentative agreement. Data by some of the sensors would need to be collected more frequently than data from other sensors. Some data needed to be collected once per day; however, some data would be downloaded hourly. This was agreed to be altered if it proved to be cost ineffective.

Through discussions with state DOTs NH and ME, and through Marguerite Zarrillo's discussions with some of the other 37 state DOTs attending the RWM Stakeholder meeting in Albuquerque, NM, Sept 7-9, additional ideas for the DSS-SLR's graphical user interface, GUI, emerged.

The first draft of a user friendly GUI was designed within the first three months of the project. For the real time data, the concept included a Google Map which displayed the weather station locations. Once the computer mouse would be moved over the location of a station on the map, the frost-thaw-profile plots for that particular station would become visible to the user. Additional points on the frost-thaw-profile plots would be generated and added to the plots, each evening, for each station, from the data collected via the CRS&SI technology during the latest 24 hour period. The data points for the plots would be generated by an SLRI Tool which would then be inserted onto the plot.

In the meantime, historical data and profile plots were in the process of being assembled to be archived in the DSS-SLR database. In order to correctly generate calibrated historical data in the correct format for the DSS-SLR database, a Macro-enabled Excel program was created. This saved much time in the establishment of the frost-thaw-profile plots archived and made available on the DSS-SLR later on.

Investigation of various predictive models and their functionality also began in the first quarter of the project. Input to these predictive models are above-ground weather data to determine frost-thaw plots, thus avoiding the use of subsurface temperature sensors. If a reliable model can be validated by this research project, it would be very beneficial to state DOTs. While at the RWM Stakeholders meeting, Marguerite Zarrillo held a discussion with Leon Osborne (Meridian Technology), who developed a "Seasonal Weight Restriction Decision Support Tool," which is based on one of those predictive models, the Enhanced Integrated Climatic Model, EICM. This model uses several parameters as input, including air temperature, wind speed, percent sunshine (100 - % cloud cover), precipitation, relative humidity and ground water table depth. It also requires input related to the pavement structure and subsoil conditions. The Meridian Technology tool was developed with RITA funding provided under the Clarus initiative. Leon indicated that the dissemination of the Meridian tool was under Paul Pisano's direction (FHWA). A request was made to Paul to acquire this tool/software for testing using historical data from NH and ME. Unfortunately, this tool never became available.

Again, during the second quarter and continuously throughout the duration of the project, the UMass Dartmouth research team held a substantial number of meetings, phone calls and conference calls. The four UMass Dartmouth faculty investigators met altogether weekly. In addition, each investigator met individually with their hired Research Assistant or student hired to work on the project. The PI also met separately with all the students weekly, as did Dr. Balasubramanian. One undergraduate student met weekly with Dr. Miller. In addition, several meetings were conducted between Dr. Miller and Dr. Balasubramanian, also involving their students. Furthermore, students often met with each other one on one. In addition, a substantial number of emails were exchanged within the research group and with advisory board members. New valuable technical contacts were established at the state DOTs, at DataGarrison and at Plymouth State University and added as new members to the advisory board.

The delivery date of the weather station from Hoskins Scientific was moved to mid to late-January 2012, later than expected. The research group planned to house the equipment in the ANDs Lab, where it would be assembled and tested. Although Hoskin Scientific was to conduct its own testing before shipping, the research group wanted to perform further calibration of the sensors. Integration of the assembled sensors was coordinated via the team consultant Ken Kestler.

Also, during the second quarter, with input from our state DOT advisory board members, two test site locations in NH and ME were identified for the placement of the two Hoskin Scientific Limited weather stations. These identified locations, Mariaville, ME and Warren Flats, NH, needed to be checked for adequate satellite coverage, two overnight field trips were conducted by Dr. Wang and his graduate student, one visit to Mariaville and one to Warren Flats. These occurred at the end of October and then in early November 2011 respectively. Dr. Wang met with State DOT representatives at the ME site. Testing equipment was picked up from DataGarrison (in Falmouth, MA) to test satellite reception at the proposed installation sites and later returned to them. The results of these tests established that satellite coverage was quite adequate at these two sites for the proposed work. DataGarrison also provided login information to their internet links and the test data was downloaded successfully, however, not imported to the DSS-SLR, as the website was still undergoing development at that point.

Several email discussions took place over the installation and means for mounting the weather stations as well as securing the stations from vandalism. Discussion occurred primarily between Dr. Miller, the consultants Richard Berg and Bob Eaton, advisory board member Maureen Kestler and state DOTs. Instrumentation topics included cable lengths, subsurface casing widths, tripods, mounting posts' heights, cement platforms, fencing, depths below the pavement surface and distances from the roadway. Some installation hardware was purchased. Some of the additional mounting hardware was ordered from Hoskin Scientific Limited and included the following.

- 30’ pop-up Mast with
    - → post brackets

  - → custom half cross arm for wind sensor
  - → Special U bolts and adapters for Sensor mounts
- 8 meter RH&T sensor (Relative Humidity and Temperature)
- 18M Pyranometer (measures solar radiation flux density)
- 10M cable extensions for wind sensor and rain gauge
- Changed thermistor string from 13 conductor to 25 conductor – the price increase was only $58 but this will be more robust
- Custom Polyurethane over mould for soil moisture extension cables

At this time, much effort was made in gathering historic data. Historic data was assembled from the nine sites listed in Table 1, below. A major task was involved figuring out how to keep future collected data consistent with what is already collected. This task ended up requiring much more effort than anticipated initially. This was because, any future data collected in a real-time manner had to be named in a way that corresponded to the historic naming schemes. Much attention was given to the units of the data collected, which were often different depending on where the stored historical data was archived. Much attention was given to the mechanism used in the collection of the historic data. This determined whether or not the future gathered data from the satellite transmission sites was of the same exact type. In summary, current challenges include establishing the correct naming of the data gathered, its units, whether the data is of the same type to be collected in the future at the two satellite transmission sites, and whether corrections to the data was required. The results of this investigation determine the design and architecture of the DSS-SLR database.

TABLE 1: sites from which historic data has been assembled (bold are to be continued as Internet sites from Plymouth State, bold italic from DataGarrison)

	Site Name	Latitude	Longitude	Elev. (ft)
K - 1	Kancamagus/Route 112 (Full Reconstruction)	N43.99259	W71.32639	1,243
K - 2	Kancamagus/Route 112 (FDR with Cement)			
K - 3	Kancamagus/Route 112 (FDR without Cement)			
LT	Lake Tarleton	N43.97870	W71.97285	1,371
NGR	N Groton Road	N43.74604	W71.85706	1,499
RUM	**Rumney Shed (203)**	**N43.79342**	**W71.83566**	**525**
SLR	Stinson Lake Road	N43.87745	W71.80280	1,416
WF	***Warren Village (Warren Flats, Rt 25C***	***N43.93322***	***W71.90703***	***791***
WS	**Wentworth Shed (Warren Patrol Shed) (202)**	**N43.89318**	**W71.89848**	**862**

In addition to these sites, and by connecting with Plymouth State University (PSU), the research team made an effort to establish numerous additional sites on the NH map of the DSS-SLR GUI. Data from these sites, listed below, are transmitted in real-time to the UMD DSS-SLR via the internet from the PSU website. At these sites, historic data also exists and was assembled for the DSS-SLR database. Thus, both historic and current real-time data can be accessed using the DSS-SLR at UMD.. The team realized that this task was outside than the scope of this project and presented some additional challenges. However, the end users of the DSS-SLR, our state DOTs, emphasized the value of having data from these additional sites on the DSS-SLR, thus the research team decided to go ahead with the implementation.

The additional new location sites were auto populated from the PSU website; all sites in NH. In other words, computer scripts were written to make historic data populate the DSS-SLR database. Additional scripts were written to enable real-time data to also populate the DSS-SLR database. In the list below, bold sites are “davis” weather station sites, not Road Weather Information Systems, RWIS, sites. However, since data is stored in the same format at the PSU website for all of the sites, this distinction is not critical.

- **Enfield**
- **Rumney**
- **Wentworth**
- **Bristol (No Subsurface)**
- Westmoreland
- Springfield
- Manchester
- Littleton
- Salem
- Derry
- Ashland
- Woodstock
- Lost River
- Sanbornton
- Canterbury
- Little Bay

Internet transmission sites in Maine were not identified at this point. However, under consideration at this time was the possibility of using a Variable Message Sign, VMS, along with the VMS computer and its internet capability to transmit subsurface temperature data via the internet. Apparently, VMS are not frequently in use over the winter months and can be transported to any site of interest where subsurface temperature sensors are already deployed and from which data is manually acquired. The advantage of this possible scenario would be to facilitate data collection at numerous sites via wireless technology.

Programming began on the SLR Interpolator Tool early on in the second quarter. This script takes the real time subsurface temperature data and determines the depth at which the temperature of the soil is approximately 32 degrees. Initially, an Excel Macro was written in which calibration corrections to historical subsurface temperature data were included in the program. The SLR Interpolator Tool was integrated onto the DSS-SLR, however, this did not occur until much later in the project activities.

Investigation of various models and protocols for predicting when to apply and remove spring load restrictions (SLRs) continued during the second quarter. Evaluation of a freeze-thaw index model originally developed at the University of Waterloo, Canada, was completed at this time. Details of that evaluation were written up in a paper presented at TRB in January 2012. This simple model predicts the depths of frost and thaw penetration based upon air temperature as the only input. The model was calibrated to local conditions based upon historical data from the nine test sites in NH. In addition to evaluating models which predict the depths of frost and thaw penetration, the research team evaluated protocols which yield "trigger dates" for applying, and in some cases removing, SLRs. Under consideration were methods developed by the FHWA, by the USFS/Berg, and by the Minnesota Department of Transportation. Evaluation of these protocols using historical data from the nine test sites in NH began this quarter and lead to a report, submitted earlier but also provided in appendix-VIII of this final report.

The two weather stations' arrival date was again moved, this time to mid-April 2012. Components of the system came from several companies, thus, the assemblage and integration took Hoskin Scientific Limited much longer to complete. Although the delivery of the hardware is delayed, much progress on the software side of the campus test-bed was being made. Thus, upon delivery of the equipment and hardware, the research team could plan on immediately testing and calibrating the sensors and testing the DSS-SLR connection via scripts of communication software to the equipment. In the meantime, Dr. Wang and his research assistant investigated other possible options to establish additional field sites for data transmission via cell modem and internet, in particular, the mobile VMS as mentioned earlier.

During the third quarter, much attention had to be given to determine consistency within the DSS-SLR database between reported historic data and future data to be collected real-time via CRS&SI technology. In addition, scripts were written that establish a real-time connection with PSU where future real-time data was to be transmitted to the DSS-SLR via the internet. Intense work also began on the DSS-SLR graphical user interface, GUI. The prototype DSS-SLR was temporarily developed and coded on a server in the CIS department at UMass Dartmouth for testing purposes, before being moved to the UMass Dartmouth Datacenter. Also during this quarter, meetings and emails between the Datacenter personnel leader, Craig Oliviera, and team members, Dr. Balasubramanian and Dr. Zarrillo, have established agreements on the structure size, security measures and required program modules to be loaded onto the University's DSS-SLR web-server.

The research team also explored the possible addition of another previously established field test site, at Stinson Lake Rd in NH, as a possible internet transmission site during this third quarter. State DOTs emphasized the value of establishing additional internet sites, not using the more expensive satellite CRS&SI technology. Subsurface temperature probes already exist at the Stinson Lake Rd site. Thus, the team purchased and modified an Amphenol Industrial 97-22-14P 19-pin socket connector. This would enable testing of the underground thermistor string (subsurface temperature sensors) located at this site. If the thermistor string proved viable, the team planned to add this site onto the DSS-SLR as an internet transmission site. Unfortunately, due to bad weather, this site became inaccessible. A tree fell upon the pole where those sensor output cables were mounted.

Meanwhile, the research team began to determine the integration process of a predictive model, the freeze-thaw index model, onto the DSS-SLR. It was anticipated that this much simpler model in which the only required input data is air temperature would be straight forward but require development of many more scripts onto the DSS-SLR. In addition, The DSS-SLR scripts would have to collect real-time air temperature input data to enable the model.

The delivery of the two satellite transmission systems and associated sensors (ordered from Hoskin Scientific Limited) was again moved into the fourth quarter of this research project, to July 9th, 2012. Upon arrival, the equipment underwent testing in UMass Dartmouth ANDS Laboratory testbed site. Although the delivery was delayed, much progress on the software side of the campus test-bed was made during this fourth quarter. For instance, development of a TCP/IP based communication software (Client-Server) to transmit the data collected from remote sites to the datacenter through real time satellite communications. Accounts were set up with a one-year subscription for two stations, purchased from Upward Innovations, Inc., at $770 each. With the equipment in hand, the research team could begin the testing phase of the project, the goal being that the DSS, its database and the sensors collecting the data would communicate in a timely and accurate manner via satellite transmission. In addition, the team underwent a one-day long training session on June 6, 2012, via conference call with Hoskin Scientific Limited Inc. Douglas Calvert. The manual for the two CRS&SI weather stations, provided in appendix-VII, *Description and Application Manual for the SolarStream Iridium Satellite Road Weather Monitoring System,* was used as the training slide presentation.

Also during this fourth quarter, a low-cost SLR monitoring system utilizing cellular transmission of data, was developed by the UMass Dartmouth team and equipment was purchased from Onset Computer Corp. This box was tested during the fourth quarter, however, it was deployed in the fifth quarter at Madison, Maine, on October 11, 2012. This third transmission site is using non-satellite cellular data transmission to send subsurface temperature data to the DSS-SLR at UMass Dartmouth. There is no historical data for this site, however, the team eventually added this site to the DSS-SLR. This extra activity for the project resulted out of discussions in which Maine DOT expressed the desire to use cellular transmission of data at locations where the internet was available. Other state DOTs, have emphasized the value of establishing additional non-satellite CRS&SI technology sites. The cost of equipment is approximately half the cost of the equipment selected for the satellite transmission sites. Much effort went into investigation of the equipment for this third site. Three technology solutions were compared: Onset, Davis and INWUSA. The Onset equipment was identified as the best configuration. Its only limitation, however, requires that the site location have cellular/internet transmission available.

Much effort and travel was required during the fourth quarter to determine the site location and to identify the cellular provider for the cellular / internet transmission site. UMass Dartmouth team member Heather Miller met with Dale

Peabody (Maine DOT) on June 21, 2012, and visited several potential cell transmission sites that are of interest to Maine DOT in terms of their SLR postings. The system tested on June 21, 2012, employed an AT&T cellular server. While they were able to transmit some data at all sites except for one, the data transmission was intermittent, and thus not ideal for our proposed project. Dr. Miller had several discussions with Herman Gustafson (technical support staff at Onset) during that day. He indicated that, although there was some AT&T service at the potential sites, the signal may just not be strong enough to support our needs. At the last site visited (Rt. 43 near Anson and Madison), Herman said that T-Mobile appeared to have stronger coverage. The research team anticipates testing T-Mobile transmission service (installed on an alternate data logger) at the Rt. 43 site on July 13. A significant amount of time was spent configuring and testing the new Onset equipment, which was eventually installed in Maine. Specifically, before deployment, the two moisture sensors were checked for accuracy, and temperature offsets for the nine thermistors were determined in an ice bath. Charging of the internal battery via the solar panel was confirmed, as was data transmission from UMass Dartmouth and downloading of data via the Onset "Hobolink" web site.

Toward the end of the fourth quarter, the research team took the DSS-SLR website design to its first stage construction, specifically the programming and its GUI, now directly on the University's Data Center's server, and pushed the latest code to production. Some of the Asynchronous JavaScript and XML (AJAX) methods used to populate the views of the stored data were refined. Integration of JpGraph with the MVC progressed considerably this quarter. This set the framework for future graph generation by given data arrays, historic or in real-time. JpGraph is an Object-Oriented Graph creating library. The library is completely written in PHP and ready to be used in any PHP scripts. PHP is a general-purpose server-side scripting language originally designed for Web development to produce dynamic web pages. It is one of the first developed server-side scripting languages embedded into HTML. Rather than calling an external file to process data, the code is interpreted by the web server's PHP processor module which generates the DSS website. The DSS web server has the address http://ne-slr.umassd.edu and is named the *New England's - Seasonal Load Restrictions* website. Separately, a project website was established and provides a public description of the project along with key personnel information at http://mzgis.prod.umassd.edu/dssslri.

Additional tasks were completed for the DSS-SLR website. For instance, the tables of the database were modeled in the MVC architecture of the web application. Thus, general CRUD operations on each of the tables were possible. In addition, scripts established a real-time connection with PSU where future real-time data could be transmitted to the DSS via the internet. Scripts to import PSU data, parse the data and display the data were created. Storage for this data was implemented as well. This included data from 12 separate site locations. This effort was in addition to activities previously mentioned in which the DSS database was being populated with PSU's historic data. In other words, expansion of the historic database continued during this quarter and into the next two quarters.

Finally, during this fourth quarter, it was decided that WeatherUnderground would provide weather data to be used in conjunction with the prediction model to be placed and integrated onto the DSS-SLR. Much work was performed to determine which prediction model to integrate onto the DSS-SLR. As mentioned, a report comparing the pros and cons of the different models is provided in the appendix-VIII. Much effort went into designing the DSS-SLR in a modular fashion, in anticipation that the Meridian Technology tool would sometime in the future be acquired. Meanwhile, the research team planned the integration of another predictive model onto the DSS-SLR – the freeze-thaw index model. This is a much simpler model in which the only required input data is air temperature.

During the fifth and sixth quarters, planning of the deployment and the actual deployment of this third site finally occurred on October 11, 2012. The location is on route 43, south of the Old County Road on the east side and River Road on the west side of route 43 intersection in Madison, Maine. The HOBO instrumentation was installed north of the intersection in a shaded area of Route 43. In addition to the station deployment, a string of Hobos were installed in a shady section of roadway nearby to the station so that differences in frost-thaw patterns in shaded versus sunny sections of road could later be quantified.

Also during the fifth and sixth quarters, the two satellite transmission sites, CRS&SI technology, were successful tested and deployed. One CRS&SI technology station was deployed at the Warren Flat site on Route 25C in New Hampshire on August 29, 2012. A second station's deployment occurred on October 9, 2012, on route 181 in Mariaville, Maine. A deployment report on the establishment of the three sites in NH and ME is provided in appendix-IX. It includes maps, site plans and necessary deployment equipment details. Photographs of the deployment are also provided. Results of the laboratory tests on soil samples taken from the sites are presented included.

Many people assisted with the many deployment tasks. Tasks included traffic control and safety, road boring, trenching, placement of the well point and road subsurface temperature and moisture sensors, collection of soil samples, post setting and installing equipment onto the post. The UMass Dartmouth team and consultants installed the road hardware, installed the groundwater well pressure transducer and installed or mounted all of the equipment onto the mast/post. The team also tested it while state DOT drilled the waterwell, installed the post, sawcut and removed the pavement, dug the trenches for the wires, obtained the soil samples, filled the trenches and patched up the road. In addition, at the Maine sites only, a string of HOBOs and surface HOBO were installed in a shady section of roadway nearby. During deployment, the team strived to ensure public safety and to remain on site as briefly as possible. There were several activities happening at the same time. Everyone was wearing ANSI safety vests, and hard hats. State DOT took care of the public notices regarding lane closure.

The deployment also incurred unexpected and additional travel expenses to adjust the instrumentation, waterproofing, recharging the battery and replacement of damaged parts.

Progress also continued on the software side of the DSS-SLR during the fifth and sixth quarters. For instance, development of TCP/IP based communication software (Client-Server) to transmit the data collected from remote sites to the data center through real time satellite communications was completed. Accounts set up with a one-year subscription for two stations, purchased from Upward Innovations, Inc. both worked well. With the phone-modem equipment in hand, the research team made progress on the integration with the DSS, its database and the sensors collecting the data. In addition, the testing of the communications began, the appropriate adequate but efficient timing-interval between transmissions was determined, and were incorporated into the database via satellite transmission. Some data was transmitted once per day, other data at smaller intervals.

Building the database/infrastructure design for the DSS-SLR was completed this quarter. For example, a script which pulls current weather data from WeatherUnderground and stored all the historic data into the UMass Dartmouth SLR DSS database was written. The script also records forecasted weather data out to 10 days, which is used as input to the prediction models. Forecasted data is updated with real-time data as time progresses and the real-time data is collected. Interns continued working on the DataGarrison and Onset data gathering scripts. There was an unexpected need to alter the current database schema to accommodate new data types which were introduced by the addition of more sources. This was a small problem which was soon resolved. The solution minimized the changes to the actual schema while maintaining the consistency of collected data. Other unexpected glitches would arise during the construction of scripts. For example, it came to the attention of the team that certain sites had been repaved, which altered the depths of the sensors in the pavement when comparing historical data to current collected data. A solution to this was to add the ability for users to attach time-stamped notes to DSS-SLr sites, or to attach events that might affect data interpretation on behalf of the users viewing the data in the future. For another example, adjustments had to be made so that the scripts incorporated calibration factors for the quantities detected by the sensors. Mapping the correct units into the desired database format was also incorporated into scripts. Units were not consistent across reported data, thus a system had to be agreed upon. In addition, at one point, it was not clear which modbus addresses corresponded to which sensors. Data columns were becoming scrambled each time the transmission instrumentation was shut off due to a water leakage into the transmission equipment and sensor instrumentation. This had to be addressed on the software side, and additional computer software scripts had to be written. These scripts use sensor serial numbers, so that scrambling of the data columns does not occur. All of this took painstaking work to resolve, of which the team grossly underestimated.

In the seventh quarter, the team began intensive work on the DSS-SLR's graphing functionality. Historic raw data that had been historically graphed would validate functionality. In addition, manual downloads of the real-time data from the CRS&SI deployed sites was graphed using Microsoft excel. By comparing the manually filtered data that was done historically with DSS-SLR website's plots, the team could determine whether the website was properly functioning. At his point, the scripts running on the UMass Dartmouth DSS-SLR automatically import the data from DataGarrison to UMass Dartmouth data center. DataGarrison provides the satellite transmission of data from our two CRS&SI location sites. The DSS-SLR GUI displays real-time data both in a tabular and graphical format. The site was tested with Firefox, Google Chrome and Internet Explorer browsers.

Raw data coming from both stations can also be viewed by going to https://datagarrison.com/ and typing in the usernames with password 'data'. The usernames are 300234010074300 and 300234011200430. The raw data from the cellular transmission site can be viewed at www.Hobolink.com using the name "research" and password "umassd." It was noted that during this seventh quarter, there was a failure of data transmission from this site. One of the UMass Dartmouth team members and his graduate student traveled to this site in Madison, Maine, to troubleshoot. The cause of the failure was identified and resolved.

As observed in the seventh quarter, debugging the code was becoming a large part of the research team's focus. This increased in the last and eighth quarter. For example, database columns were not always aligned with the correct sensors and adjustments in the scripts had to be completed. Validation of the data was also on-going and required more work than anticipated. Addressing these software bugs was the focus of this last quarters of the project. To facilitate this, and in order to track the bugs, a bug-tracking system for the DSS-SLR with specific logins was set up for the UMass Dartmouth team members. It was and is still located at http://ne-slr.umassd.edu/redmine.

One of the last script coding challenges during the eighth quarter, was the integration of the SLR Interpolation tool or application. This tool filters out erroneous data and alerts users of any data collection errors. Ranges of acceptable values limit data incorporation into the database. In other words, malfunctioning sensors and/or bad data being transmitted are flagged. Other improper functioning alerts are identified to be installed for future refinement of the DSS-SLR . Again, the bug-tracking system was a great facilitator.

Also, during the last quarters of the project, communication between State DOTs and the UMass Dartmouth research team increased in frequency. Feedback on the GUI and its user friendliness became useful and crucial. A tutorial was under the planning stage for the final project meeting and the feedback assisted with the development of this tutorial.

DOT representatives, the project Advisory Board and Team members were invited to a final project meeting, August 22, 2013. A list of participants is provided in appendix-I of this final report, as well as an agenda in appendix-II. The UMass Dartmouth research team provided a training tutorial to NH DOT, ME DOT and US DOT at the final meeting, using the Project Flowchart slides, appendix-III, and the *Tutorial and Manual,* provided as a separate document in conjunction with this final report. The manual includes an *Implementation Guide.*

I — TECHNICAL STATUS – EXTENSION PERIOD ONLY

Accomplishments by Milestone

Brief description of work performed by individual milestone(s) accomplished/deliverable(s) produced labeled by Task Number.

Task No. 1: Establish Advisory Board completed

Task No. 2: Day-Long Kick-Off Meeting completed

Task No. 3: Meeting Minutes & Quarterly Reports completed

In order to ensure progress, the UMass Dartmouth research team continued to hold meetings and make phone calls within the research group and with our partners during the 3-month extension period. In addition to our consultants, State DOT partners and advisory board members, partners include technical contacts at Hoskin Scientific Limited, Douglas Calvert, Onset Computer Corporation, Plymouth State University partners and partners with Upward Innovations and DataGarrison, Tom Stalcup.

Task No. 4: UMass Dartmouth Test-bed Established completed

Task No. 5: Three Remote Test Sites Established completed

Task No. 6: Project Website & DSS-SLR Established completed

Task No. 7: SLR Interpolator Tool completed

Coding the first version of the SLR Interpolation application, or SLRI, has been completed and is installed onto the DSS-SLR; debugging and validation is now also complete. This tool finds the average daily temperatures at subsurface locations, and then interpolates to determine the depth at which the subsurface temperature is 32 degrees Fahrenheit or 0 degrees Centigrade.

The Team has also completed the graphing functionality using the SLRI tool. Manually generated frost-thaw plots generated for the winter months 2012-13 assisted in the validation of the code. Plots are generated by downloading from our DataGarrison provider, the satellite transmitted data from the two test sites at Mariaville, ME, and Warren Flats, NH. Plots are also generated by downloading from our Hobolink provider, the cellular transmitted data from the third test site at Madison ME. By comparing the manually graphed data to that of the DSS-SLRI's filtered data output, the team has found differences. Rather than using average daily temperatures to interpolate, the manual generated graphs perform the interpolation prior to finding the average. These differences in the frost-thaw plots are not critical and it has been decided that for the purpose of efficient coding, the average temperatures are performed daily prior to performing the interpolation.

Task No. 8: Historic Database Expansion completed

Task No. 9: Predictive Model Identification & Installation completed

A relatively simplistic frost-thaw index model has been initially installed onto the DSS-SLR; validation of the output has been completed. A report ranking all the predictive models that are under consideration for deployment onto the DSS-SLR has been provided to the US DOT. It includes a discussion of the selected top ranking Predictive Model identified as appropriate for implementation onto the DSS-SLR.

Task No. 10: Predictive Model's Outputs vs. SLRI's Real Data Output completed

A preliminary manually generated comparison study of the Predictive Model’s output with the SLRI's real data plots has been completed. The integration of the SLRI onto the

DSS-SLR has been completed. Assessment continued during the 3-month extension period. Debugging and validation is now complete.

In addition, a preliminary manually generated comparison of the plots comparing frost-thaw depths at the sunny versus the shady locations in the two sites in Maine has also been completed. There were significant differences in frost-thaw patterns, especially at the Madison site. There was about a 4 to 5 week delay in the end-of-thaw-date at the shady site versus the sunny site. This drastically affects when the SLR should be removed.

Task No. 11: DSS-SLR Demonstration & User Guide completed

The website User Guide (version 1.0) and login access to the finalized DSS-SLR website was presented at the final meeting to NH DOT, ME DOT and US DOT. Complete access to the DSS-SLR product is available to USDOT at http://ne-slr.umassd.edu. Username and Password are guest and guest.

Task No. 12: Dissemination Report to NH & ME & US DOT completed

DOT representatives, the project Advisory Board and Team members attended a final project meeting, August 22, 2013. A training tutorial was presented to NH DOT, ME DOT and US DOT. A flowchart of the project focuses on all aspects of the project was also presented.

Task No. 13: Final Project Report Submission completed

Upon successful review by the program manager, a final project report will be submitted. The final report will be disseminated to other State DOTs in other New England States.

Task No. 14: Dissemination to National Professional Communit completed

The project flowchart has been completed and can be accessed at the prezi.com website where viewers can zoom into slides of the chart http://prezi.com/53zyouvf_uq5/?utm_campaign=share&utm_medium=copy.
A snapshot of the chart is provided in appendix-III. Note the following.
1. In order to see it full screen, Left-click full screen box (bottom right corner)
2. In order to zoom in or out,
   a. you can use the mouse-scroll-wheel
   b. or you can bring mouse to right-edge of your monitor screen and you'll see + and - to scroll
3. Move around in the flow chart when you left-click and drag.
4. escape key will get you out of full screen.
5. In order to see the slide show, use the right and left arrow at the bottom of the screen.

Problems Encountered:

The debugging of the computer software's scripts was naturally time consuming. Addressing these software bugs has been the focus of this extension period. The process became significantly more efficient when a bug-tracking system for the DSS with specific logins was set up for the UMass Dartmouth research team members. It is located at http://ne-slr.umassd.edu/redmine. To add a new bug, 'New Issue' was clicked and a title added with description. The 'Target Version' must be set as well as the 'Assigned To fields'. Also, if users want to add a note to any of the sites' database, historic or current, it is now possible for users to add information on that particular site's information page using the 'Note' feature. Much back and forth communications with the State DOT users occurred as part of the debugging process and making the GUI user-friendly.

Tom Stalcup of DataGarrison traveled to one of the satellite sites in Mariaville, Maine, to troubleshoot transmission difficulties and to replace a dead battery. Maine DOT provided roadside safety provisions.

Sometimes the *sensor failure system alarm* is tripped at the Madison cellular transmission site and all system alarms become disabled. One must login into the provider's website at www.hobolink.com and re-enable the system alarms. Re-enabling this type of system alarm will require the U30 logger to be re-launched. To view alarms, visit https://www.hobolink.com/users/2010/devices/3068/alarms. Instructions for re-launching is provided in the DSS-SLR *Manual and Tutorial*, submitted separately in conjunction with this final report. The manual also includes an *Implementation Guide.*

II — BUSINESS STATUS

Hours/Effort Expended

As agreed, Hours/Efforts will not be determined, but rather percentage of time for each of the research team members has been adhered to according to Attachment 3 of the contract.

Funds Expended and Cost Share

Indirect account moneys covered spending shortage gaps. In addition, funds in the budget categories were shuffled and approved by USDOT. For instance, a subcontract to the FROST Associates consultants on this grant award was revised a second time and additional funds were allocated. The new subcontract total is for $45,830 rather than $40,000. The funds in the 'Other Non-Personnel', were shuffled to cover costs for additional graduate students, additional travel costs and additional supply costs. These categories' expenses were initially underestimated.

As the grant costs and expenditures were winding down, budget meetings were held with the UMass Dartmouth Office of Research Administration (ORA). They assisted in the determination of the budget categories for which expenses were underestimated and for which expenses were overestimated. For instance, the research team as well as the Consultants had to make more than the anticipated number of trips to the sites in NH and Maine where the CRS&SI technology was deployed. Additional supplies to repair and re-design the CRS&SI technology was also an additional expense.

ADVISORY/STEERING COMMITTEE MEETING

The Final Meeting of the Advisory Board members, Consultants for this project and the UMass Dartmouth Research Team, faculty and students, occurred on Thursday, August 22, 2013, at 9:20 a.m. See the appendix-II and appendix-III for the agenda and project flowchart presented.

APPENDICES

I. List of Project Participants and attendees to the Final Meeting
II. Final Meeting Agenda
III. Slides of the Flowchart presented at the Final Meeting
IV. Project Dissemination List – Presentations and Papers
V. List of the parameters for the database
VI. List of the DSS software modules
VII. Description and Application Manual for the SolarStream Iridium Satellite Road Weather Monitoring System
VIII. Report evaluating and ranking SLR predictive models
IX. Deployment report, establishment of deployment sites
   - Deployment maps, Site Plans and Equipment Details
   - Deployment Photographs
   - Deployment Soil Test Results

Appendix-I:

List of Project Participants and attendees to the Final Meeting

University of Massachusetts Dartmouth
285 Old Westport Road
North Dartmouth
Massachusetts 02747-2300
508-999-8000

Final meeting, Thursday, August 22, 2013
Board of Trustees Room, Foster Building, UMass Dartmouth
or Call in number
Freephone/Toll Free Number: 877-988-5998
Local/Toll Number: 517-466-9381
Everyone use the Participant Passcode number: 4660512
USDOT RITA Grant Award RITARS-11-H-UMDA
Data Collection via CRS&SI Technology to Determine When to Impose SLR

Project Participants

ADVISORY BOARD MEMBERS

- Caesar Singh, USDOT RITA program manager
- Vasanth Ganesan, USDOT RITA assistant to program manager
- Jennifer Nicks, USDOT FHWA
- Alan Hanscom, District Engineer, NHDOT Highway District 2 and his staff
- Dale Peabody, Transportation Research Division, Office of Safety, Training & Research, MaineDOT; and also from MaineDOT, Brian Burne, Cliff Curtis and other staff
- David Silvia, Advanced Concepts Engineer, Naval Undersea Warfare Center
- Maureen A. Kestler, USDA Forest Service, San Dimas Technology & Development Center
- Tom Stalcup, Upward Innovations
- Douglas Calvert, Hoskin Scientific Ltd.
- Brendon Hoch, Plymouth State University

CONSULTANTS

- Robert (Bob) Eaton, Research Civil Engineer, FROST Associates
- Richard L. Berg, Research Civil Engineer, FROST Associates
- Kenneth Kestler Inc.

UMASS DARTMOUTH RESEARCH TEAM

- Marguerite Zarrillo, Prof. Physics
- Heather Miller, Prof. Civil & Environmental Engineering (CEN)
- Ramprasad Balasubramanian, COE Associate Dean / Prof. Computer & Information Science (CIS)
- Honggang Wang, Assoc. Prof. Electrical & Computer Engineering (ECE)
- Shekar, Venkateswaran, Ph.D. graduate student, ECE
- Christopher Cabral, M.S. graduate student, CEN
- Scott O'Connor, M.S. graduate student, CIS
- Zhang, Zhaoyang, Ph.D. graduate student, ECE
- Ide, Mark, M.S. graduate student, CIS

Appendix-II:

Final Meeting Agenda

University of
Massachusetts
Dartmouth

285 Old Westport Road
North Dartmouth
Massachusetts 02747-2300

508-999-8000

Final meeting, Thursday, August 22, 2013
Board of Trustees Room, Foster Building, UMass Dartmouth
or Call in number
Freephone/Toll Free Number: 877-988-5998
Local/Toll Number: 517-466-9381
Everyone use the Participant Passcode number: 4660512
USDOT RITA Grant Award RITARS-11-H-UMDA
Data Collection via CRS&SI Technology to Determine When to Impose SLR

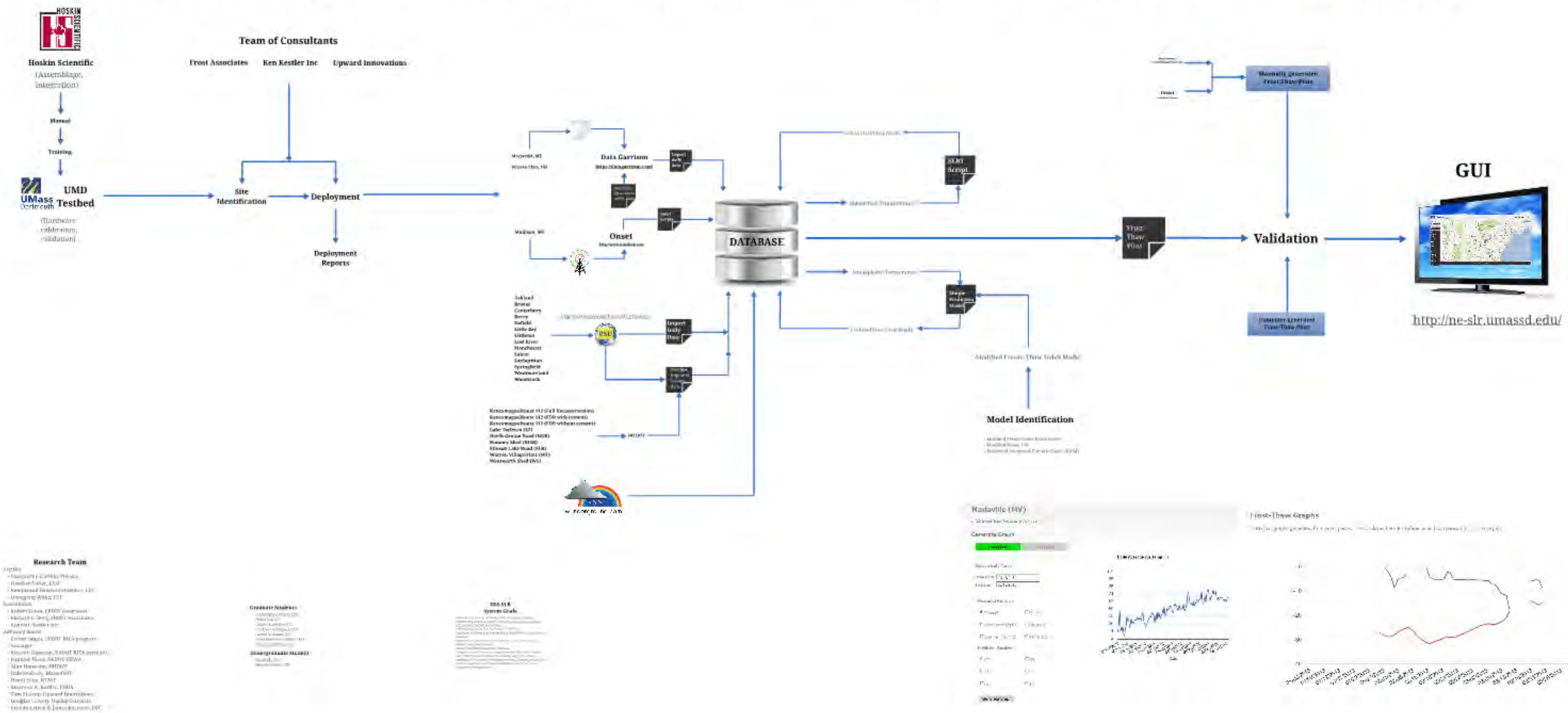
Agenda

- **9:20 a.m. Registration/Arrival with coffee, fruit & pastry**
- **9:50 a.m. Welcome & Introductions**
- **10:10 a.m. Project Flow Chart & Discussion Topics**
- **11:10 a.m. DSS-SLR Tutorial & Manual**
- **12:00 p.m. Lunch Break and Informal Discussion**
- **1:00 p.m. Transfer of Operations & Maintenance**
- **Discussion: Lessons Learned & Advisory Board Comments**
- **2:00 p.m. Other Business**

Appendix-III:

Slides of the Flowchart presented at the Final Meeting

Development for the DSS - SLR
Decision Support System - Seasonal Load Restriction
USDOT RITA Grant Award RITA ARS-11-H-UMDA



Research Team

Faculty

- Marguerite Zarrillo, Physics
- Heather Miller, CEN
- Ramprasad Balasubramanian, CIS
- Honggang Wang, ECE

Consultants

- Robert Eaton, FROST Associates
- Richard L. Berg, FROST Associates
- Kenneth Kestler Inc.

Advisory Board

- Caesar Singh, USDOT RITA program manager
- Vasanth Ganesan, USDOT RITA assistant
- Jennifer Nicks, USDOT FHWA
- Alan Hanscom, NHDOT
- Dale Peabody, MaineDOT
- David Silva, NUWC
- Maureen A. Kestler, USDA
- Tom Stalcup, Upward Innovations
- Douglas Calvert, Hoskin Scientific
- Brendon Hoch & James Koermer, PSU

Graduate Students

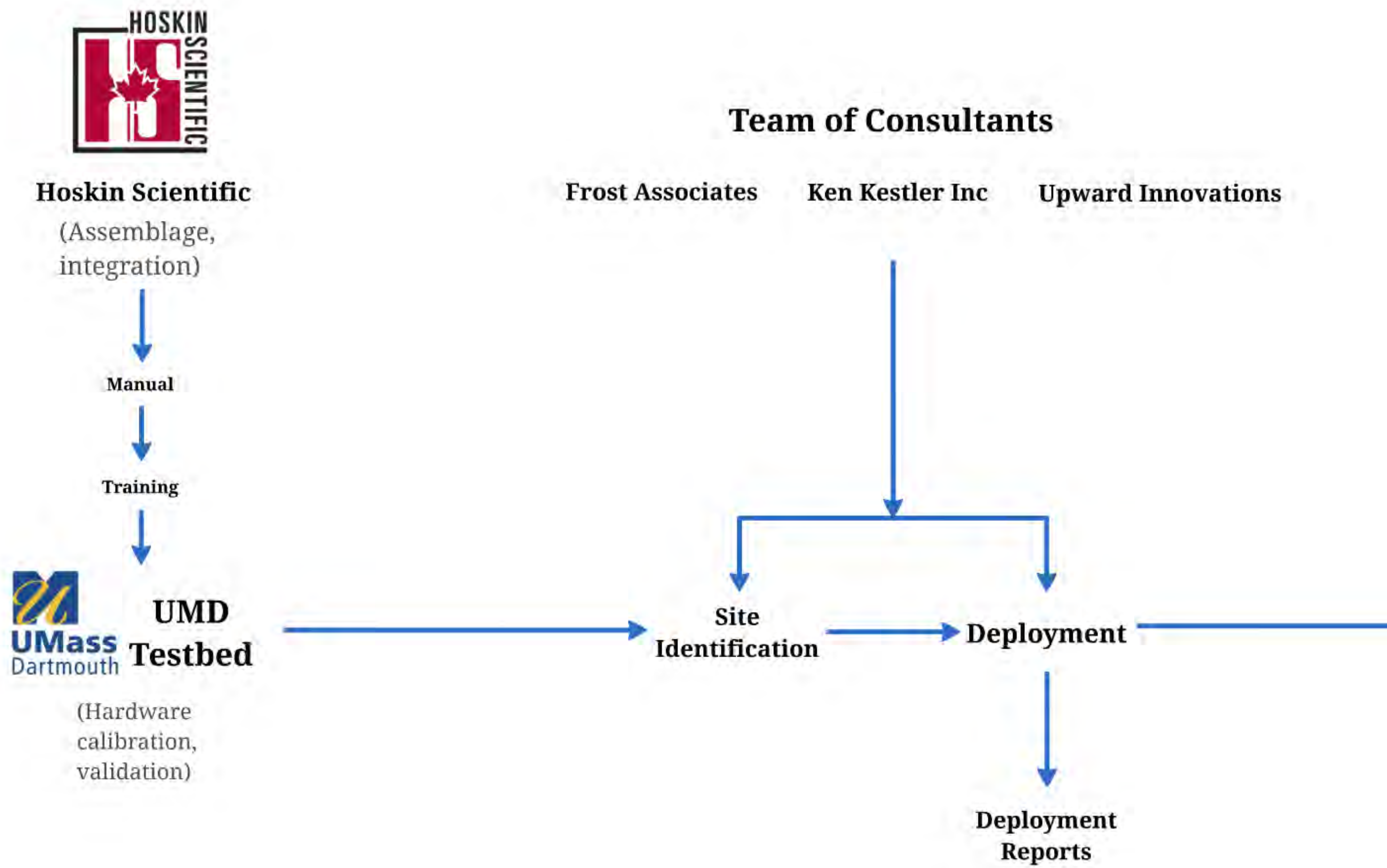
- Christopher Cabral, CEN
- Mark Ide, CIS
- Aaron Larocque, CIS
- Andrew Rodriguez, CEN
- Navid Tadayon, ECE
- Venkateswaran Shekar, ECE
- Zhaoyang Zhang, ECE

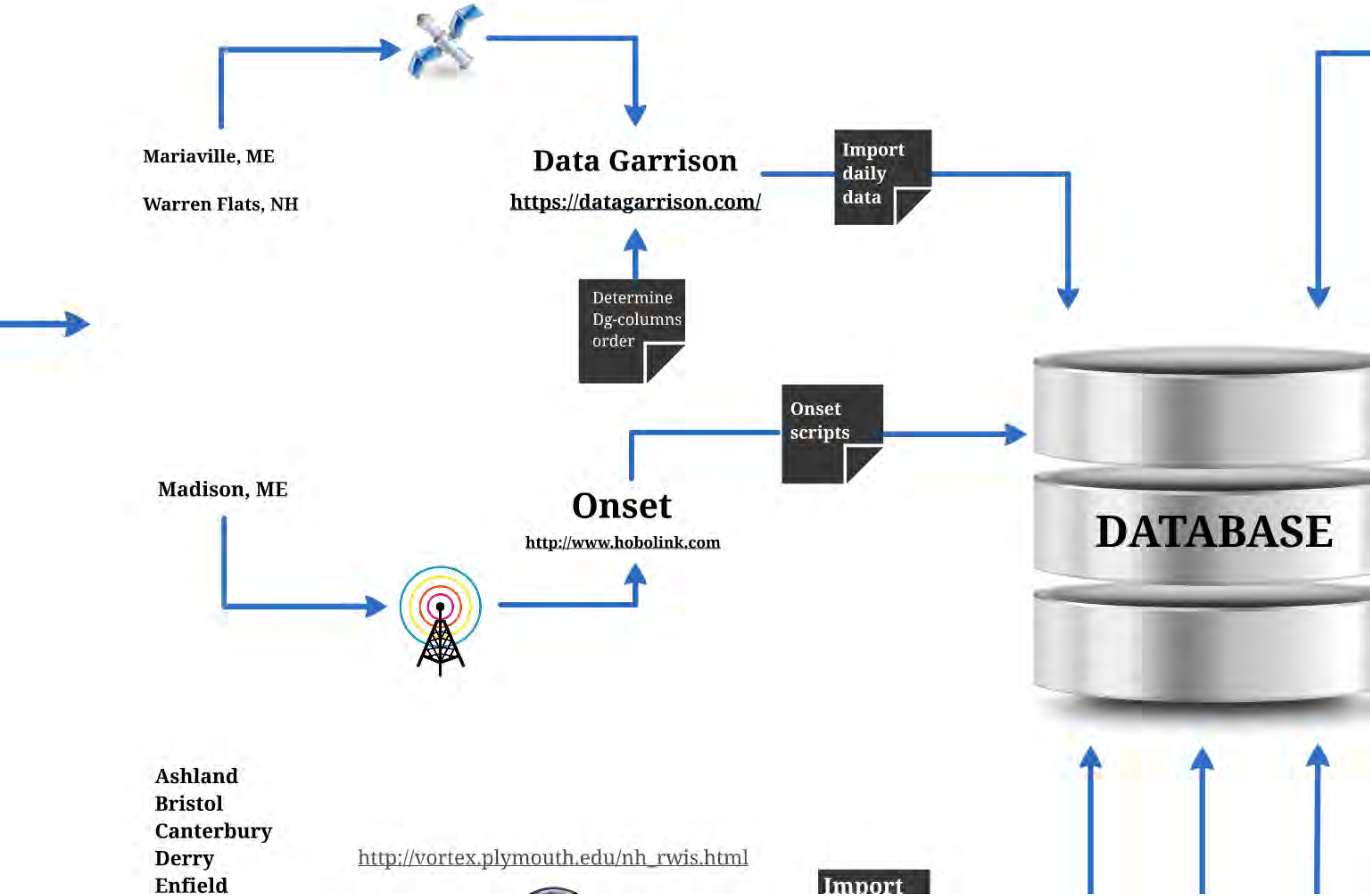
Undergraduate Student

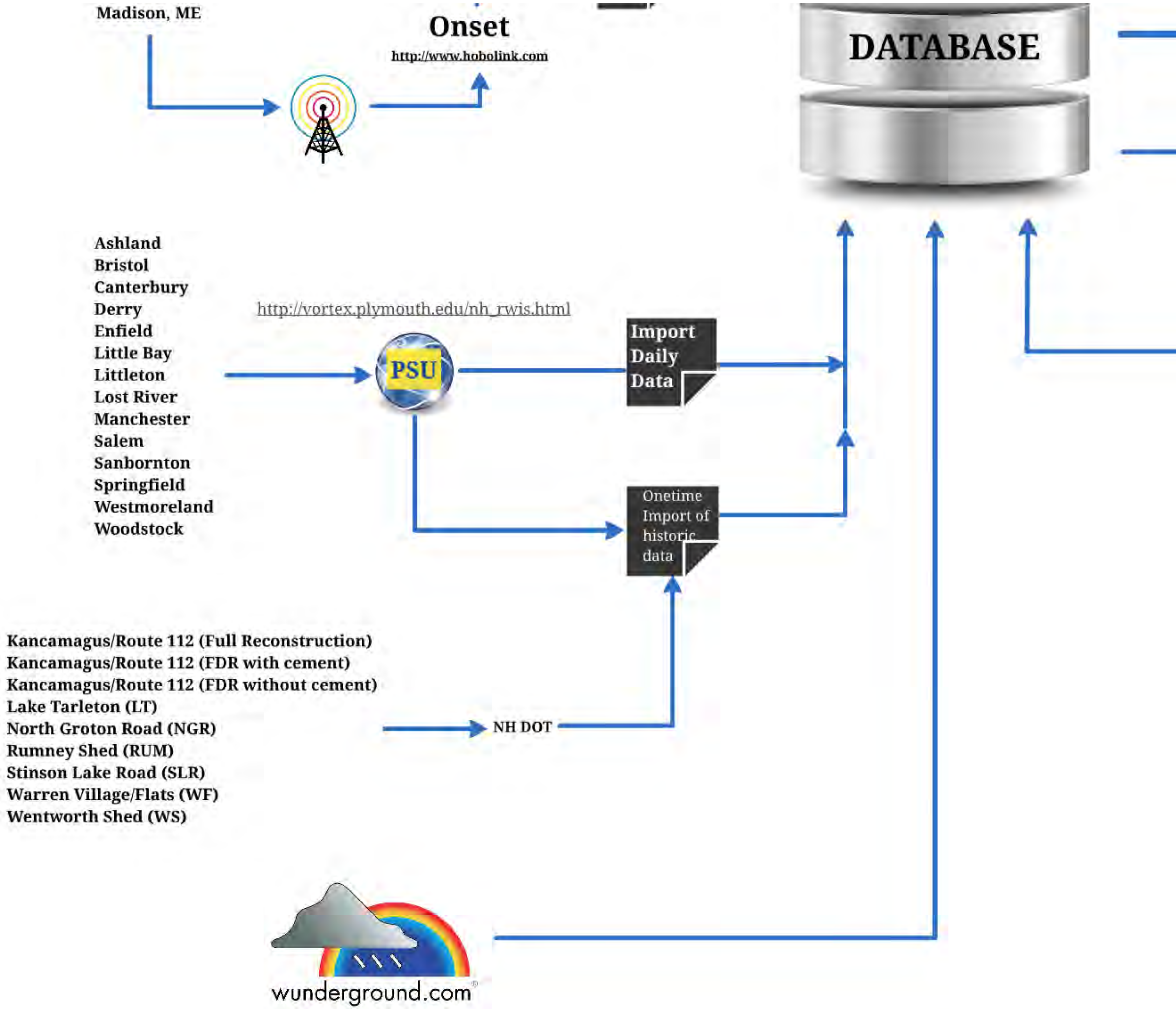
- Mark Ide, CIS
- Kendra White, CEN

DSS-SLR
System Goals

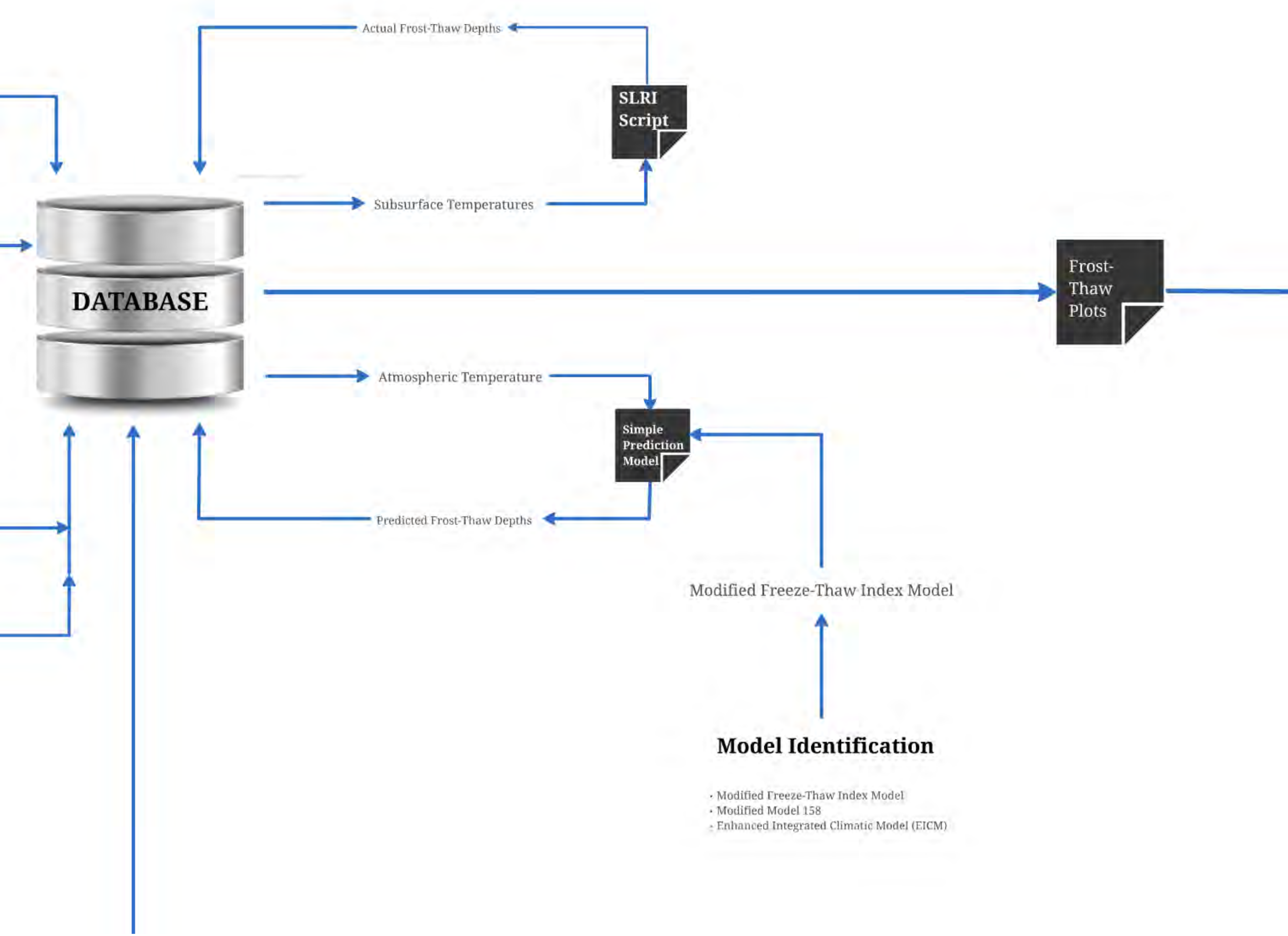
- Eliminate the need to manually collect roadway subsurface temperature data and replace it with remote sensing and spatial information, CRS &SI, technology.
- Collect atmospheric data via CRS&SI technology.
- Aggregate real-time data sources & historical data into one central database.
- Automate the processing of raw data into a more meaningful display for decision makers.
- Create Frost-Thaw depth plots from data.
- Design and build a Decision Support System, DSS, website with a user friendly Graphical User Interface for our DOT partners.
- Automate the collection of atmospheric data. Integrate a model on the DSS to predict Frost Thaw depths based on the forecast of atmospheric temperatures.

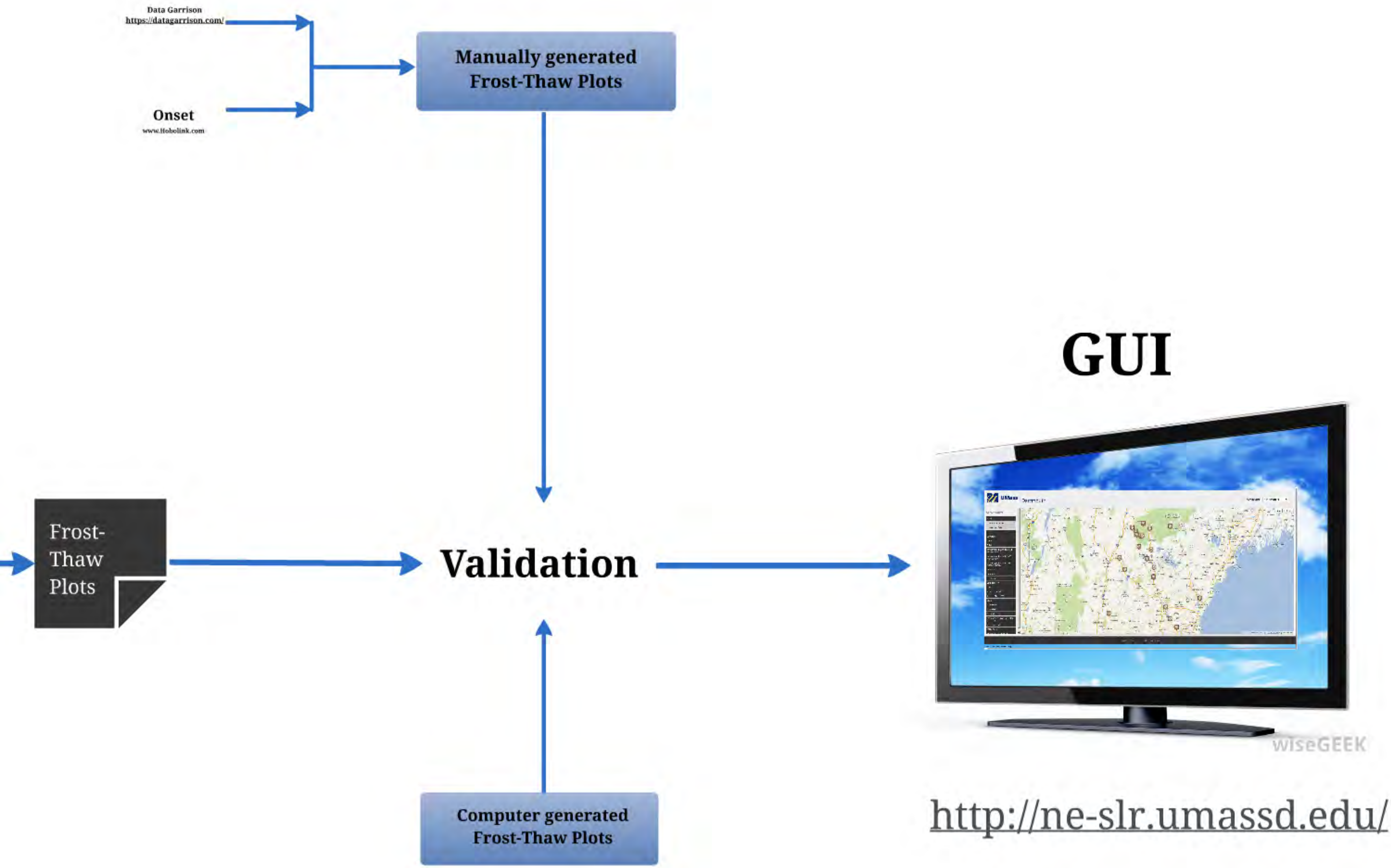

Hoskin Scientific
(Assemblage, integration)
Manual
Training
UMD Testbed
(Hardware calibration, validation)
Team of Consultants
Frost Associates
Ken Kestler Inc
Upward Innovations
Site Identification
Deployment
Deployment Reports


Mariaville, ME
Warren Flats, NH
Data Garrison
https://datagarrison.com/
Import daily data
Determine Dg-columns order
Onset scripts
Madison, ME
Onset
http://www.hobolink.com
DATABASE
Ashland
Bristol
Canterbury
Derry
Enfield
http://vortex.plymouth.edu/nh_rwis.html
Import



Madison, ME
Onset
http://www.hobolink.com
DATABASE
Ashland
Bristol
Canterbury
Derry
Enfield
Little Bay
Littleton
Lost River
Manchester
Salem
Sanbornton
Springfield
Westmoreland
Woodstock
http://vortex.plymouth.edu/nh_rwis.html
PSU
Import Daily Data
Onetime Import of historic data
Kancamagus/Route 112 (Full Reconstruction)
Kancamagus/Route 112 (FDR with cement)
Kancamagus/Route 112 (FDR without cement)
Lake Tarleton (LT)
North Groton Road (NGR)
Rumney Shed (RUM)
Stinson Lake Road (SLR)
Warren Village/Flats (WF)
Wentworth Shed (WS)
NH DOT
wunderground.com


Actual Frost-Thaw Depths
SLRI Script
Subsurface Temperatures
DATABASE
Frost-Thaw Plots
Atmospheric Temperature
Simple Prediction Model
Predicted Frost-Thaw Depths
Modified Freeze-Thaw Index Model
Model Identification
• Modified Freeze-Thaw Index Model
• Modified Model 158
• Enhanced Integrated Climatic Model (EICM)



Data Garrison
https://datagarrison.com/
Onset
www.Hobolink.com
Manually generated
Frost-Thaw Plots
GUI
Frost-
Thaw
Plots
Validation
wiseGEEK
Computer generated
Frost-Thaw Plots
http://ne-slr.umassd.edu/

Mariaville (MV)

> Advanced Graph Features & Download

Generate Graph

Atmospheric | Subsurface

Select a Date Range

From date: 01/01/2013

To date: 08/12/2013

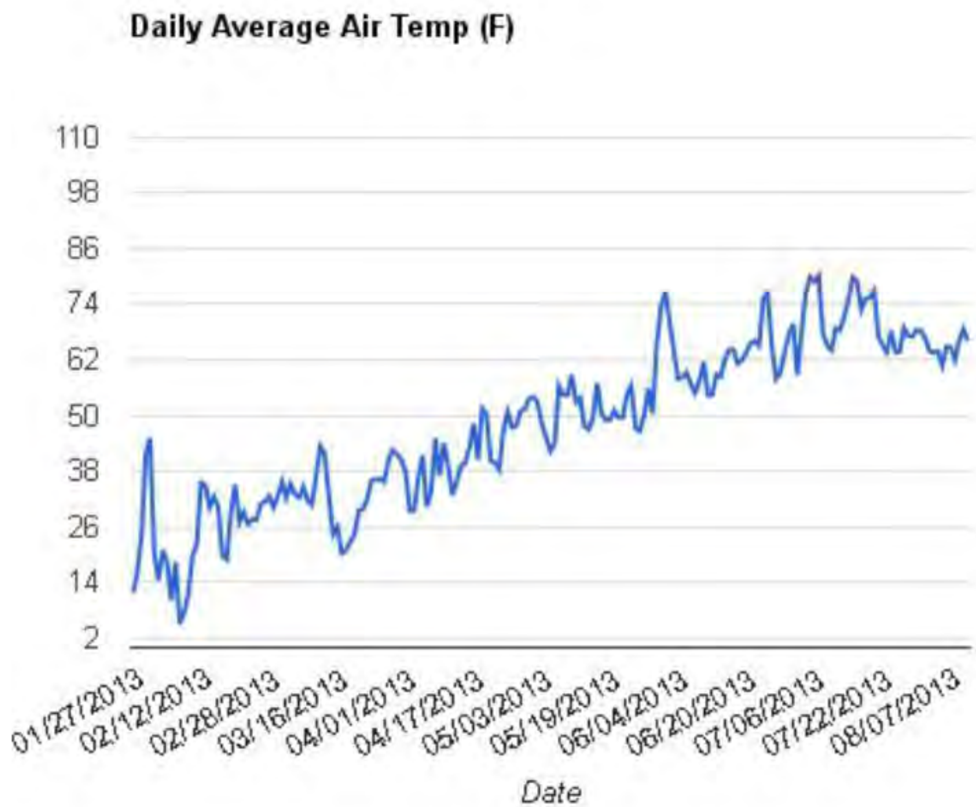
Measured Variables

- Temp (F)
- Rh (%)
- Wind Speed (mph)
- Bar. (inHg)
- Solar Rad (W/m^2)
- Rainfall (in)

Predicted Variables

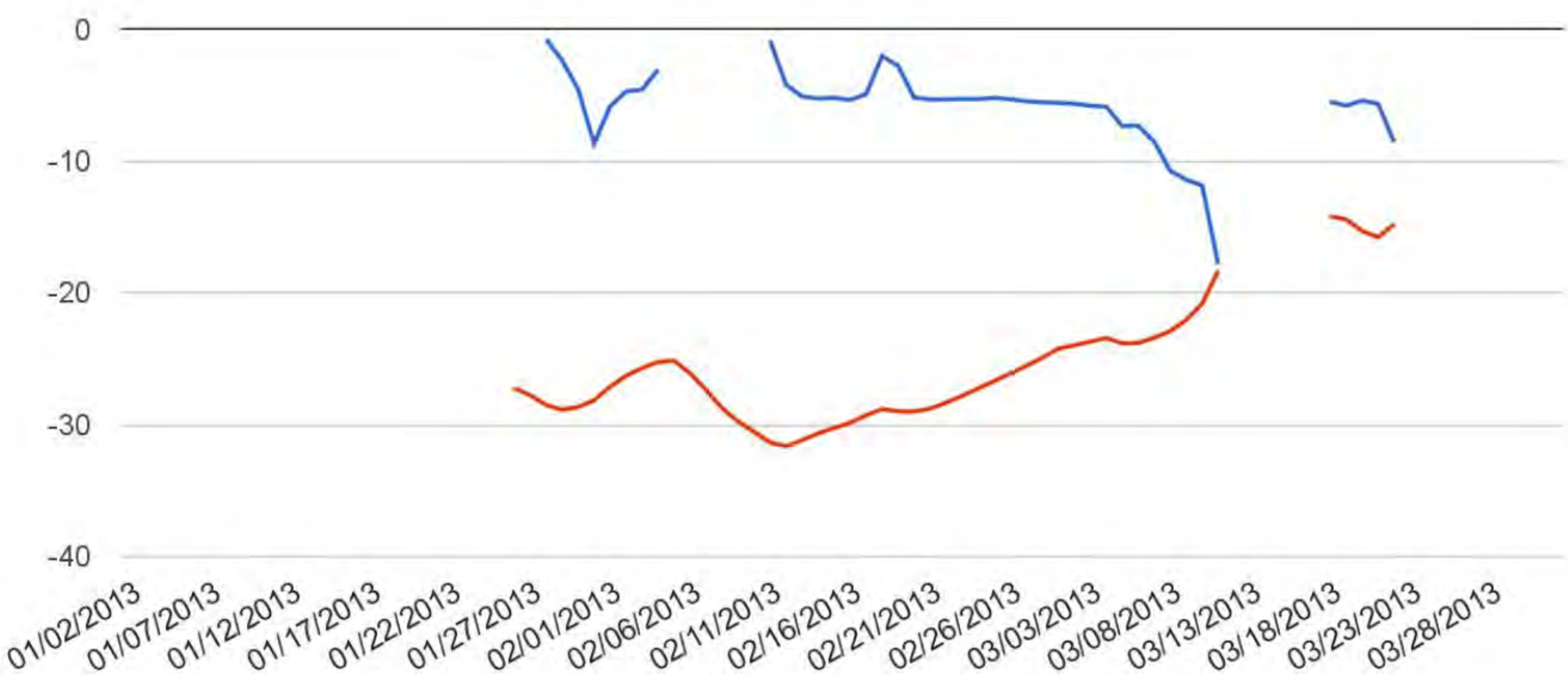
- CTI
- CFI
- DTI
- DFI
- FD
- TD

Generate Graph

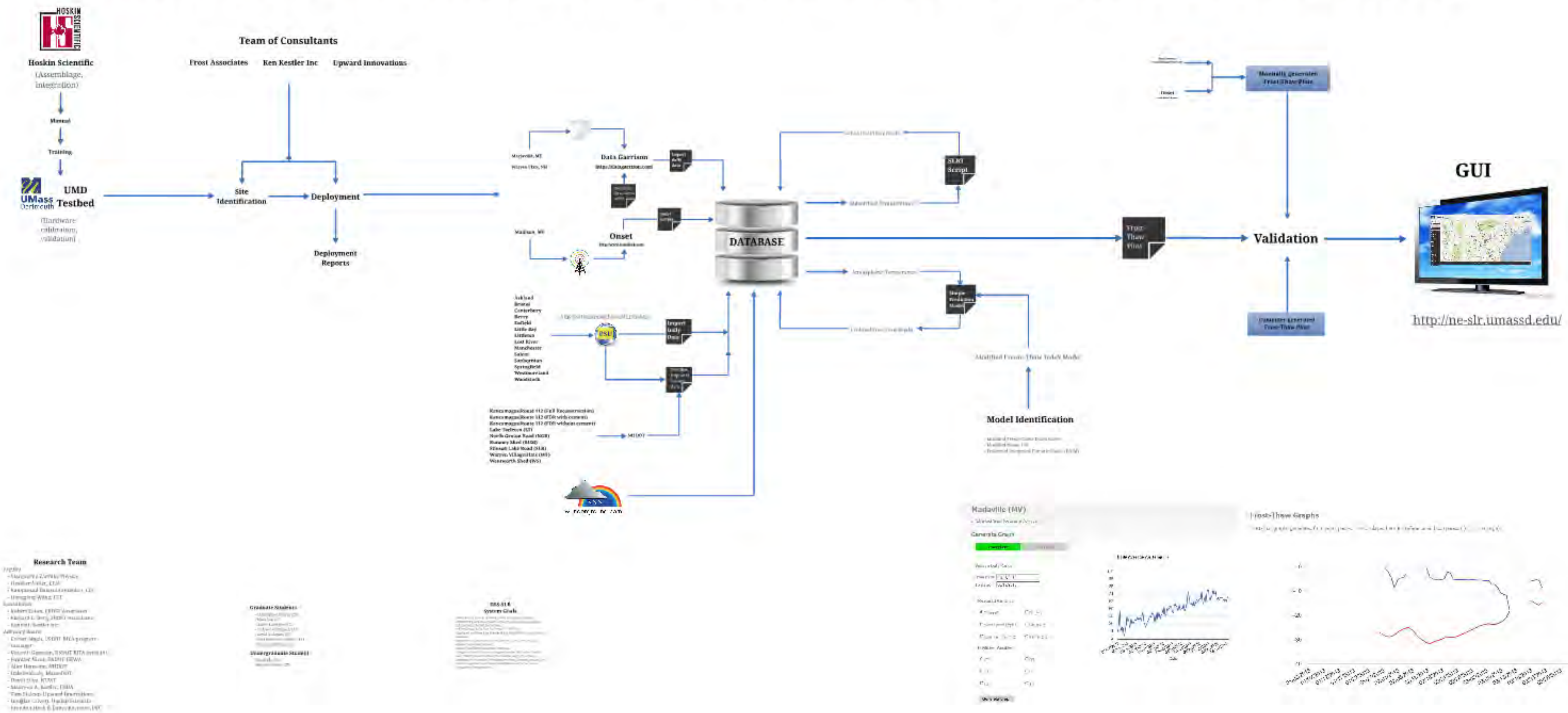


Frost-Thaw Graphs

Frost-That graphs generated from years past will be displayed here for reference and comparison (click to enlarge).



Development for the DSS - SLR
Decision Support System - Seasonal Load Restriction
USDOT RITA Grant Award RITA ARS-11-H-UMDA



Appendix-IV:

Project Dissemination List – Presentations and Papers

DISSEMINATION: Presentations & Publications in Chronological Order:

– Presentation entitled, *Data Collection via CRS&SI Technology to Determine When to Impose SLR*, by Marguerite Zarrillo, FHWA's Road Weather Management Program (RWM) Stakeholder's meeting ,Albuquerque, NM, (09/09,/2011).

http://www.its.dot.gov/presentations/roadweather/Zarrillo_RemoteSensing_files/frame.htm

– Presentation entitled *Data Collection via Commercial Remote Sensing and Spatial Information Technology to Determine When to Impose Spring Load Restrictions,* by Heather Miller, TRB 91st Annual Meeting; workshop # 184 Sensing Technologies for Transportation Applications, Presentation P12-6178, (01/22/2013).

http://pressamp.trb.org/conferenceinteractiveprogram/EventDetails.aspx?ID=22545

– Paper and Presentation entitled *Evaluation of a Freeze-Thaw Index Model for Predicting Frost Penetration in Soils,* by Heather Miller, Andrew Rodriguez, Maureen A. Kestler, Richard L. Berg, Robert Arthur Eaton, TRB 91st Annual Meeting; Presentation 12-2519, (01/24/2013).

http://pressamp.trb.org/conferenceinteractiveprogram/EventDetails.aspx?ID=23528&Email=

– Poster Presentation entitled *Calibration of a Freeze-Thaw Prediction Model for Spring Load Restriction Timing in Northern New England,* 18th UMass Dartmouth Annual Sigma Xi Research Exhibit, (04/30/2012).

– Poster Presentation entitled *Data Collection via CRS&SI Technology to Determine When to Impose SLR Spring Load Restrictions,* 18th UMass Dartmouth Annual Sigma Xi Research Exhibit, (04/30/2012).

– Presentation for Training of UMass Dartmouth Research Team, *Hoskins CRS&SI Technology Stations,* (06/06/2012).

– Presentation and Paper entitled *Preliminary Development of a Real Time Seasonal Load Restriction System for Remote Sites,* 15th International Conference on Cold Regions Engineering, Preliminary (08/2012).

http://extranet.csce.ca/2012/iccre/Conference-Program

– Presentation and Paper entitled *Calibration of a Freeze-Thaw Prediction Model for Spring Load Restriction Timing in Northern New England,* 15th International Conference on Cold Regions Engineering, (08/2012).

http://extranet.csce.ca/2012/iccre/Conference-Program

– Paper entitled *Modeling and Decision Support System to Determine When to Impose Seasonal Load Restriction (SLR),* by Scott O'Connor, Ramprasad Balasubramanian, Marguerite Zarrillo, Heather Miller and Honggang Wang, International Workshop on Applied Modeling and Simulation (WAMS'12) Proceedings Publication (09/2012).

http://www.msc-les.org/conf/wams2012/

– Task 5 *Deployment Report* describing deployment of equipment at the remote test sites, as well as photos, problems encountered and lessons learned from the development, design and deployment, by Heather Miller (01/2013).

– Presentation entitled *DSS for New England DOTs that Best Determine When to Impose SLRs using Data Collected via CRS&SI Technology*, TRB 92nd Annual Meeting; Workshop #135 Sensing Technologies for Transportation Applications; Presentation P13-6289, (01/13/2013). http://amonline.trb.org/39g3na/1

– Presentation at the USDOT RITA meeting with the program manager, by Marguerite Zarrillo, (01/16/2013).

– Presentation and Thesis entitled, *Modeling and Decision Support System to Determine When to Impose Seasonal Load Restriction (SLR),* CIS MS student Scott O'Connor, (03/2013).

– Presentation and Thesis entitled, *Analysis and Evaluation of Freeze-Thaw Prediction Models for Use with Spring Load Restriction Application and Removal,* CEN MS student Christopher Cabral, (04/2013).

– Presentation and Paper entitled *Comparative Analyses of Methods for Posting Spring Load Restrictions,* by Heather Miller, Christopher CabralProceedings of ISCORD 2013, Anchorage, Alaska, (05/2013).

http://submissions.miracd.com/ASCE/ColdRegions2013/Itinerary/ConferenceMatrixEventDetail.asp?id=17

Appendix-V:

List of the parameters for the database

9-25-11 Updated_List of Parameters for Database

List of sensors (Real-Time Data):

Presumably, will be able to download the data transmitted from the sensors as a csv file from the Data Garrison site

Moisture Sensors, 4 per site

Thermistor Probes:
 will each probe have 12 sensors plus 3 fly sensors (total of 15 sensors)?
 or will each probe have 9 sensors plus 3 fly sensors (total of 12 sensors)?

Wind Speed
 Will that sensor also measure wind direction?
 If so, will this be 2 different data fields, separated by a comma?

Air Temperature

Relative Humidity

Precipitation (Rain Gage)

Solar Radiation (Pyranometer)

Barometric Pressure

Water Table Depth (Pressure Transducer)

Also, it is assumed that there will be a column or field of data with a date & time stamp. Will that be 2 fields of data separated by a comma, or will the date & time be in the same field?

Will there be any other fields of data (such as battery voltage or any other parameters) which will be transmitted?

Additional Data Requirements for Database (Real-Time Data)
(not necessarily to be transmitted through the Data Garrison site)

- Each subsurface sensor (temperature and moisture) will have a depth associated with it.

  Each temperature sensor will have a "Temp. Correction Factor" associated with it. For each reading, it will be necessary for the database software to compute a "Corrected Temperature."

- "Forecasted" atmospheric weather data will need to be brought in and archived in the database (for purpose of the predictive model).

  Details of this will vary, depending upon whether we utilize an EICM-based SLR tool from Meridian Technology (or possibly from Greg Larson), or whether we utilize a simpler model based on freeze-thaw indices.

9-25-11 Updated_List of Parameters for Database

- In addition, there will be certain data that needs to be associated with each test site (these data will remain constant for a given site):

  Site Name

  Latitude

  Longitude

  Elevation

  Zip code

  Nearest city or town or Route number

  Nearby weather station (where forecast weather data is obtained)

<u>Historical Information to be entered/housed in Database</u>:

  Frost thaw plots and/or Data tables of frost and thaw depths

  GSD curves and/or Data tables

Appendix-VI:

List of the DSS software modules

Software Modules

1. DSS - data processing and decision making
2. Receive data, catalog and pass along to the DSS (software that creates a seamless transfer of subsurface temperature data and climatic data to the Decision Support System for Imposing Seasonal Load Restrictions (DSS-SLR).)
3. Archiving and web-application for accessing data by location via data as well a geographic UI
4. A data evaluator and SLR Interpolator (SLRI)
5. Frost-thaw predictive model - implementation
6. Web hosting
7. The DSS will classify and analyze all the measured data, and will provide visualized forms and graphical plots of the subsurface temperature data used by SLR-timing decision makers
8. The DSS-SLR will make it possible to display the CRS&SI data on a simple web interface for NH and ME DOT personnel with an interactive map illustrating the test sites' spatial information.
9. The user will be able to "click" on a particular test site and obtain up to date information from the site, including: measured air temperatures, subsurface temperatures and soil moisture profiles, as well as predicted frost and thaw depths
10. Categories of performance issues are quality of service, reliability, security and privacy.

Appendix-VII:

Description and Application Manual for the SolarStream Iridium Satellite Road Weather Monitoring System

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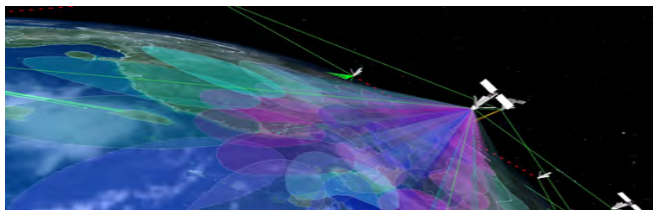
Date: June 6th / 2012

Project: University of Massachusetts

SolarStream Iridium Road Weather Monitoring System :

UPWARDINNOVATIONS Inc.



Station: SolarStream Iridium Monitoring System

SolarStream Modbus RTU

For Sales & Service Contact:
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Edmonton Ph. (780) 434-2645
Vancouver Ph. 1-800-663-3023

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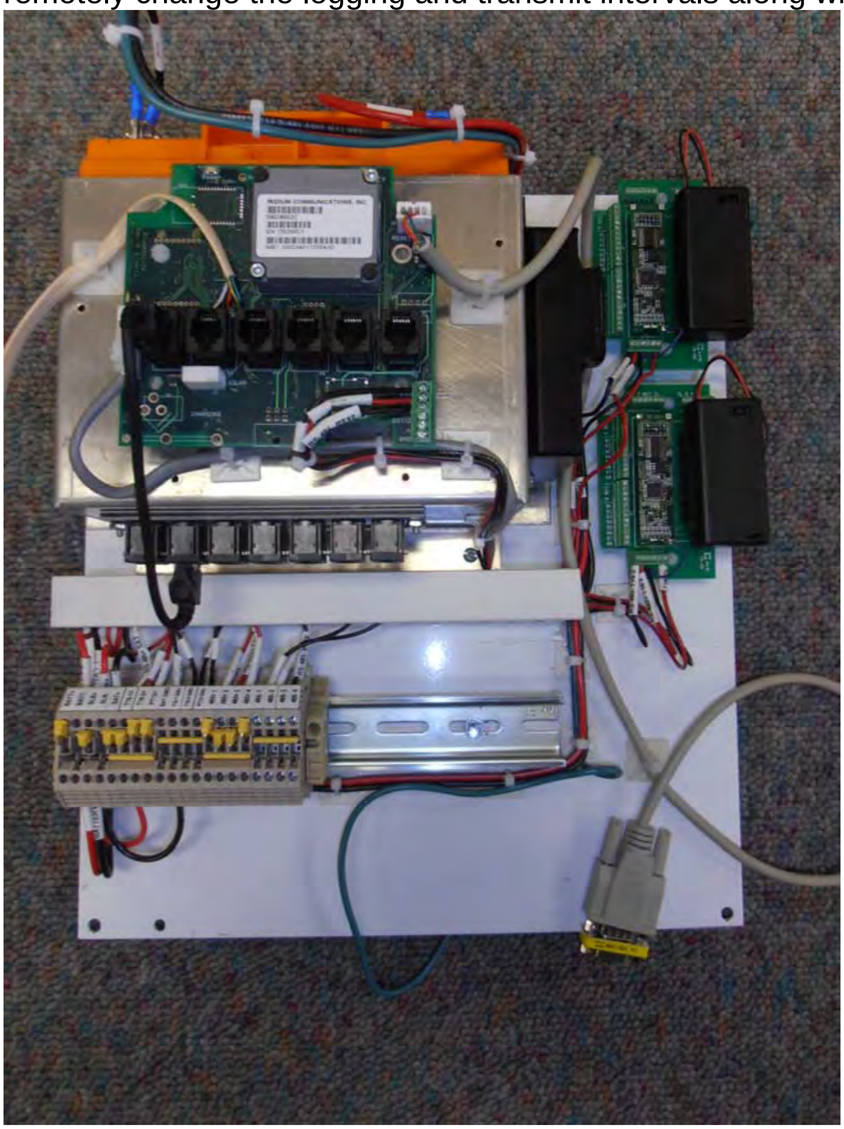
System: Overview:

The road weather monitoring comprises of a Iridium based satellite modem with a SolarStream communication interface module. SolarStream is manufactured by Upward Innovations in Falmouth, MA which also provide the DataGarrison web hosting system. The system is designed to monitor up to 50 parameters using Onset Smart Sensors and Modbus RTU protocol for the thermistor string interface. Connected to the system are Qty 4 soil moisture sensors, wind speed, water level and water temperature, rainfall, RH & T, , barometric pressure, solar radiation, Qty 12 temperature string thermistors using the YSI 44006 thermistor which have a interchangeability of +/-0.2C. The solarStream module communicates to the INW sensors and ICPDAS thermistor modules using Modbus RTU over RS-485. With the DataGarrison web hosting system the user can remotely change the logging and transmit intervals along with alarm parameters.



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IRIDIUM SATELLITE COMMISSIONING GUIDE

Follow these steps to activate your system:

1) Open satellite / datalogger enclosure connect the Onset Smart sensors to smart sensor inputs as per the provided wiring chart. Cut off anti snag hooks on Onset smart sensors to allow them to pass through cable gland. Push cables side ways into slit in rubber cable gland. If provided with liquid tight conduit seal conduit opening in the enclosure with silicon or conduit putty.

2) Open orange disconnect PWR & I/O Terminals: SLR+, BATT+, SAT+, PT12 1+, T16#1+, T16#2+

3) Connect Solar panel:

White (+) lead ←--→ Satellite Terminal SLR(+)
Black (-) lead ←---→ Satellite Terminal SLR(-)

a) Close : Satellite Terminal Batt(+)
b) Close : Satellite Terminal SLR(+)
Note Charging LED on solar regulator should come on if in sunlight.

4) Connect the sensors to the terminals as per the wiring chart. Connect the thermistor string to the bulk head connector.

5) Connect the Iridium antenna and then close terminal SAT(+) which will turn on power to the satellite/datalogger transceiver. The satellite *Power* LED will come on and flash. The *Power* and *Receiver* LED's will start to flash. Wait for a couple minutes and note that the *In Range* LED comes on. This indicates that the system has locked onto a satellite and will begin transmitting data. After the *In Range and Receive* LED's goes out data should be available on DataGarrison web site: www.datagarrison.com .

6) Using DataGarrison launch the datalogger by selecting: Control Panel – Start/Restart Logger. Then select the logging and transmit interval along with the Modbus parameter set up. Send the launch command after the datalogger is powered on.

Once the above steps are followed, data from your station should be available online within about 15-30 minutes. You will then be able to configure the SolarStream device remotely from the web-interface (see WEB ACCOUNT section above).
-WEB ACCOUNT—Contact Upward Innovations to Activate your Account: Ph. 774-392-0856 or Ph. (780) 434-2645 (Hoskin Scientific Ltd.)

Your online account is now set up at https://datagarrison.com user ID Satellite IMEI# (label on satellite module): XXXXXXXXXXXX **pwd: [**hobo**]**

Warning: When turning the power off to the system open terminal SLR(+) before opening terminal BATT(+)

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Fax (604 872-0281	Fax (780) 435-1788	Fax (905) 333-4976	Fax (514) 735-3454

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Sensor / Power Connections:

Battery Connection 12VDC System Power

Description	Terminal
12VDC+	BATT+ (15VDC Max)
12VDC-	BATT-

Solar Panel Connection

Description	Terminal
Solar Panel +	SLR+ (White Wire)
Solar Panel -	SLR- (Black Wire)

INW PT12 Modbus Address #1

Wire Color	Description	Terminal
Red	+12VDC	PT12#1+
Black	-12VDC	PT12 GND
Yellow	RS-485 +	485+ 3
Purple	RS-485 -	485- 3

ICPDAS M-7005 Thermistor Module Address #2

Wire Color	Description	Terminal	M-7055 Terminal
Red	+ 12VDC	T16#1+	(R)+VS
Black	- 12VDC	T16#1 GND	(B) GND
Red	RS-485 +	485+ 1	(Y) Data+
Black	RS-485 -	485- 1	(G) Data-

ICPDAS M-7005 Thermistor Module Address #3

Wire Color	Description	Terminal	M-7055 Terminal
Red	+ 12VDC	T16#2+	(R)+VS
Black	- 12VDC	T16#2 GND	(B) GND
Red	RS-485 +	485+ 2	(Y) Data+
Black	RS-485 -	485- 2	(G) Data-

Onset Smart Sensors

Sensor	Smart Sensor Port (Main or Expansion)
Rain Gauge	Main
Pyranometer	Main
Wind Speed	Main
RH & Temp	Main
Wind Speed	Main
Barometric Pressure	Main
Soil Moisture #1	Main
Soil Moisture #2,3,4	Expansion

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Thermistor String Wiring as Per Chart below

Wire Color Pairs	Description	M-7055 Address #2 Terminal	Modbus Register
White	Thermistor #1	A0	0
Orange	Thermistor #1	B0	
White	Thermistor #2	A1	1
Purple	Thermistor #2	B1	
White	Thermistor #3	A2	2
Yellow	Thermistor #3	B2	
White	Thermistor #4	A3	3
Black	Thermistor #4	B3	
White	Thermistor #5	A4	4
Blue	Thermistor #5	B4	
White	Thermistor #6	A5	5
Green	Thermistor #6	B5	
White	Thermistor #7	A6	6
Red	Thermistor #7	B6	
White	Thermistor #8	A7	7
Grey	Thermistor #8	B7	
		M-7055 Address #3 Terminal	Modbus Register
White	Thermistor #9	A0	0
Brown	Thermistor #9	B0	
White	Thermistor #10	A1	1
Pink	Thermistor #10	B1	
White	Thermistor #11	A2	2
Tan	Thermistor #11	B2	
Orange	Thermistor #12	A3	3
Purple	Thermistor #12	B3	

Modbus Address	Sensor	Description
1	INW PT12	Water Level and Water Temperature
2	ICPDAS M-7055	Thermistors #1 to 8
3	ICPDAS M-7055	Thermistors #9 to 12

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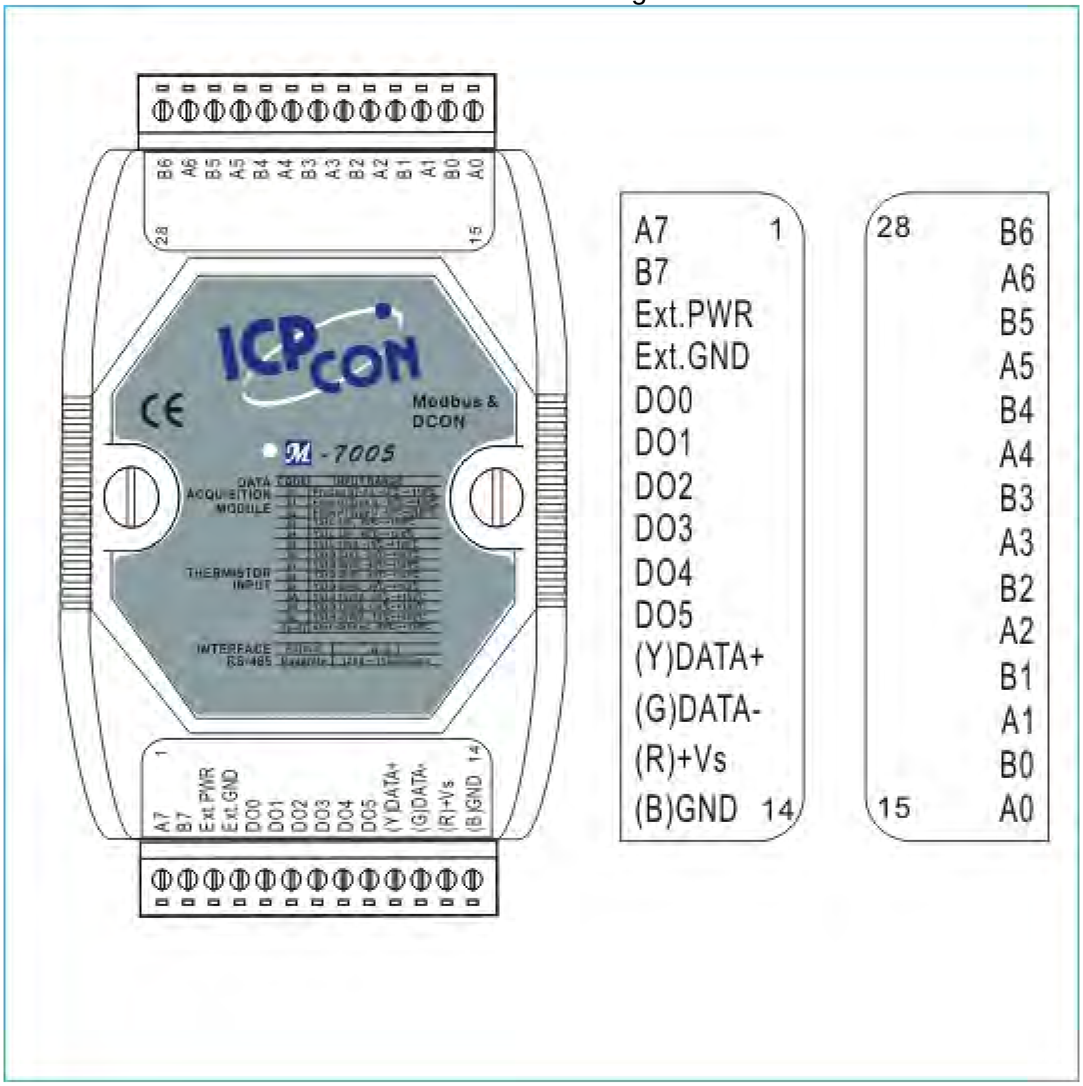
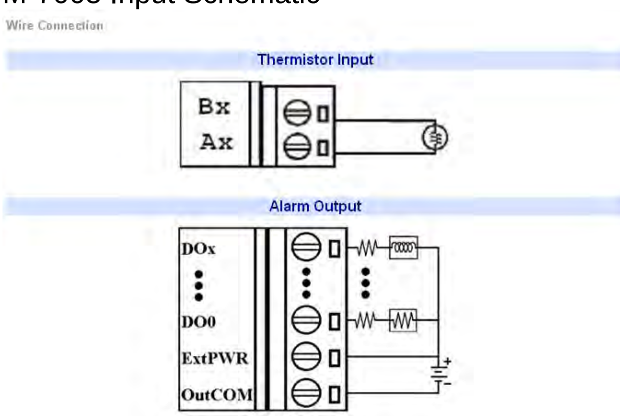
ICPDAS M-7005 Thermistor Module Pin Out Diagram



M-7005 Input Schematic



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M-7005 Thermistor Module Specifications

Specifications & Additional Information

Analog Input	
Input Channels	8 differential
Input Type	Thermistor
Thermistor Type	Precon ST-A3, Fenwell U, YSI L100, YSI L300, YSI L1000, YSI B2252, YSI B3000, YSI B5000, YSI B6000, YSI B10000, YSI H10000, YSI H30000, User-defined
Resolution	16-bits
Sampling Rate	8 samples/second (Total)
Accuracy	+/- 0.1%
Zero Drift	+/-20uV/°C
Span Drift	+/-25 ppm/°C
Common Mode Rejection	86dB
Normal Mode Rejection	100dB
Voltage Input Impedance	>1M Ohms
Individual Channel Configurable	Yes
Open Wire Detection	Yes
Intra-module Isolation, Field to Logic	3000 VDC
Digital Output	
Output Channels	6
Output Type	NPN, Sink, Open Collector to 30V
Output Load	100mA max. per channel
Interface	
Interface	RS-485
Format	N, 8, 1
Baud Rate	1200~115200 bps
LED Display	
1 LED	as Power/ Communication indicator
Power	
Input Voltage Range	+10 ~ +30 Vdc
Power Consumption	1.3 W
Protocol	
Support Modbus and DCON Protocol	Yes
Environment	
Operating temperature	-25 to 75°C
Storage temperature	-40 to 85°C
Humidity	5 to 95%, non-condensing

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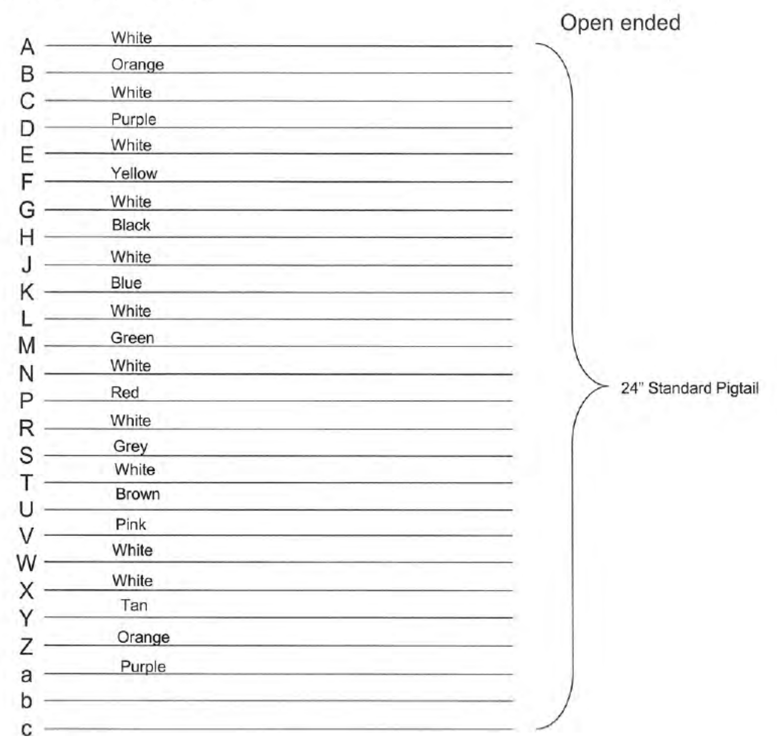
Thermistor String Connector Pinout

Wiring Diagram Box Mount connector PT02A-16-26P



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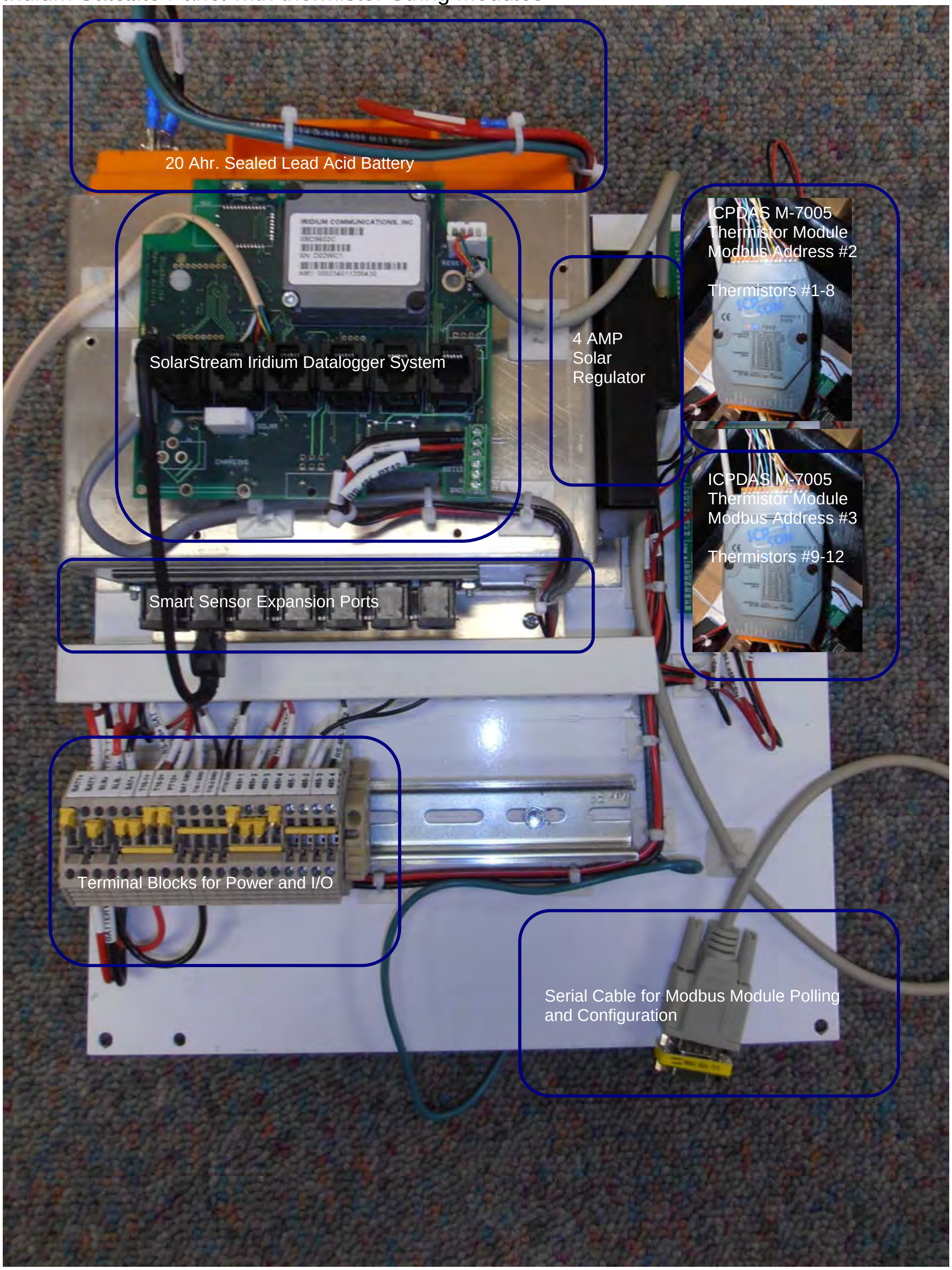
Iridium Satellite Panel with thermistor String Modules



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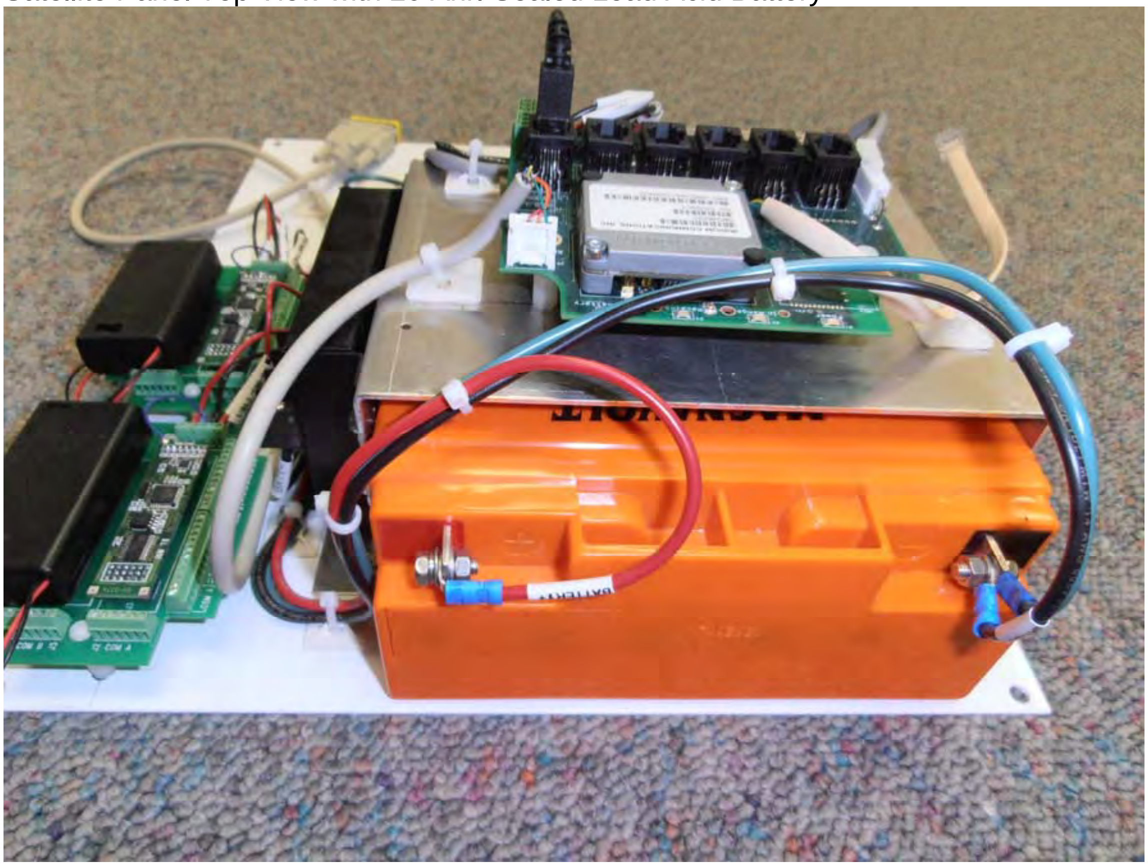
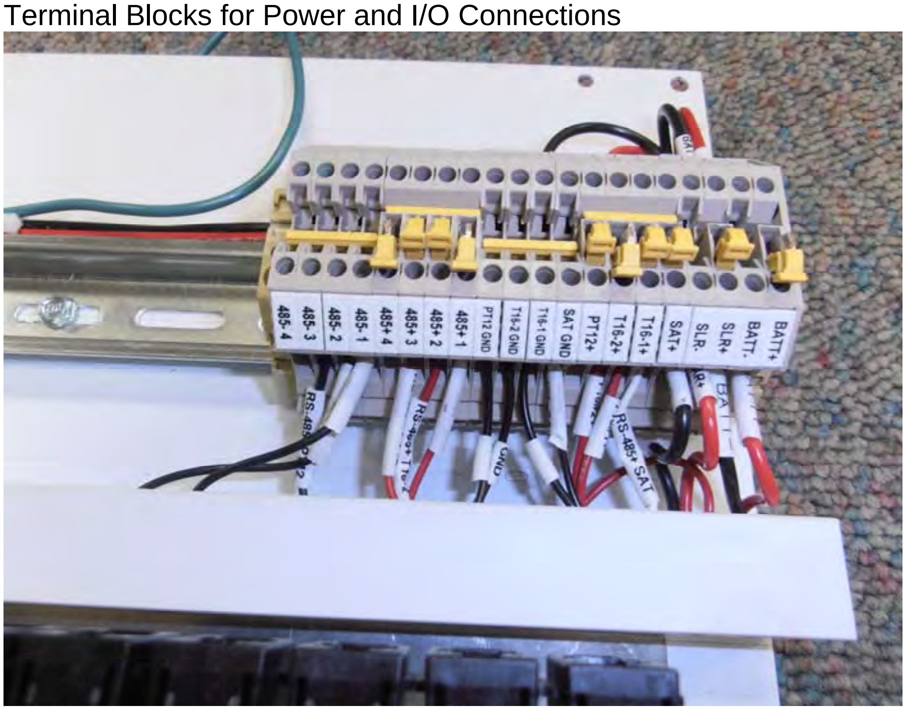
Satellite Panel Top View with 20 Ahr. Sealed Lead Acid Battery



Terminal Blocks for Power and I/O Connections



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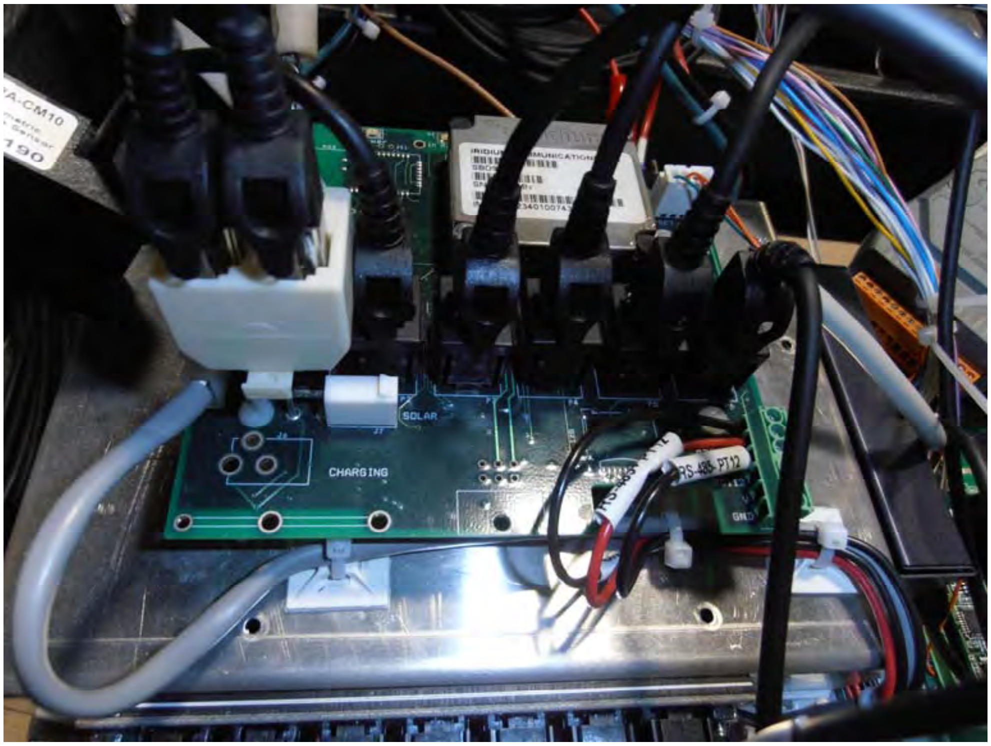
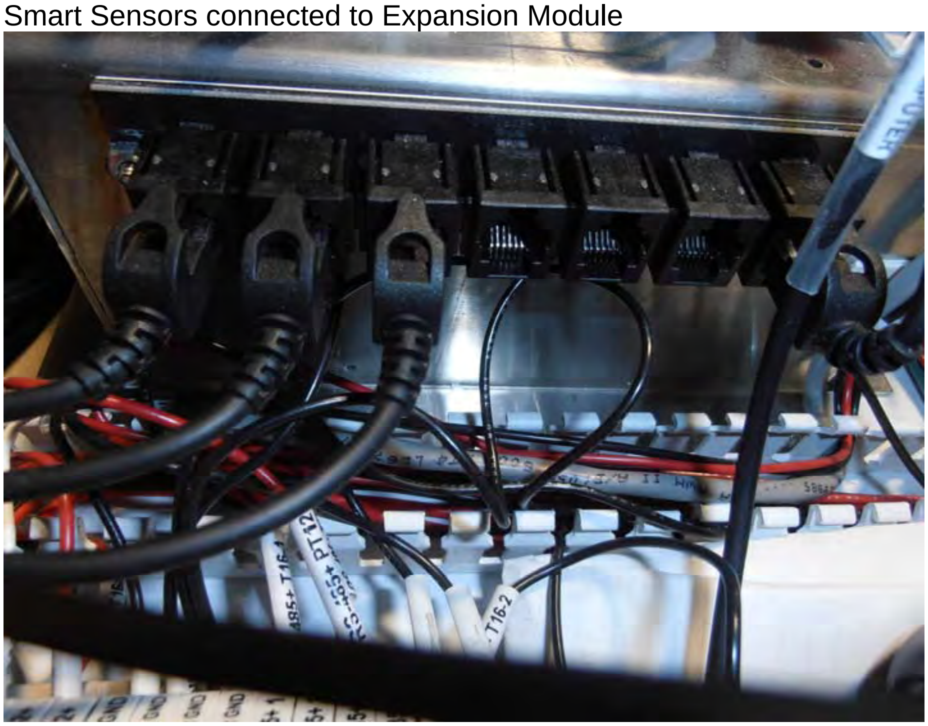
Smart Sensors Connected to Main SolarStream Circuit Board



Smart Sensors connected to Expansion Module



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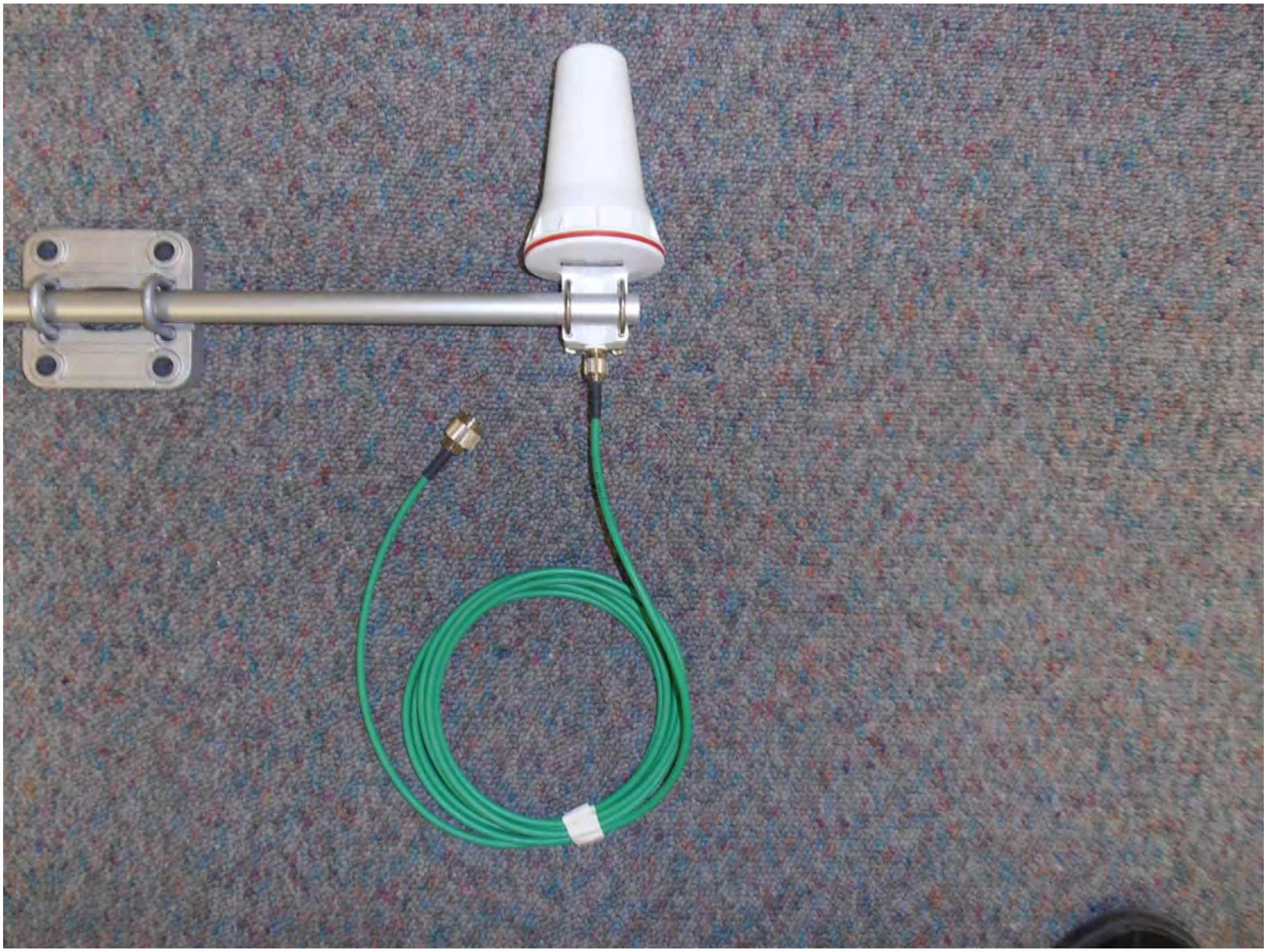
Iridium Antenna with Cross Arm Bracket



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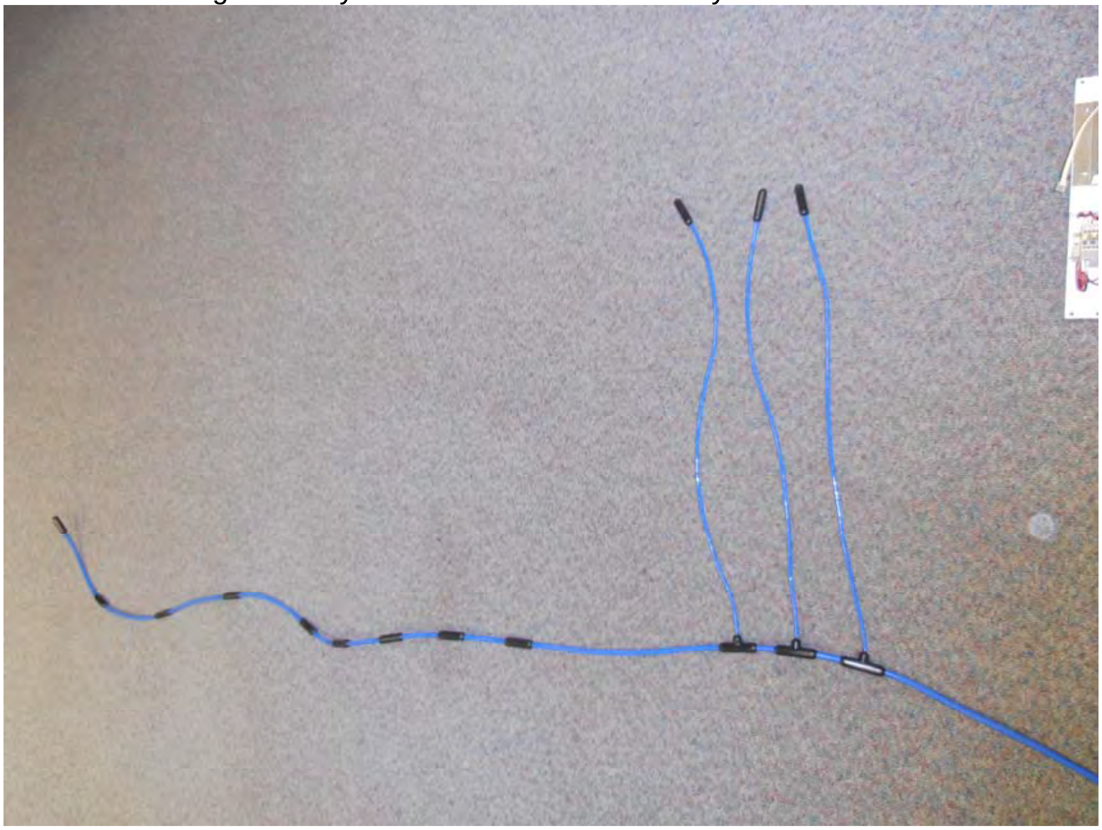
Thermistor String with Polyurethane Overmould and Fly Thermistors



Fly Thermistor Overmould Unions

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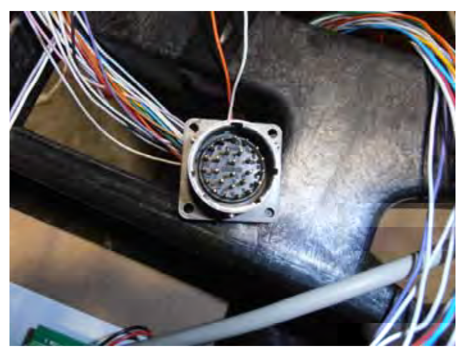
Thermistor String Thermistor Polyurethane Shot

Thermistor String Military Connector with Overmould

Bulkhead Mount Connector



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Decagon EC-5 Soil Moisture Sensor with Extension Cable with Overmould

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Solar Panel with Pole Mount / Cable Gland and Cable to Satellite Enclosure

Solar Panel Junction Box with Liquid tight conduit Connection (seal top of connector with sealing puddy)

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Satellite Enclosure Pole Mount Bracket with U bolt
(note use special self tapping screws and 2 washers provided per screw as provided)

Opening Fused Terminal

Hoskin Scientific Ltd.
239 East 6th Ave.
Vancouver, B.C., V5T 1J7
Ph (604) 872-7894
Fax (604 872-0281

Hoskin Scientific Ltd.
6103 148 St.
Edmonton, Alberta T6H 4J3
Ph (780) 434-2645
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Hoskin Scientific Ltd.
4210 Morris Dr.
Burlington, Ontario, L7L 5L6
Ph (905) 333-5510
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Hoskin Scientific Ltd.
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Montreal, Quebec, H4P 2L1
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Example Iridium Climate Station with 30 Foot Pop-Up Mast

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UPWARDINNOVATIONS Inc. DataGarrison Satellite Station

Specifications	
Temperature Range	Temperature Range -30 to 60º C (-22 to 140º F) Optional industrial battery packs available to extend temperature range up to 80º C (176º F)
Power	A 1.2 Watt solar panel and the optional 2.5 AH industrial grade rechargeable battery pack are designed to last up to 15 years
Solar charging	Temperature compensated charging voltage optimizes battery life and performance. Typically requires an average of one to two hours of direct sunlight per day. Will typically operate for one month in clouded conditions
Weight	2.8 kg (6 lbs)
Dimensions	20 X 15 X 10 cm (8 X 6 X 4 inches)
Environmental Rating	NEMA 6 weatherproof. Indoor and outdoor versions available.
Communication ports	Two serial ports for configuration and interfacing with external serial devices
Smart Sensor ports	Six ports available
Average power consumption	Satellite linking/transmitting/receiving (70 mA) and sleep (1.1 mA)
LED's	Four LED's on main circuit board indicate Power, In Range, Receiver On, and Low Battery.
Server updates (satellite xmission frequency)	User configurable from every 5 minutes to once a month
Minimum recommended logging interval	every 2.5 minutes
Remote alarms	User configurable low battery alarm and high/low sensor value alarms Average sensor alarm latency: logging interval plus 30 seconds during typical network conditions.
Remote control	Can be controlled over the Internet. Functions include setting alarm limits and changing the data logging or transmission intervals
Data formats	Tab-delimited text
Data access	Raw data is accessible from any Web browser via a password-protected, secure 256-bit connection. Live plots can be configured and viewed from the same online account.
Mounting	Sun-facing wall or pole. Sold with clamps for mounting on poles from 1.5 to 2 inches in diameter.
Frequency	1616 to 1626.5 MHz
Satellite Network	Iridium Satellite Constellation
Coverage	Works throughout the world in areas with lines of sight to the sky
Federal specifications	FCC certified for use in the U.S. and authorized for use throughout the world. Call for details regarding worldwide operation.
Enclosure Access	Hinged door secured by two latches, which can be further secured with user-supplied padlocks

Upward Innovations Inc.
19 Research Rd.
East Falmouth, MA 02536

Phone: 877-943-4328
Fax: 508-495-0956

Email:
sales@upwardinnovations.com

About Upward Innovations

- World Record: An Upward Innovations Inc. satellite transmitter is presently the furthest north land-based transmitting station on earth. It is transmitting weather data daily on top of the Milne Ice shelf in Northern Canada.
- Upward Innovations Inc. develops and manufactures remote data retrieval systems. Their environmental monitoring stations can operate virtually anywhere on earth via satellite and cellular data networks.
- All systems include fully automated field-to-Internet data transfer, remote alarming, real-time plotting and 24/7 data access.
- Users are provided with password-protected accounts and 256-bit encryption for data transfers at DataGarrison.com

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DataGarrison
User Area

Maine Road Weather Station #1

DataGarrison Remote Sites Control Panel **Plotting** Preferences Log out

Latest Conditions
06/06/12 9:55 am

Transmitter Battery
100%

Solar Radiation
0.625 W/m^2

Pressure
925.150 mbar

Water Content_10002280
-0.191 m^3/m

Temperature
18.343 °C

RH
51.100 %

Water Content_10002281
-0.117 m^3/m

Water Content_10050944
-0.188 m^3/m

Water Content_10050945
-0.184 m^3/m

Thermistor 1
18.600 C

Thermistor 2
18.550 C

Thermistor 3
18.560 C

Thermistor 4
18.540 C

Thermistor 5
18.610 C

Thermistor 6
18.540 C

Thermistor 7
18.560 C

Thermistor 8
18.550 C

Water Level
0.005 mH20

Water Temperature
18.500 C

Wind
Speed: 0.000 m/s
Gust: 0.000 m/s

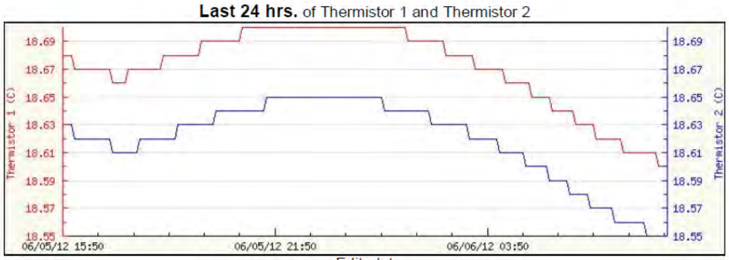
Rainfall
Last hour: 0 mm
Last 24 hrs: 0 mm

Station Status
Trans: every 20 min.
Logging: every 5.0 min.

Next Update
00 Hr 13 Min 27 Sec

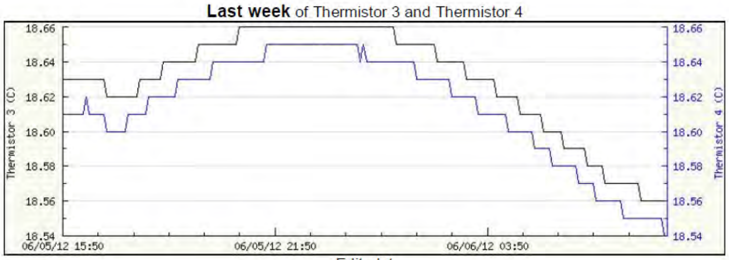
21 sensors
Solar Radiation

Last 24 hrs. of Thermistor 1 and Thermistor 2



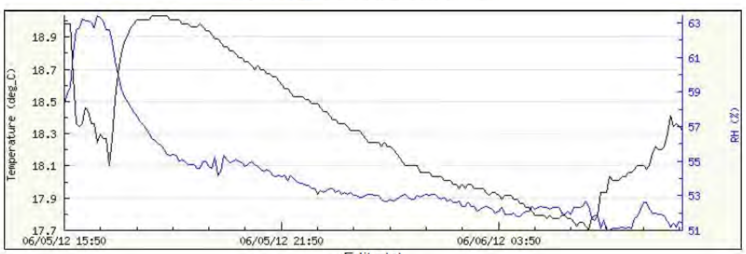
Edit plot

Last week of Thermistor 3 and Thermistor 4



Edit plot

Last 24 hrs. of Temperature and RH



Edit plot

Rain
Pressure
Wind Speed
Gust Speed
Water Content
Temperature
RH
Water Content
Water Content
Water Content
Thermistor 1
Thermistor 2
Thermistor 3
Thermistor 4
Thermistor 5
Thermistor 6
Thermistor 7
Thermistor 8
Water Level
Water Temperature

Download Data

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Datagarrison Preference Page for Sensor Naming and Formatting

DataGarrison
User Area

Maine Road Weather Station #1

DataGarrison Remote Sites Control Panel Plotting **Preferences** Log out

Latest Conditions
06/06/12 9:55 am

Transmitter Battery
100%

Solar Radiation
0.625 W/m²

Pressure
925.150 mbar

Water Content_10002280
-0.191 m^3/m

Temperature
18.343 °C

RH
51.100 %

Water Content_10002281
-0.117 m^3/m

Water Content_10050944
-0.188 m^3/m

Water Content_10050945
-0.184 m^3/m

Thermistor 1
18.600 C

Thermistor 2
18.550 C

Thermistor 3
18.560 C

Thermistor 4
18.540 C

Thermistor 5
18.610 C

Thermistor 6
18.540 C

Thermistor 7
18.560 C

Thermistor 8
18.550 C

Water Level
0.005 mH20

Water Temperature
18.500 C

Wind
Speed: 0.000 m/s
Gust: 0.000 m/s

Rainfall
Last hour: 0 mm
Last 24 hrs: 0 mm

Station Status
Trans: every 20 min.
Logging: every 5.0 min

Next Update
00 Hr **10** Min **35** Sec

21 sensors
Solar Radiation
Wind Speed
Gust Speed
Water Content
Temperature
RH
Water Content
Water Content
Water Content
Thermistor 1
Thermistor 2
Thermistor 3
Thermistor 4
Thermistor 5
Thermistor 6
Thermistor 7
Thermistor 8
Water Level
Water Temperature

Download Data

Units

Current units are metric. **Switch to US.**

Humidity displayed as RH. **Switch to Dew Point.**

Time zone

UTC - 420 min. **Edit time zone.**

Sensors

After customizing sensors, click the 'Submit' button below.

Factors and offsets are applied to the raw sensor value as follows:
New value = offset + factor*raw value.

Sensor	SN	Value	Factor	Offset	Formula	Units
Solar Radiation	10017760	0.625	1	0		W/m^2
Rain	10037855	0.000	1	0		mm
Pressure	9892190	925.150	1	0		mbar
Wind Speed	10029393	0.000	1	0		m/s
Gust Speed	10029393	0.000	1	0		m/s
Water Content	10002280	-0.191	1	0		m^3/m
Temperature	10037659	18.343	1	0		°C
RH	10037659	51.100	1	0		%
Water Content	10002281	-0.117	1	0		m^3/m
Water Content	10050944	-0.188	1	0		m^3/m
Water Content	10050945	-0.184	1	0		m^3/m
Thermistor 1	2_0	18.600	0.01	0		C
Thermistor 2	2_1	18.550	0.01	0		C
Thermistor 3	2_2	18.560	0.01	0		C
Thermistor 4	2_3	18.540	0.01	0		C
Thermistor 5	2_4	18.610	0.01	0		C
Thermistor 6	2_5	18.540	0.01	0		C
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Thermistor 8	2_7	18.550	0.01	0		C
Water Level	1_1	0.005	0.70308	0		mH20
Water Temperatur	1_3	18.500	1	0		C

Submit Restore Add virtual sensor

*Clicking 'Restore' will restore all sensors to their factory defaults and remove any virtual sensors.

Formula Tips
1) Formulas must be valid PHP code snippets, without syntax errors.
2) Formulas must begin with "$val = " and end with a semicolon.
3) For example, y = x + 3.4 must be written as $val = $s[0] + 3.4; , where x was assumed to be the first sensor.
4) Sensor 1 is $s[0] , sensor 2 is $s[1] , etc...
5) When working with roots, like $y = x^3 + 2.6$, just put in this form: $val = $s[0]*$s[0]*$s[0] + 2.6;

The remote device acknowledged that no sensor alarms are now set.

Messaging emails (where to send alarm and command response messages)

Add/Edit email address(es)

Recipients:

Connectivity Alarm (sent if remote device stops reporting)

Enter connectivity alarm period

Alarm: off

Site coordinates

0 N, 0 E. **Edit coordinates.**

Change Password

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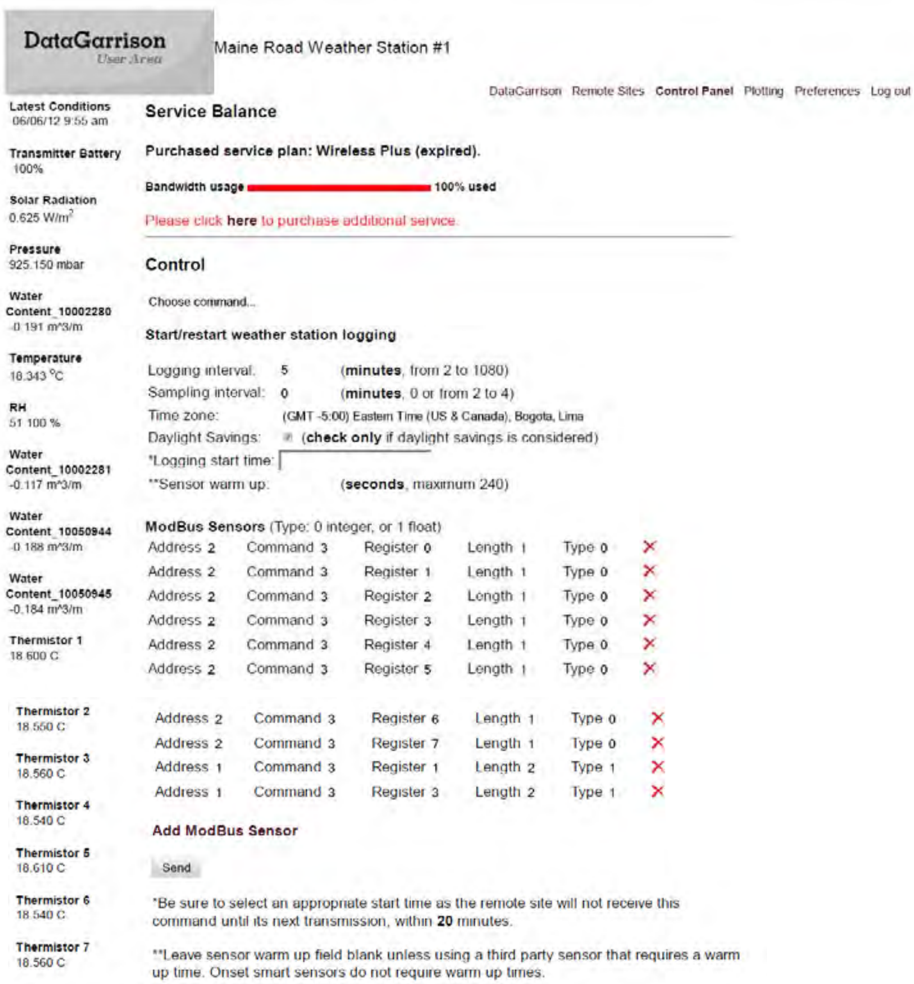
Example Data Download – Select download Data – Tab Delimited

```
Blue Sky Station - ID 300234010074300
Time zone: UTC -420 minutes
Date_Time       Solar Radiation_10017760_W/m^2 Rain_10037855_mm           Pressure_9892190_mbar         Wind Speed_10029393_m/s       Gust
Speed_10029393_m/s              Water Content_10002280_m^3/m  Temperature_10037659_deg_C    RH_10037659_%  Water Content_10002281_m^3/m  Water
Content_10050944_m^3/m          Water Content_10050945_m^3/m  Thermistor 1_2_0_C            Thermistor 2_2_1_C            Thermistor 3_2_2_C
                Thermistor 4_2_3_C            Thermistor 5_2_4_C            Thermistor 6_2_5_C            Thermistor 7_2_6_C            Thermistor 8_2_7_C
Wa Level_1_1_mH20               Water Temperature_1_3_C
06/05/12 16:50:00               0.625         0.000         929.750       0.000         0.000         -0.191        19.008        58.100        -
0.120           -0.188          -0.183        18.680        18.630        18.630        18.610        18.690        18.610        18.630
                18.620          0.004         19.062
06/05/12 16:55:00               0.625         0.000         929.650       0.000         0.000         -0.191        19.008        58.600        -
0.120           -0.188          -0.184        18.680        18.630        18.630        18.610        18.690        18.610        18.630
                18.620          0.004         19.062
06/05/12 17:00:00               0.625         0.000         929.550       0.000         0.000         -0.191        19.008        59.000        -
0.120           -0.188          -0.183        18.680        18.630        18.630        18.610        18.690        18.610        18.630
                18.620          0.005         19.125
06/05/12 17:05:00               0.625         0.000         929.550       0.000         0.000         -0.191        18.675        60.900        -
0.120           -0.188          -0.183        18.680        18.630        18.630        18.610        18.690        18.610        18.630
                18.620          0.005         19.062
06/05/12 17:10:00               0.625         0.000         929.550       0.000         0.000         -0.191        18.390        62.300        -
0.120           -0.189          -0.184        18.670        18.620        18.630        18.610        18.690        18.610        18.630
                18.620          0.004         18.875
06/05/12 17:15:00               0.625         0.000         929.250       0.000         0.000         -0.191        18.366        62.400        -
0.120           -0.188          -0.184        18.670        18.620        18.630        18.610        18.690        18.610        18.630
                18.620          0.004         18.812
06/05/12 17:20:00               0.625         0.000         929.050       0.000         0.000         -0.191        18.390        62.900        -
0.120           -0.189          -0.183        18.670        18.620        18.630        18.610        18.680        18.600        18.630
                18.620          0.005         18.750
06/05/12 17:25:00               0.625         0.000         929.150       0.000         0.000         -0.191        18.485        62.800        -
0.120           -0.189          -0.184        18.670        18.620        18.630        18.610        18.680        18.610        18.630
                18.620          0.004         18.750
```

DataGarrison System Launch using the Control Panel



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Alarm Set Up using the DataGarrison Preferences Page

Messaging emails (where to send alarm and command response messages)

Add/Edit email address(es)

Recipients:

Connectivity Alarm (sent if remote device stops reporting)

To turn off, set to zero. Must be equal to or greater than twice the transmission interval, which is currently set to every 20 minutes on this device.

Alarm period: 0 minutes

Set alarm

Site coordinates

0 N, 0 E. **Edit coordinates.**

Change Password

Current Password:

New Password:

Submit

User Accounts

Administrators: stock_room_09,
Guests:

Add a user | **Delete a user**

Public access

Public access is restricted. **Allow limited*** **public access.**

*Limited to viewing and downloading data. No control or editing privileges.

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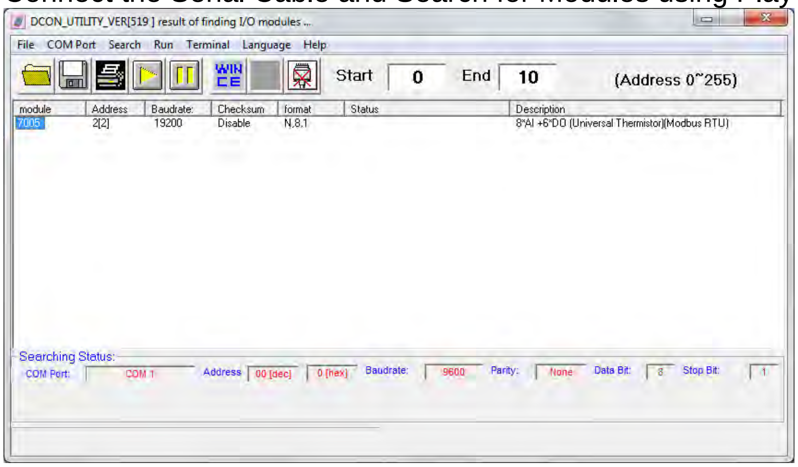
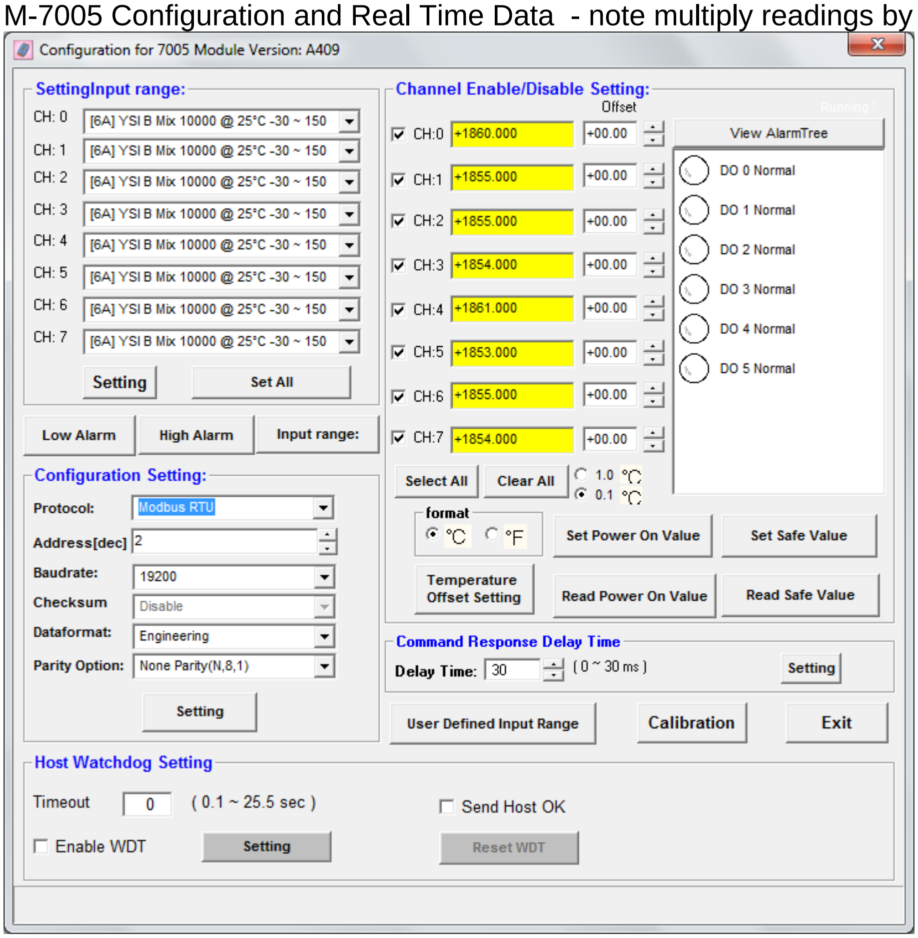
ICPDAS DCON Utility for M-7005 Thermistor Module Configuration and for Viewing of Real Time Data

Connect the Serial Cable and Search for Modules using Play Button, Select Module in the List



M-7005 Configuration and Real Time Data - note multiply readings by 0.01 to get degrees C



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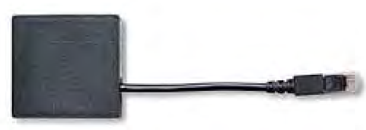
HWS Barometric Pressure Sensor - S-BPA-CM10



Measurement parameters: average over logging interval, user-defined sampling interval from 1 second

Measurement range: 660 mb to 1070 mb (19.47 to 31.55 in. Hg)

Operating Temperature Range: -40° to 70°C (-40° to 158°F)

Accuracy: ±3.0 mbar (0.088 in. Hg) over full pressure range at 25°C (77°F); maximum error of ±5.0 mbar (0.148 in. Hg) over -40° to 70°C (-40°F to 158°F)

Resolution: 0.1 mbar (0.003 in. Hg)

Drift: Typical ±0.6 mb (0.018 in. Hg) per year, maximum <2.5 mb (0.074 in. Hg) per six months

Dimensions: 4.5 cm x 4.8 cm x 1.6 cm (1 3/4" x 1 7/8" x 5/8")

Approximate Weight: 30 g (1 oz)

Cable Length: 10 cm (4")

Note: Must be used inside logger enclosure to assure protection from direct exposure to the weather

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SPECIALTIES

44006RC Precision Epoxy NTC Thermistor

- 10,000 ohm Resistance @ 25°C
- Interchangeable ±0.2°C, 0°C to 70°C,
- Pressed Disk Ceramic Sensor
- High sensitivity
- Thermally conductive epoxy coating
- 0.095″ (2.4 mm) Maximum Diameter
- 32 AWG, 3″ (7.6 cm) long Silver plated copper leads
- RoHS Compliant

DESCRIPTION

Epoxy Encapsulated Precision Interchangeable NTC Thermistor utilizing high stability pressed-disk ceramic sensor for general applications.

FEATURES

- 10,000 Ohm Resistance @ 25°C
- Interchangeability
- Good Long Term Stability
- High Sensitivity
- Thermally Conductive Epoxy Coating
- RoHS Compliance

APPLICATIONS

- Mid-range Temperature Applications
- Tight Tolerance Instrumentation
- General Applications Requiring Stability
- Applications Requiring Sensing Small Changes in Temperature
- Non-condensing Moisture Environments
- Allows use in Applications World-wide

PERFORMANCE SPECS

Parameter	Units	Value
Resistance @ 25°C	Ohms	10,000
Tolerance 0°C to 70°C	°C	± 0.2
Beta Value 25/85	K	3694
Tolerance on Beta Value	%	0.8
Time response in air	Seconds	< 10
Dissipation Constant in air	mW/°C	1
Insulation Resistance (Min. of 100Mohms for 1 Sec.)	Volts	500

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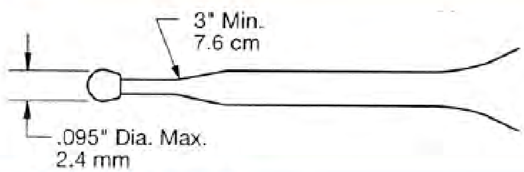
44006RC Precision Epoxy NTC Thermistor

MECHANICAL DETAILS



RESISTANCE V TEMPERATURE TABLE

Temp °C	K-Ohms	Temp °C	K-Ohms	Temp °C	K-Ohms	Temp °C	K-Ohms	Temp °C	K-Ohms
-55	607.800	-15	61.020	25	10.000	65	2.3390	105	0.7126
-54	569.600	-14	58.010	26	9.605	66	2.2640	106	0.6936
-53	534.100	-13	55.170	27	9.227	67	2.1910	107	0.6753
-52	501.000	-12	52.480	28	8.867	68	2.1220	108	0.6575
-51	470.100	-11	49.940	29	8.523	69	2.0550	109	0.6403
-50	441.300	-10	47.540	30	8.194	70	1.9900	110	0.6235
-49	414.500	-9	45.270	31	7.880	71	1.9280	111	0.6073
-48	389.400	-8	43.110	32	7.579	72	1.8680	112	0.5916
-47	366.000	-7	41.070	33	7.291	73	1.8100	113	0.5764
-46	344.100	-6	39.140	34	7.016	74	1.7540	114	0.5616
-45	323.700	-5	37.310	35	6.752	75	1.7000	115	0.5473
-44	304.600	-4	35.570	36	6.500	76	1.6480	116	0.5334
-43	286.700	-3	33.930	37	6.258	77	1.5980	117	0.5199
-42	270.000	-2	32.370	38	6.026	78	1.5490	118	0.5068
-41	254.400	-1	30.890	39	5.805	79	1.5030	119	0.4941
-40	239.800	0	29.490	40	5.592	80	1.4580	120	0.4818
-39	226.000	1	28.150	41	5.389	81	1.4140	121	0.4698
-38	213.200	2	26.890	42	5.193	82	1.3720	122	0.4582
-37	201.100	3	25.690	43	5.006	83	1.3320	123	0.4469
-36	189.800	4	24.550	44	4.827	84	1.2930	124	0.4359
-35	179.200	5	23.460	45	4.655	85	1.2550	125	0.4253
-34	169.300	6	22.430	46	4.489	86	1.2180	126	0.4149
-33	160.000	7	21.450	47	4.331	87	1.1830	127	0.4049
-32	151.200	8	20.520	48	4.179	88	1.1490	128	0.3951
-31	143.000	9	19.630	49	4.033	89	1.1160	129	0.3856
-30	135.200	10	18.790	50	3.893	90	1.0840	130	0.3764
-29	127.900	11	17.980	51	3.758	91	1.0530	131	0.3674
-28	121.100	12	17.220	52	3.629	92	1.0230	132	0.3587
-27	114.600	13	16.490	53	3.504	93	0.9942	133	0.3503
-26	108.600	14	15.790	54	3.385	94	0.9663	134	0.3420
-25	102.900	15	15.130	55	3.270	95	0.9393	135	0.3340
-24	97.490	16	14.500	56	3.160	96	0.9132	136	0.3263
-23	92.430	17	13.900	57	3.054	97	0.8879	137	0.3187
-22	87.660	18	13.330	58	2.952	98	0.8634	138	0.3113
-21	83.160	19	12.790	59	2.854	99	0.8397	139	0.3042
-20	78.910	20	12.260	60	2.760	100	0.8168	140	0.2972
-19	74.910	21	11.770	61	2.669	101	0.7946	141	0.2904
-18	71.130	22	11.290	62	2.582	102	0.7731	142	0.2838
-17	67.570	23	10.840	63	2.497	103	0.7523	143	0.2774
-16	64.200	24	10.410	64	2.417	104	0.7321	144	0.2712
								145	0.2651
								146	0.2592
								147	0.2534
								148	0.2478
								149	0.2423
								150	0.2370

Hoskin Scientific Ltd.
239 East 6th Ave.
Vancouver, B.C., V5T 1J7
Ph (604) 872-7894
Fax (604 872-0281

Hoskin Scientific Ltd.
6103 148 St.
Edmonton, Alberta T6H 4J3
Ph (780) 434-2645
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Hoskin Scientific Ltd.
4210 Morris Dr.
Burlington, Ontario, L7L 5L6
Ph (905) 333-5510
Fax (905) 333-4976

Hoskin Scientific Ltd.
8425 Devonshire
Montreal, Quebec, H4P 2L1
Ph (514) 735-5267
Fax (514) 735-3454

PT12 / SDI-12

SUBMERSIBLE PRESSURE/TEMPERATURE SMART SENSOR

AquiStar™
Data Collection Systems

APPLICATIONS

Rugged construction can replace analog sensors

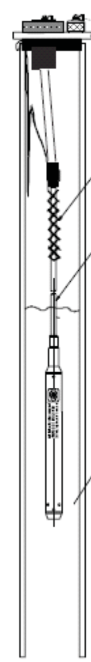
Monitor groundwater, well, tank, and tidal levels

Pump testing

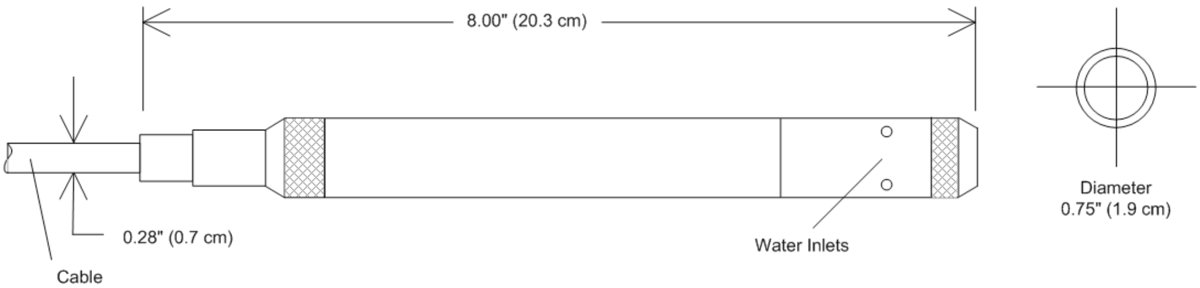
Flow monitoring

Features

- SDI-12 v1.3 interface and Modbus® interface
- Small diameter — *0.75"*
- Pressure and temperature
- 316 stainless steel, Viton® and Teflon® construction — *titanium optional*
- Polyethylene, polyurethane, and FEP Teflon® cable options
- End cone interchangeable with a 1/4" NPT inlet
- The U.S.G.S OSW accuracy enhanced calibration is an option on the 15 psig (10.5 mH_2O) and 30 psig (21 mH_2O) units



AquiStar™ Data Collection Systems



MECHANICAL

SENSOR

Body Material	316 stainless steel or titanium
Wire Seal Materials	Viton® and Teflon®
Desiccant	High- and standard- capacity packs
Terminating Connector	Available
Weight	0.80 lbs. (0.4 kg)
Diameter	0.75" (1.9 cm)
Length	8" (20.3 cm)

CABLE

OD	0.28" (0.7 cm) maximum
Break Strength	138 lbs. (62.7 kg)
Maximum Length	2000 feet (610 m) for Modbus® 200 feet (61 m) for SDI-12
Weight	4 lbs. per 100 feet (1.8 kg per 30 m)

OPERATIONAL

PRESSURE

Pressure Ranges	
PSIG (gauge)	5, 15, 30, 50, 100, 300
PSIA (absolute)	20, 30, 50, 100, 300
mH_2O (gauge)	3.5, 10.5, 21, 35, 70, 210
mH_2O (absolute)	14, 21, 35, 70, 210
Static Accuracy (B.F.S.L. 25° C)	± 0.1% FSO (maximum) ± 0.06% FSO (typical) *± 0.25% available on request*
Maximum Zero Offset	± 0.25% FSO @ 25° C
Resolution	16 bit
Over Range Protection	2x [except 300 PSI (210 H_2O) and higher]

TEMPERATURE

Compensated Temp. Range	
Standard	-20° C to 40° C
Extended	-10° C to 50° C
Operating Temp. Range	
Standard	-20° C to 60° C
Extended	-40° C to 80° C

POWER

Operating Voltage	9 - 16 VDC
Over Voltage Protection	24 VDC
Power Supply Current	Active 3mA avg./10mA peak
Power Supply Current	Sleep 150 μA
Electomagnetic & Transient Protection	IEC-61000 – 4-3, 4-4, 4-5, 4-6

Contact factory for extended temperature ranges.

SALES & SERVICE LOCATIONS

8902 122nd Avenue NE
Kirkland, WA 98033 USA
425-822-4434
FAX 425-822-8384 / info@inwusa.com

4620 Northgate Boulevard, Suite 170
Sacramento, CA 95834 USA
916-922-2900
FAX 916-648-7766 / inwsw@inwusa.com

1-800-PRO-WELL
WWW.INWUSA.COM

Soil Moisture Smart Sensors (S-SMx-M005)

Soil moisture smart sensors are used for measuring soil water content and are designed to work with smart sensor-compatible HOBO® data loggers. They combine the innovative ECH_2O® Dielectric Aquameter probe from Decagon Devices, Inc. with Onset's smart sensor technology. All sensor conversion parameters are stored inside the smart sensor adapter so data is provided directly in soil moisture units without any programming or extensive user setup.

Specifications	S-SMC-M005	S-SMD-M005*
Measurement Range	In soil: 0 to 0.550 m³/m³ (volumetric water content)	In soil: 0 to 0.570 m³/m³ (volumetric water content)
Extended range	-0.401 to 2.574 m³/m³; see Note 1	-0.659 to 0.6026 m³/m³; see Note 1
Accuracy	±0.031 m³/m³ (±3%) typical 0 to 50°C (32° to 122°F) for mineral soils up to 8 dS/m ±0.020 m³/m³ (±2%) with soil specific calibration; see Note 2	±0.033 m³/m³ (±3%) typical 0 to +50°C (+32° to 122°F) for mineral soils up to 10 dS/m ±0.020 m³/m³ (±2%) with soil specific calibration; see Note 3
Resolution	±0.0007 m³/m³ (±0.07%)	±0.0008 m³/m³ (±0.08%)
Volume of Influence	0.3 liters (10.14 oz)	1 liter (33.81 oz)
Sensor Frequency	70 MHz	70 MHz
Soil Probe Dimensions	89 x 15 x 1.5 mm (3.5 x 0.62 x 0.06 in.)	160 x 32 x 2 mm (6.5 x 1.25 x 0.08 in.)
Weight	180 grams (6.3 oz)	190 grams (6.7 oz)
Decagon ECH_2O Probe Part No.	EC-5	10HS

***** HOBOware® 3.2.1 or greater is required for the S-SMD-M005 model only.

Specifications	Both models
Sensor Operating Temperature	0° to 50°C (32° to 122°F). Although the sensor probe and cable can safely operate at below-freezing temperatures (to -40°C/F) and the smart sensor tube (the white portion of the sensor cable that houses the electronics) can be exposed to temperatures up to 70°C (158°F), the soil moisture data collected at these extreme temperatures is outside of the sensor's accurate measurement range. Extended temperatures above 50°C (122°F) will decrease logger battery life when using the S-SMD-M005 smart sensor.
Bits per Sample	12
Number of Data Channels**	1
Measurement Averaging Option	No
Cable Length Available	5 m (16 ft)
Length of Smart Sensor Network Cable **	0.5 m (1.6 ft)

****** A single smart sensor-compatible HOBO logger can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables). Note that the S-SMD-M005 smart sensor uses more battery power than other models. Therefore, when connecting the S-SMD-M005 smart sensor to H21-00x loggers that use 4 AA batteries, attach no more than 6 of these sensors to maintain battery life of one year.

Part #: MAN-SM, Doc #: 15081-B

Note 1: The sensor is capable of providing readings outside the standard volumetric water content range. This is helpful in diagnosing sensor operation and installation. See the Operation section below for more details.

Note 2: This is a system level accuracy specification and is comprised of the probe’s accuracy of ±0.03 m^3/m^3 typical (±0.02 m^3/m^3 soil specific) plus the smart sensor adapter accuracy of ±0.001 m^3/m^3 at 25°C (77°F). There are additional temperature accuracy deviations of ±0.003 m^3/m^3 / °C maximum for the probe across operating temperature environment, typical <0.001 m^3/m^3 / °C. (The temperature dependence of the smart sensor adapter is negligible.)

Note 3: This is a system level accuracy specification and is comprised of the probe’s accuracy of ±0.03 m^3/m^3 typical (±0.02 m^3/m^3 soil specific) plus the smart sensor adapter accuracy of ±0.003 m^3/m^3 at 25°C (77°F). There are additional temperature accuracy deviations of ±0.003 m^3/m^3 / °C maximum for the probe across operating temperature environment, typical <0.001 m^3/m^3 / °C. (The temperature dependence of the smart sensor adapter is negligible.)

Inside this Package

- Soil Moisture Smart Sensor

Installation

This sensor measures the water content in the space immediately adjacent to the probe surface. Air gaps or excessive soil compaction around the probe can profoundly influence soil water content readings. Do not mount the probes adjacent to large metal objects, such as metal poles or stakes. Maintain at least 8 cm (3 inches) of separation between the probe and other objects. Any objects, other than soil, within 8 cm (3 inches) of the probe can influence the probe’s electromagnetic field and adversely affect output readings. The S-SMC-005 sensor must be installed at least 3 cm (1.18 inches) from the surface and the S-SMD-005 sensor must be installed at least 10 cm (3.94 inches) from the surface to obtain accurate readings.

It is important to consider the particle size of the medium in which you are inserting the sensor because it is possible for sticks, tree bark, roots, or other materials to get stuck between the sensor prongs, which will adversely affect readings. Be careful when inserting these sensors into dense soil as the prongs can break if excessive sideways force is used to push them into the soil.

To install the soil moisture sensors, follow these guidelines:

- Good soil contact with the sensor probes is required.
- Install the sensor probes into undisturbed soil where there aren’t any pebbles in the way of the probes.
- Use a soil auger to make a hole to the desired depth (an angled hole is best) and push the probes into undisturbed soil at the bottom of the hole. Alternatively, dig a hole and push the probes into the side of the hole.
- If the probe has a protective cap on the end, remove it before placing the probe into the hole.
- To push the probe into the soil, use a PVC pipe with slots for the sensor and a longer slot for the cable.
- Thoroughly water the soil around the sensor after it is installed with the hole partially backfilled to cause the soil to settle around the sensor.
- As the hole is back-filled, try to pack the soil to the same density as the undisturbed soil.
- Secure the sensor cable to the mounting pole or tripod with cable ties.
- The white tube on the sensor cable that houses the smart sensor electronics is weatherproof; mount it to the pole or tripod outside the logger enclosure with cable ties.

- Use conduit to protect the cable against damage from animals, lawn mowers, exposure to chemicals, etc.

If you need to calibrate your probe for the soil, you may want to gather soil samples from each sample depth at this time.

When removing the probe from the soil, **do not pull it out of the soil by the cable!** Doing so may break internal connections and make the probe unusable.

Connecting

To start using the Soil Moisture smart sensor, stop the logger and insert the sensor's modular jack into an available port on the logger. If a port is not available use a 1-to-2 adapter (Part # S-ADAPT), which allows you to plug two sensors into one port. The next time you use the logger, it will automatically detect the new smart sensor. Note that the logger supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly. See the logger user's guide for more details about connecting smart sensors to the logger.

Operating Environment

The Soil Moisture smart sensor provides accurate readings for soil between 0 and 50°C (32° and 122°F). The sensor will not be damaged by temperatures as low as -40°C (-40°F); it is safe to leave the sensor in the ground year-round for permanent installation. The smart sensor adapter electronics (housed in the white tube on the sensor cable) are rated to 70°C (158°F) and are mounted outside the logger enclosure and secured to the mounting pole. The cable and smart sensor adapter are weatherproof.

Operation

The Soil Moisture smart sensor measures the dielectric constant of soil in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m^3/m^3 are possible. A value of 0 to 0.1 m^3/m^3 indicates oven-dry to dry soil respectively. A value of 0.3 or higher normally indicates a wet to saturated soil. Values outside the operating range may be a sign that the sensor is not properly installed (poor soil contact or foreign objects are adjacent to the sensor) or that a soil-specific calibration is required. Note that sudden changes in value typically indicate that the soil has settled or shifted, which are signs that the sensor may not be installed properly or that it has been altered or adjusted during deployment. This sensor does not support measurement averaging. (See your logger user's guide for more information about measurement averaging.)

Maintenance

The Soil Moisture smart sensor does not require any regular maintenance. If cleaning, rinse the sensor with mild soap and fresh water.

Calibration

The Soil Moisture smart sensor comes pre-calibrated for most soil types. If, however, your soil type has high sand or salt content, the standard calibration will not be accurate. In such cases, you will need to convert the data provided by the probe with a specific calibration for your individual soil type. To determine the soil specific calibration formula, refer to the *Calibrating ECH$_2$O Soil Moisture Probes* application note, available at:

http://www.onsetcomp.com/files/support/pdfs/Soil_calibration.pdf

Verifying Sensor Functionality

To quickly check sensor functionality before deployment, perform the following two tests:

1. Wash the probe with water and let it dry.
2. Plug the sensor into the logger.
3. Open the logging software and go to the status screen.
4. Conduct an air test: Hold the sensor by the cable letting the sensor hang freely in the air, and compare the value in the status screen with the table below.

Sensor	Air	Water
S-SMC-M005	-0.193 to -0.139	+0.521 to +0.557
S-SMD-M005	-0.473 to -0.134	+0.474 to +0.692

5. Distilled water test: Insert the probe in a room temperature container of fresh water, completely covering the entire ECH_2O probe. Compare the value in the status screen with the table above.

If these tests pass, your sensor is working normally. If not, please contact Onset for assistance. If you believe your sensor is defective or broken, you can send the smart sensor back to Onset for testing if needed. Contact Onset or your place of purchase for a Return Merchandise Authorization (RMA) number and associated costs before sending it.

Rain Gauge Smart Sensor (Part # S-RGA-M002, S-RGB-M002)

The Rain Gauge smart sensor is designed to work with HOBO Station loggers. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO® Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive user setup.

Inside this Package:

- Rain Gauge Smart Sensor
- Mounting Accessories: 2 hose clamps, 3 screws

Specifications	**Rain Gauge Smart Sensor**
Measurement Range	0 to 12.7 cm (0 to 5 in.) per hour, maximum 4000 tips per logging interval
Calibration Accuracy	±1.0% at up to 20 mm/hour (1 in./hour)
Resolution	0.01 in. (S-RGA-M002) or 0.2 mm (S-RGB-M002)
Calibration	Requires annual calibration: can be field calibrated or returned to the factory for re-calibration
Operating Temperature Range	0° to +50°C (+32° to +122°F), survival -40° to +75°C (-40° to +167°F)
Environmental Rating	Weatherproof
Housing	15.24 cm (6 in.) aluminum collector and base
Mechanism	Tipping bucket; stainless steel shaft with brass bearings
Dimensions	22.8 cm height x 15.4 cm diameter (9 x 6 in.), 15.4 cm (6.06 in.) receiving orifice
Weight	1 Kg (2 lbs)
Bits per Sample	12
Number of Data Channels*	1
Data Format	Number of tips per recorded measurement, reported in inches or millimeters
Measurement Averaging	No
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft)
Part Numbers	S-RGA-M002 (0.01 in. per tip with 2 m cable) S-RGB-M002 (0.2 mm per tip with 2 m cable)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

***** A single HOBO Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

WARNING: The black-anodized aluminum knife-edged ring is extremely sharp and can cause injury if not handled properly. Do not press edge against any body parts as severe cuts and bleeding may occur.

Mounting

NOTICE: During shipment the tipping assembly has been secured to avoid possible damage to the pivot assembly. Lift off the collector ring assembly (ring, screen, and funnel), and remove the rubber band from inside to release the tipping-bucket mechanism before installation.

Mounting Considerations

- For the most accurate rainfall measurements, it is recommended that you mount the Rainfall sensor upslope, about 3 meters (10 feet) away from the tripod, on a 1.5 meter high mounting pole (Part # M-MPB). Alternatively, you can mount the Rainfall sensor on the tripod mast. This section includes steps for both configurations.
- Tall objects can interfere with accurate rain measurements. It is recommended that you place the rain bucket away from the obstruction by a distance greater than three times the height of the obstruction. If that is not possible, raise the rain bucket as high as possible to avoid shedding.
- Avoid splashing and puddles. Be sure the gauge is high enough above any surface that rain will not splash into the top of the collector.
- Vibration can significantly degrade accuracy of the tipping bucket mechanism. In windy locations make sure that the bucket will be vibration-free. Consider using guy wires to secure a pole or tower-mounted bucket.
- Refer to the *HOBO Station Tripod Setup Guide* for more information.

Mounting the Sensor on a HOBO Station Tripod

Accessories:

- Guy Wire Kit (Part # M-GWA)

Secure the Rain Gauge sensor near the top of the mast on the side opposite the cross arm, using the two hose clamps provided.

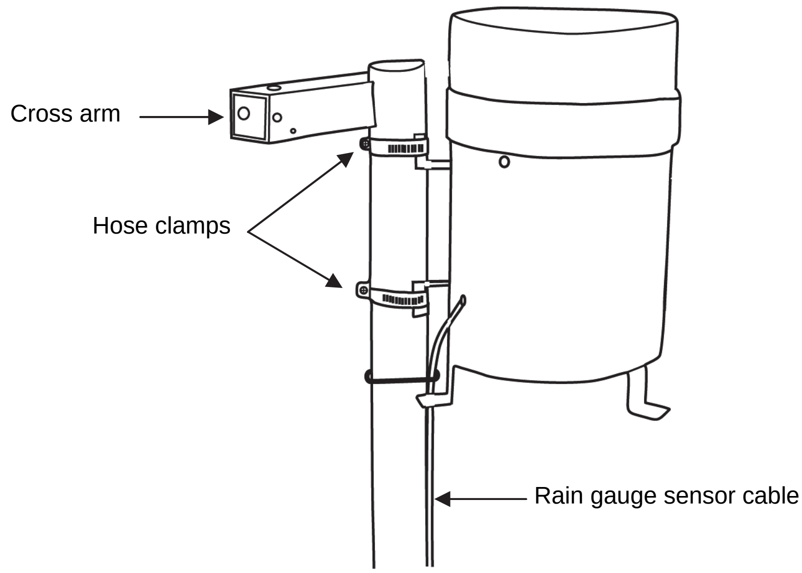


Figure 1: Rain Gauge sensor on the tripod mast

1. Open each hose clamp and place it around the mast.
2. Close the hose clamps until the rain gauge side bracket easily slides into the clamp.
3. Hold the Rain Gauge sensor bracket against the mast with the top of the Rain Gauge sensor above the top of the mast.
4. Slip the upper clamp over the side bracket and tighten the clamp until the rain gauge is secure. **Note:** Be sure the collector is above the top of the mast so you don't get any splashing, wind, shedding, or shadow effects.
5. Install the lower clamp and check that the top of the bucket is level. **Note:** For windy locations, it is recommended that you use the Guy Wire Kit (Part # M-GWA) to reduce vibration and ensure data collection accuracy.

Mounting the Sensor on a Pole

Accessories:

- 1.5 Meter Mast (Part # M-MPB)
- Mast Level (Part # M-MLA)

Secure the Rain Gauge sensor to the separate mounting pole, using the two hose clamps provided (see the instructions on the next page). This separate mounting pole can either be pounded in the ground or mounted in concrete, depending on how firm the ground is.

In either case, be sure the pole is vertical when you install it. The top of the pole should be slightly less than the height desired for the top of the Rain Gauge sensor (1 meter or 3 feet is typical).

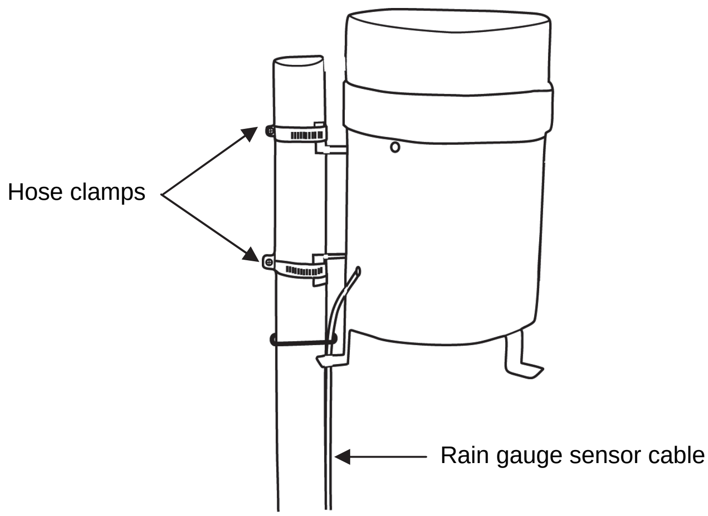


Figure 2: Rain Gauge sensor on separate mounting pole

Horizontal Surface Mounting

If mounting the Rain Gauge on a horizontal surface:

- The Rain Gauge housing MUST be mounted in a LEVEL position, clear of overhead structures, and in a location free from vibration
- Place the bucket on the mounting surface and mark the holes for the three mounting screws
- For wood surfaces, drill three 1/16th inch holes
- For concrete, drill three appropriately sized holes with a masonry bit, and install screw plug inserts
- Use shims as required to level the bucket
- Fasten the bucket with the screws shipped with the Rain Gauge

Connecting the Sensor to a Logger

To start using the Rain Gauge smart sensor, stop the logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adapter (Part # S-ADAPT), which allows you to plug two sensors into one port. The next time you use the HOBO Station, it will automatically detect the new sensor. Note that a HOBO Station supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly.

Operation

The Rain Gauge smart sensor measures rainfall by counting the number of tips per recorded measurement, up to 4000 tips per logging interval (40 inches or 80 cm of rain).

Maintenance

Clean the filter screen, funnel, and tipping-bucket mechanism with mild soap and water and a cotton swab. An accumulation of dirt, bugs, etc. on the tipping bucket will adversely affect the calibration. Oil the needle bearings with light oil on an annual basis. In harsh environments, it is recommended that you lubricate the needle bearings more frequently.

Field Calibration

The tipping-bucket mechanism is a simple and highly reliable device. Absolutely accurate Rain Gauge smart sensor calibration can be obtained only with laboratory equipment, but an approximate field check can be easily done. The Rain Gauge smart sensor must be calibrated with a controlled rate of flow of water through the tipping-bucket mechanism.

The maximum rainfall rate that the Rain Gauge smart sensor can accurately measure is one inch of rain per hour (36 seconds between bucket tips). Therefore, the Rain Gauge smart sensor should be field calibrated using a water flow rate equivalent to, or less than, one inch of rain per hour (more than 36 seconds between bucket tips).

To Check Calibration

1. Obtain a plastic or metal container of at least one liter capacity. Make a very small hole (a pinhole) in the bottom of the container.
2. Place the container in the top funnel of the Rain Gauge Smart Sensor. The pinhole should be positioned so that the water does not drip directly down the funnel orifice.
3. Follow the instructions for the Rain Gauge model you have.

   S-RGA-M002: Pour exactly 473 ml of water into the container. Each tip of the bucket represents 0.01 inch of rainfall.

   S-RGB-M002: Pour exactly 373 ml of water into the container. Each tip of the bucket represents 0.2 mm of rainfall.

   - If the test takes less than one hour for this water to run out, the hole (step 1) is too large. Repeat the test with a smaller hole.
   - Successful field calibration of this sort should result in one hundred tips plus or minus two.
   - Adjusting screws are located on the outside bottom of the Rain Gauge housing. These two socket head set screws require a 5/64 inch Allen wrench. Turning the screws clockwise increases the number of tips per measured amount of water. Turning the screws counterclockwise decreases the number of tips per measured amount of water. A ¼ turn on both screws either clockwise or counterclockwise increases or decreases the number of tips by approximately one tip. Adjust both screws equally; if you turn one a half turn, then turn the other a half turn.
   - Repeat these steps as necessary until the sensor has been successfully calibrated.

Wind Speed Smart Sensor (S-WSA-M003)

The Wind Speed smart sensor is designed to work with HOBO® Station loggers. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive user setup.

Inside this Package

- Wind Speed smart sensor with mounting rod

Specifications

Measurement Range	0 to 45 m/sec (0 to 100 mph)
Accuracy	±1.1 m/sec (2.4 mph) or ±4% of reading, whichever is greater
Resolution	0.38 m/sec (0.8 mph)
Service Life	> 5 year life typical, factory replaceable mechanism
Distance Constant	3 m (9.8 ft)
Starting Threshold	≤ 1 m/sec (2.2 mph)
Maximum Wind Speed Survival	54 m/sec (120 mph)
Measurements	Wind speed: Average wind speed over logging interval Gust: Highest 3-second gust during the logging interval See *Measurement Operation* for more information.
Operating Temperature Range	-40° to 75°C (-40° to 167°F)
Environmental Rating	Sensor and Cable Jacket: Weatherproof
Housing	Three cup polycarbonate anemometer: Modified Teflon® bearings and hardened beryllium shaft with ice shedding design
Dimensions	41 x 16 cm (16 x 6.5 in.) including 1.27 cm (0.5 in) diameter mounting rod; 5.5 cm (2.1 in.) drip overhang
Weight	300 g (10 oz)
Bits per Sample	8 for each channel, 16 total
Number of Data Channels*	2
Measurement Averaging Option	No
Cable Length Available	3.5 m (11.5 ft)
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft)
Part Number	S-WSA-M003
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Weather Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Placement and Mounting Considerations

- The Wind Speed smart sensor should be mounted vertically in a location free of wind shadows.
- For accurate wind speed measurements, mount the sensor at a distance of at least five times the height of the nearest tree, building, or other obstruction.
- Be sure to secure the sensor cable with cable ties to protect the cable from damage.
- The tripod or mounting mast must be properly grounded. For field installations, you can use Onset's Grounding Kit (M-GKA).
- Secure the mast the wind sensor is mounted on so that it does not vibrate. If you are using Onset masts or tripods, secure them with guy wires.
- Although the wind sensor is designed to operate in 100+ mph winds, it can be damaged with improper handling. Store the sensor in its shipping box until you are ready to install it.
- Refer to the *HOBO Station Tripod Setup Guide* for more information.

Mounting the Sensor to a Tripod Cross Arm

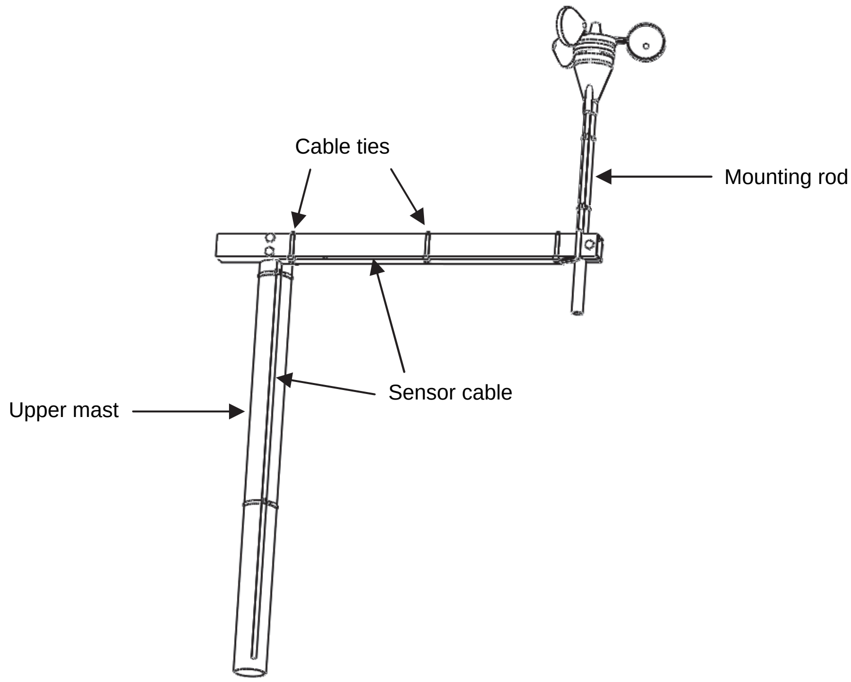
Accessories

- Full Cross Arm (Part # M-CAA)
- Half Cross Arm (Part # M-CAB)

Steps

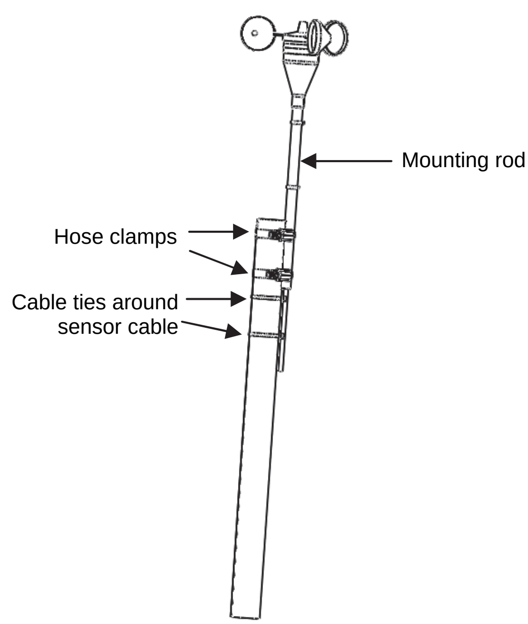
1. Insert a 1/4-20 x 1-3/4 inch hex head bolt with a flat washer on it through the 1/4 inch hole on the end of the cross arm. Tighten with a 7/16 inch wrench until snug.
2. Install another flat washer and nylock nut on the bolt, allowing the black mounting rod to protrude 1/2 inch (1.3 cm) from the bottom of the cross arm.
3. Insert the sensor mounting rod into the cross arm. Secure the ground wire to the lug nut on the cross arm.
4. Tighten the nut and bolt until the rod is clamped in place.
5. Adjust the height of the sensor in the cross arm as necessary using one of the following methods and then tighten the nut and bolt until the cross arm just starts to deform.
   a. Loosen the tri-clamp bolts and raise or lower the entire mast so that the wind sensor is close to the desired height. Make sure there is at least 5 cm (2 inches) of mast extending below the lower tri-clamp.
   b. Make sure the upper mast dimple is still facing north (if in northern hemisphere) and then re-tighten the tri-clamps. Once the tri-clamp bolts are tight, tighten the lock nuts to lock the bolts in place. This requires two wrenches: one to hold the bolt and one to tighten the lock nut against the tri-clamp.
   c. Loosen the bolt holding the wind sensor mounting rod and raise or lower it as necessary so the center of the wind sensor anemometer cups is at the desired height. Re-tighten the bolt.

6. Use cable ties to secure the sensor cables to the cross arm, bracket, and mast. The sensor cables should run below the cross arm and brackets to minimize the chance of birds pecking and damaging the cables. Cable ties should be spaced no more than .3 m (1 foot) apart.



Mounting the Sensor to a Pole

1. Loosely secure the sensor mounting pole with two hose clamps (not included) as shown below. Adjust the height of the sensor as necessary, but make sure the hose clamps are separated by at least 4 inches (10 cm).
2. Secure the sensor cable with cable ties.



3. Tighten the hose clamps making sure the mounting rod remains vertical.

Connecting the Sensor to a Logger

To start using the Wind Speed sensor, stop the logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adapter (S-ADAPT), which allows you to plug in two sensors into one port. The next time the logger is launched, it will automatically detect the new smart sensor. Note that the HOBO Station supports a maximum of 15 data channels. This sensor requires two data channels for wind speed and gust. Launch the logger and verify the sensor is functioning correctly.

Measurement Operation

Wind speed measurements are averaged over the logging interval or a 3-second timeframe (whichever is greater). If you set up the sensor to log faster than every 3 seconds, the same sensor reading will be recorded until a new 3-second average is calculated. For example, if the sensor is logging at a 1-second interval, the sensor will report the same wind speed (its calculated average) for three samples before calculating and reporting a new value for another three samples. Gust speed is the highest three-second wind recorded during the logging interval.

Maintenance

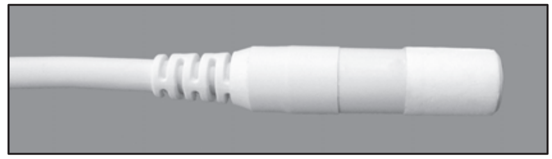
The sensor does not require any maintenance other than an occasional cleaning. If dust, cobwebs, salt or other contaminants collect in the cups of the anemometer, rinse the sensor with mild soap and fresh water.

Verifying Sensor Accuracy

Onset recommends that you check the accuracy of the sensor annually. The Wind Speed smart sensor cannot be calibrated. Onset uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it may be damaged or possibly worn out if it has been in use for several years. If you are unsure of the smart sensor's accuracy, you can send the smart sensor back to Onset for re-certification and replacement of the mechanism if needed. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

Temperature/RH Smart Sensor (S-THB-M00x)

The Temperature/RH smart sensor is designed to work with smart sensor-compatible HOBO® data loggers. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without any programming, calibration or extensive user setup.



Specifications	Temperature	RH
Measurement Range	-40°C to 75°C (-40°F to 167°F)	0-100% RH at -40° to 75°C (-40° to 167°F); exposure to conditions below -20°C (-4°F) or above 95% RH may temporarily increase the maximum RH sensor error by an additional 1%
Accuracy	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F); see Figure 1	+/- 2.5% from 10% to 90% RH (typical), to a maximum of +/- 3.5%. See Figure 2 for full range.
Resolution	0.02°C at 25°C (0.04°F at 77°F); see Figure 1	0.1% RH at 25°C (77°F)
Bits Per Sample	12	10
Drift	< 0.1°C (0.18°F) per year	< 1% per year typical; hysteresis 1%
Response Time	5 minutes in air moving 1 m/sec	5 minutes in air moving 1 m/sec with protective cap
Operating Temperature Range	-40°C to +75°C (-40°F to +167°F)	
Environmental Rating	Weatherproof: 0 to 100% RH intermittent condensing environments. For best results, the Temp/RH Smart Sensor should be mounted inside a protective enclosure, such as a solar radiation shield.	
Housing	PVC cable jacket with ASA styrene polymer RH sensor cap; modified hydrophobic polyethersulfone membrane	
Sensor Dimensions	10 x 35 mm (0.39 x 1.39 in)	
Weight	S-THB-M002 - 110 g (3.88 oz); S-THB-M008 - 180 g (6.35 oz)	
Number of Data Channels *	2	
Measurement Averaging Option	No	
Cable Lengths Available	2.5 m (8.2 ft); 8 m (26.2 ft)	
Length of Smart Sensor Network Cable *	0.5 m (1.6 ft); 6 m (19.6 ft)	
Part Numbers	S-THB-M002, S-THB-M008	
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).	

* A single smart sensor-compatible HOBO logger can accommodate 15 data channels and up to 100 m (325 ft) of smart sensor cable (the digital communications portion of the sensor cables).

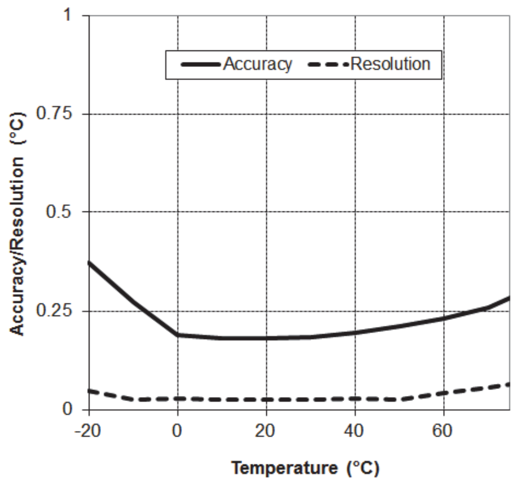


Figure 1: Temperature Accuracy and Resolution

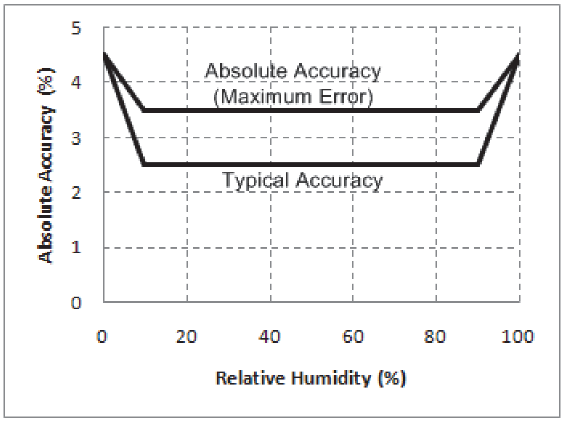


Figure 2: Relative Humidity Accuracy

Inside this Package

- Temp/RH Smart Sensor

Mounting

Accessories

Solar Radiation Shield (part # M-RSA or RS3)
Replacement RH Sensor (part # HUM-RHPCB-2)

Typical Mounting

- Solar Radiation Shield: Use the washer and screw (included with the M-RSA radiation shield) or cable clamps (included with the RS3 radiation shield) to secure the smart sensor in the radiation shield as shown in Figures 3 and 4.

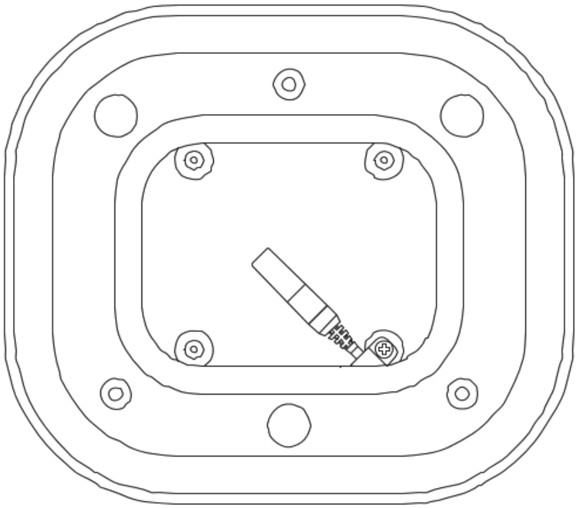


Figure 3: Temp/RH Sensor mounted in the Solar Radiation Shield M-RSA

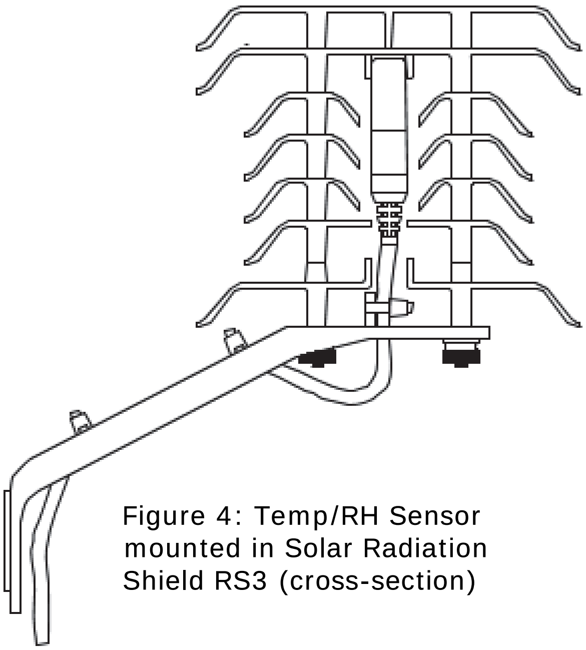


Figure 4: Temp/RH Sensor mounted in Solar Radiation Shield RS3 (cross-section)

Mounting Considerations

- A solar radiation shield is strongly recommended when measuring air temperature in direct sunlight. Solar radiation can be a significant source of error in the temperature and RH readings.
- When mounting the probe, care should be taken to thermally isolate the sensor from the mounting surface to ensure accurate air temperature and humidity readings. The probe's temperature sensor is at the end of the cable, just below the cup.
- It is recommended that the probe be protected from direct exposure to the weather. This will prolong the sensors' accuracy.
- If you are running sensor cables along the ground, it is recommended that you use conduit to protect against animals, lawn mowers, exposure to chemicals, and so on.
- The protective housing on the cable contains the smart sensor's electronics. It is waterproof, but it is not designed for prolonged submergence in puddles, saturated soils, etc.
- Refer to the logger user's guide for more information regarding setting up complete weather stations.

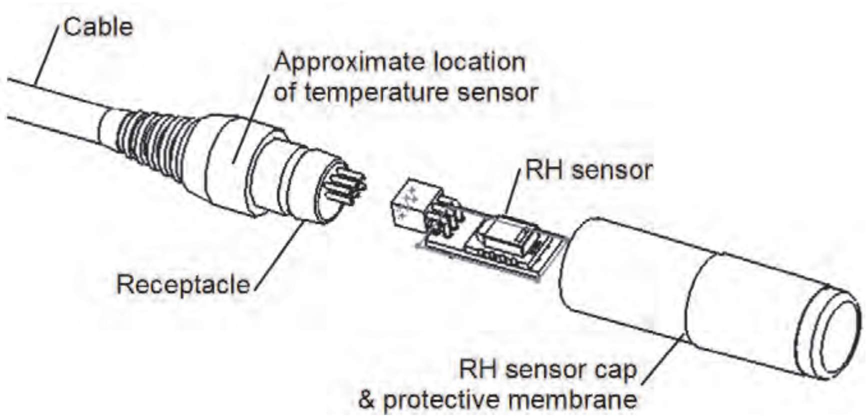
Connecting

To use the sensor with the smart sensor-compatible HOBO logger, stop the logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adapter (Onset Part # S-ADAPT). The next time you launch the logger, it will automatically detect the new sensor. Note that the logger supports a maximum of 15 data channels. Use the software to launch the logger and verify the sensor is functioning correctly. See the logger user's guide for more details about connecting HOBO smart sensors to loggers.

Replacing the RH sensor

The RH sensor is protected by an ASA styrene polymer cap and a modified hydrophobic polyethersulfone fluid barrier membrane that allows vapor to penetrate while protecting the sensor from condensation. RH sensor performance may degrade over time. To replace the RH sensor, take the following steps:

1. Remove the tape fastening the sensor cap to the receptacle. Discard the tape.
2. Grasp the cap and membrane and pull firmly to remove them. Discard them.
3. **Note the orientation of the small circuit board containing the RH sensor.** Pull it out and discard it in compliance with local disposal guidelines for circuit boards.



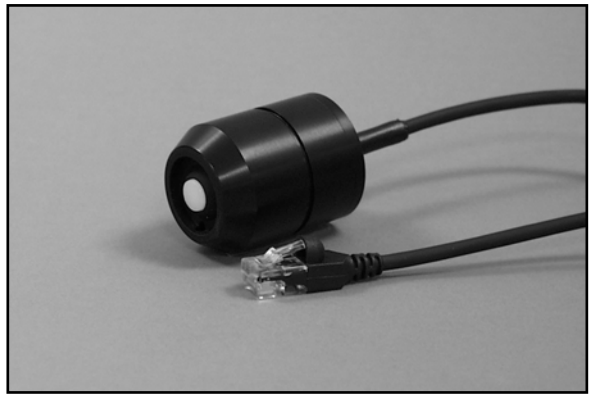
4. Push gently but firmly to install the new sensor (Onset part # HUM-RHPCB-2) **in the same orientation.**

5. Put the new sensor cap and membrane on. Do not force the cap. If it does not go on easily, the sensor may be installed backwards. Reverse the sensor and try again.

Maintenance

The Temperature/RH smart sensor is sensitive to dust, salts and other airborne contamination. Periodically inspect the RH sensor. If contamination is present on the protective cap, gently rinse it with cool fresh water. If the sensor itself is contaminated, you can rinse it with distilled water. Do not use hot water, organic solvents, or detergents. Dry before use.

Silicon Pyranometer Smart Sensor (Part # S-LIB-M003)



The Silicon Pyranometer smart sensor is designed to work with the HOBO® Weather Station logger. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Weather Station. All calibration parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming, calibration, or extensive setup.

Inside this Package

- Silicon Pyranometer smart sensor

Specifications	Silicon Pyranometer Smart Sensor
Measurement Range	0 to 1280 W/m^2
Spectral Range	300 to 1100 nm (see Figure 4)
Accuracy	Typically within ± 10 W/m^2 or ± 5%, whichever is greater in sunlight; Additional temperature induced error ± 0.38 W/m^2/°C from +25°C (0.21 W/m^2/°F from +77°F)
Angular Accuracy	Cosine corrected 0 to 80 degrees from vertical (see Figure 5); Azimuth Error < ±2% error at 45 degrees from vertical, 360 degree rotation
Resolution	1.25 W/m^2
Drift	< ±2% per year
Calibration	Factory recalibration available
Operating Temperature Range	-40° to +75°C (-40° to +167°F)
Environmental Rating	Weatherproof
Housing	Anodized aluminum housing with acrylic diffuser and O-ring seal
Dimensions	4.1 cm height x 3.2 cm diameter (1 5/8 in. x 1 1/4 in.)
Weight	120 g (4 oz)
Bits per Sample	10
Number of Data Channels *	1
Measurement Averaging Option	Yes
Cable Length Available	3.0 m (9.8 ft)
Length of Smart Sensor Network Cable *	3.0 m (9.8 ft)
Part Number	S-LIB-M003
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Weather Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Part #: MAN-S-LIB
Doc #: 6708-D

Mounting

Accessories

- Light Sensor Mounting Bracket (Part # M-LBB)
- Light Sensor Level (Part # M-LLA)

Bracket Mounting

It is recommended that you mount the Silicon Pyranometer smart sensor with the light sensor bracket on a pole or tripod (see Figure 1). To mount the sensor using the bracket:

1. Attach the light sensor bracket to a 1¼ inch to $1^{5}/_{8}$ inch pole with the provided U-bolts.

   Note: The bracket can also be mounted on a flat, vertical surface using four screws.

2. Position the Silicon Pyranometer sensor on top of the bracket with its cable running through the slot in the bracket.
3. Using the two screws supplied, attach the sensor to the bracket through the two holes on either side of the slot.

   Note: Do not completely tighten the screws until you level the sensor.

4. Position the bracket so it faces toward the equator, minimizing the chance of shading.
5. Mount the bracket on the mast with the two U-bolt assemblies, mounting it high enough on the mast to avoid the possibility of shading the sensor.

   Note: If you mount the sensor above eye level, use a step ladder or other secure platform when leveling the sensor so that you can clearly view the Light Sensor Level (Part # M-LLA).

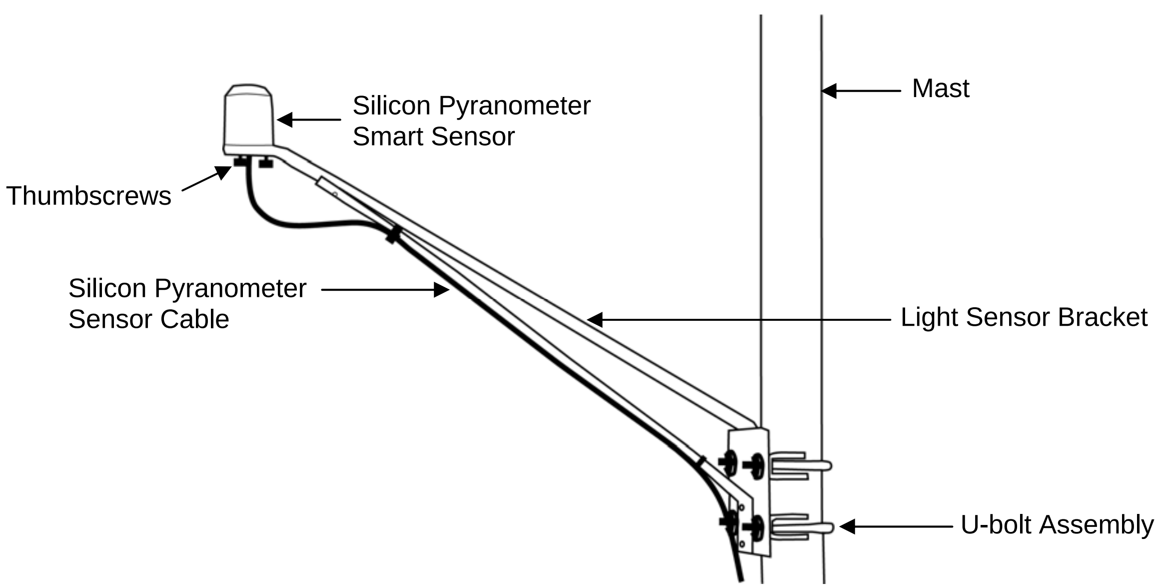


Figure 1: Silicon Pyranometer Sensor Bracket Mounting

6. Make sure the screws holding the sensor to the mounting bracket are loose.

7. Place the Light Sensor Level on the Silicon Pyranometer smart sensor.
8. Adjust the height of the thumbscrews to level the sensor (start with the thumbscrews protruding about 1/16 inch from the bracket).
9. Once the sensor is near level, tighten the Phillips head screws.
10. Check the level and repeat above steps if necessary (see Figure 2).
11. **IMPORTANT**: Don't forget to remove the level when you are done with it.

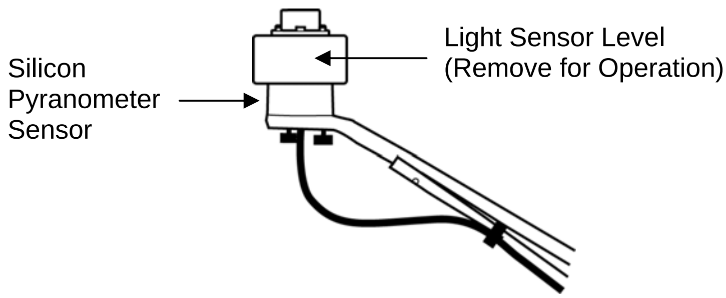


Figure 2: Leveling the Sensor on the Light Sensor Bracket

Specialized Application Mounting

To mount the Silicon Pyranometer sensor using a mounting plate of your own design:

1. Drill a 0.56 (9/16) inch hole in the middle of the plate, then drill two #25 holes 1.063 (1-1/16) inches apart on either side of the center hole. Cut a 0.31 (5/16) inch-wide slot in the mounting plate. See Figure 3. The plate should be a thickness of 1/8 inch or less.
2. Slide the sensor through the 0.31 (5/16) inch-wide slot.
3. Attach the sensor using two 6-32 x 3/8 inch screws and lock washers (not included).
4. Shim the sensor as necessary to level it.

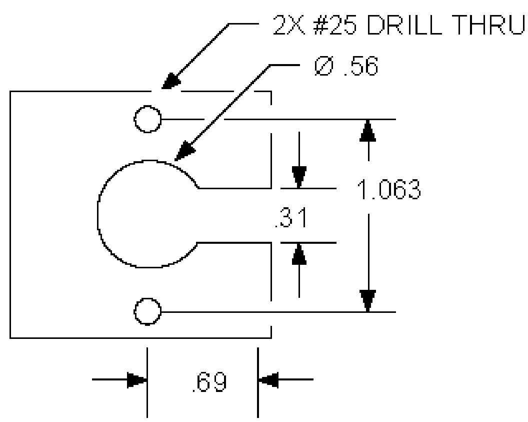


Figure 3: Recommended Mounting Plate Dimensions

Mounting Considerations

- Small errors in alignment can produce significant errors. Be certain the sensor is mounted level.
- Mount the sensor where it will not be in a shadow. Any obstruction should be below the plane of the sensor head. If that is not possible, try to limit obstructions to below 5 degrees, where the effect will be minimal.
- If possible, avoid placing the sensors in dusty locations. Dust, pollen, and salt residue that collect on the top of the sensor can significantly degrade accuracy.
- Refer to the *HOBO Weather Station User's Guide* for more information about setting up complete HOBO Weather Stations.

Connecting the Sensor to the Logger

To start using the Silicon Pyranometer smart sensor, stop the HOBO Weather Station logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adaptor, which allows you to plug two sensors into one port (Part # S-ADAPT). The next time you use the HOBO Weather Station, it will automatically detect the new smart sensor.

The HOBO Weather Station supports a maximum of 15 data channels; this sensor uses one channel. Launch the logger and verify the sensor is functioning correctly. See the *HOBO Weather Station User's Guide* for more details about connecting smart sensors to the HOBO Weather Station.

Operation

The Silicon Pyranometer smart sensor supports measurement averaging. When measurement averaging is enabled, data is sampled more frequently than it is logged. The multiple samples are then averaged together and the average value is stored as the data for the interval. For example, if the logging interval is set at 10 minutes and the sampling interval is set at 1 minute, each recorded data point will be the average of 10 measurements.

Measurement averaging is useful for reducing noise in the data. It is recommended that you use measurement averaging whenever the Silicon Pyranometer smart sensor is placed in an area where the light level can vary quickly with respect to the logging interval (for example, during partly cloudy conditions). Note that fast sampling intervals (less than 1 minute) may significantly reduce battery life. See the *HOBO Weather Station User's Guide* for more details about sensor operation and battery life.

Spectral Characteristics

This sensor uses a silicon photodiode to measure solar power per unit area (watts per square meter). Silicon photodiodes are not ideal for use as solar radiation sensors and the photodiode in this Silicon Pyranometer is no exception (see Figure 4). An ideal pyranometer has equal spectral response from 280 to 2800 nm. However, when calibrated properly and used correctly, the Silicon Pyranometer smart sensor should perform well in most situations.

The sensor is calibrated for use in sunlight (an Eppley Precision Spectral Pyranometer is used as reference standard). Accordingly, if the sensor is used under natural sunlight, the measurement errors will be small. Note that significant errors may result from using the sensor under artificial light, within plant canopies, in greenhouses, or any other conditions where the spectral content differs from sunlight.

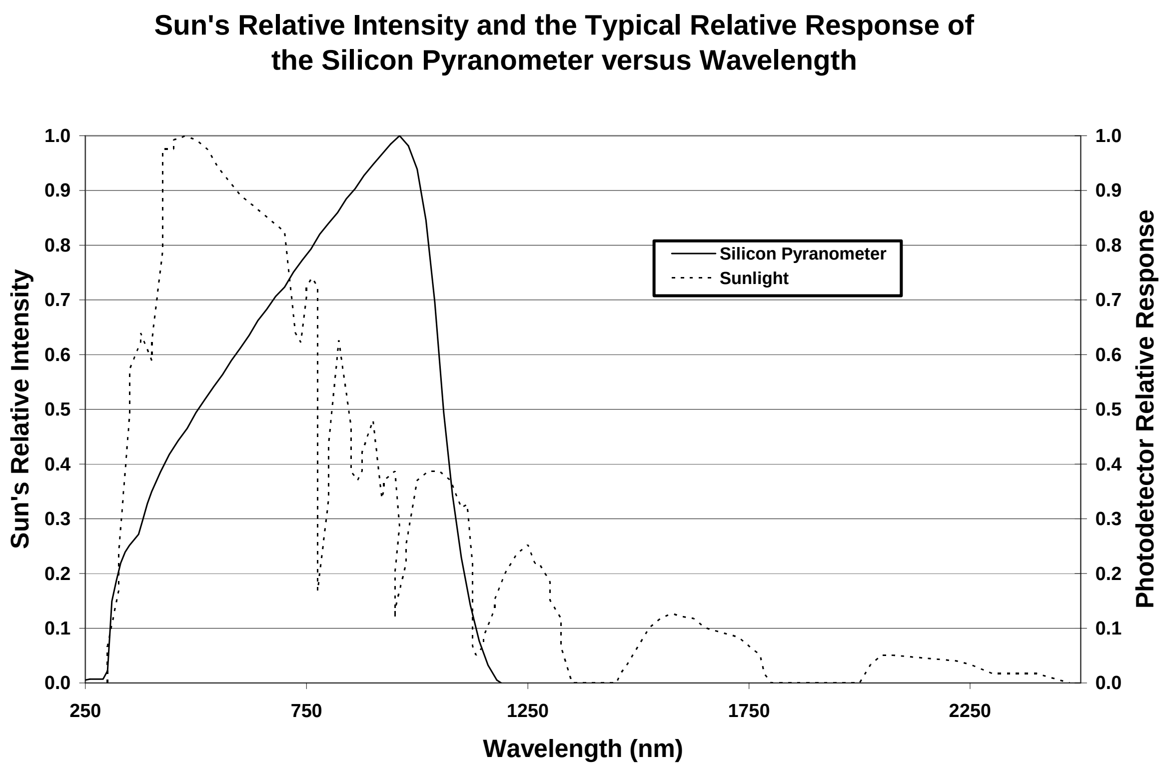


Figure 4: S-LIB-M003 Silicon Pyranometer Response Curve

Cosine Correction

The Silicon Pyranometer smart sensor housing is designed to give an accurate cosine response. Figure 5 shows a plot of relative intensity versus angle of incidence for a typical sensor and for the theoretical ideal response. Deviation from ideal response is less than 5% from 0 to 70 degrees and less than 10% from 70 to 80 degrees.

Note that as the angle approaches 90 degrees, the ideal cosine response approaches zero. As a result, small errors in measured intensity will result in very large percentage errors compared to the ideal response from 80 to 90 degrees.

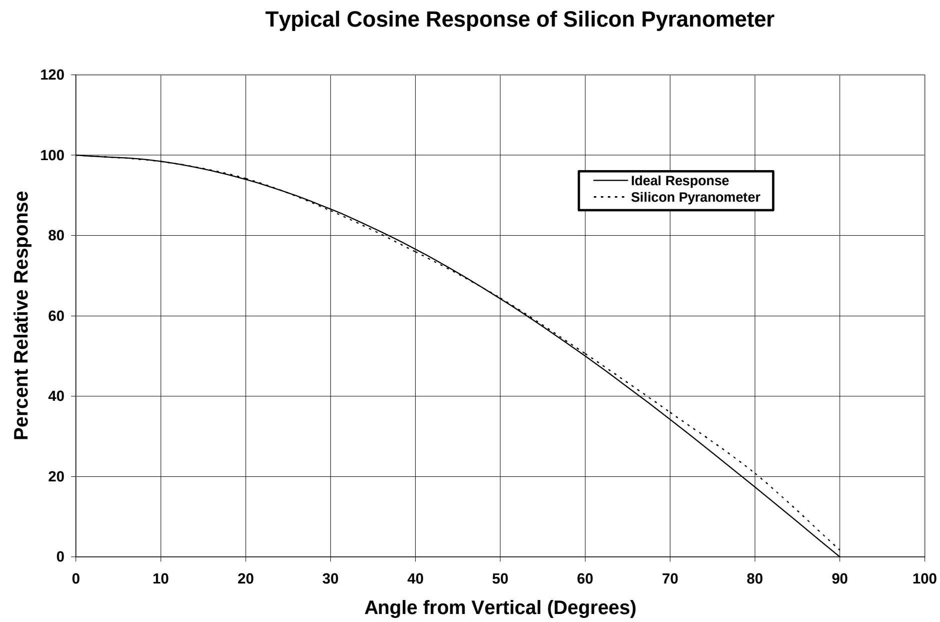


Figure 5: S-LIB-M003 Typical Cosine Response Curve

Maintenance

Dust on the sensor will degrade sensor accuracy. Periodically inspect the sensor and if necessary, gently clean the diffuser with a damp sponge. Do not open the sensor as there are no user serviceable parts inside.

Warning: DO NOT use alcohol, organic solvents, abrasives, or strong detergents to clean the diffuser element on the Silicon Pyranometer smart sensor. The acrylic material used in the sensor can be crazed by exposure to alcohol or organic solvents. Clean the sensor only with water and/or a mild detergent such as dishwashing soap if necessary. It is recommended that you use vinegar to remove hard water deposits from the diffuser element. Under no circumstances should the sensor be immersed in any liquid.

Verifying Sensor Accuracy

It is recommended that you test the Silicon Pyranometer smart sensor annually for accuracy. If the sensor is not providing accurate data, it may be damaged or out of calibration. If you are unsure of accuracy, send the smart sensor back to Onset for testing and possible re-calibration. Only Onset can complete calibration. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

Barometric Pressure Smart Sensor (Part # S-BPA-CM10)

The Barometric Pressure smart sensor is designed to work with the HOBO® Weather Station Logger. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Weather Station. All calibration parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without any programming or extensive user setup.

Inside this Package

- Barometric Pressure smart sensor
- Mounting Accessories: Hook and loop tape

Specifications	Barometric Pressure Smart Sensor
Measurement Range	660 to 1070 mbar (19.47 to 31.55 in. Hg)
Accuracy	± 3.0 mbar (0.088 in. Hg) over full pressure range at +25°C (+77°F); maximum error of ±5.0 mbar (0.148 in. Hg) over -40° to +70°C (-40° to +158°F)
Resolution	0.1 mbar (.003 in. Hg)
Drift	1.0 mbar (0.03 in. Hg) per year
Operating Temperature Range	-40° to +70°C (-40° to +158°F)
Environmental Rating	Weatherproof when used inside logger enclosure
Dimensions	4.5 x 4.8 x 1.6 cm (1 3/4 x 1 7/8 x 5/8 in)
Weight	30 g (1 oz)
Bits per Sample	12
Number of Data Channels *****	1
Measurement Averaging Option	Yes
Cable Length Available	10 cm (4 in)
Length of Smart Sensor Network Cable *****	0.1 m (0.3 ft)
Part Number	S-BPA-CM10
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

***** A single HOBO Weather Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Part #: MAN-S-BPA
Doc #: 6122-D

Mounting

Typical Mounting

Self-adhesive hook and loop tape is supplied for mounting the sensor on top of the battery cover inside the logger enclosure (see Figure 1 below).

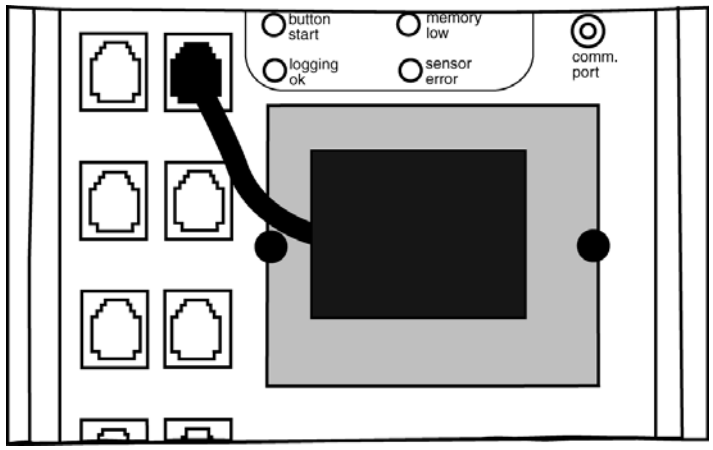


Figure 1: Barometric Pressure Smart Sensor Mounted in the HOBO Weather Station Logger

Mounting Considerations

- The Barometric Pressure smart sensor must be used inside the logger housing.
- The Barometric Pressure smart sensor measures the air pressure inside the enclosure. Therefore, the vent at the bottom of the enclosure must be free from obstructions for the sensor to function correctly.
- Refer to the *HOBO Weather Station User's Guide* for more information regarding setting up complete weather stations.

Connecting the Sensor to the Logger

To start using the Barometric Pressure smart sensor, stop the logger and insert the sensor's modular jack into an available port on the logger. If a port is not available, use a 1-to-2 adaptor (Onset Part # S-ADAPT), which allows you to plug two sensors into one port. The next time the HOBO Weather Station is launched it will automatically detect the new sensor. Note that the HOBO Weather Station supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly. See the *HOBO Weather Station User's Guide* for more details about connecting smart sensors to the HOBO Weather Station.

Operation

The Barometric Pressure smart sensor supports measurement averaging. When measurement averaging is enabled, data is sampled more frequently than it is logged. The multiple samples are then averaged together and the average value is stored as the data for the interval. For example, if the logging interval is set at 10 minutes and the sampling interval is set at 1 minute, each data point in the data file will be the average of 10 measurements. Measurement averaging is useful for reducing noise in the data. It is recommended that measurement averaging be used when the Barometric Pressure smart sensor is used in a windy location. Note that fast sampling intervals (less than 1 minute) may significantly reduce battery life. Refer to the *HOBO Weather Station User's Guide* for more details about smart sensor operation and battery life.

Maintenance

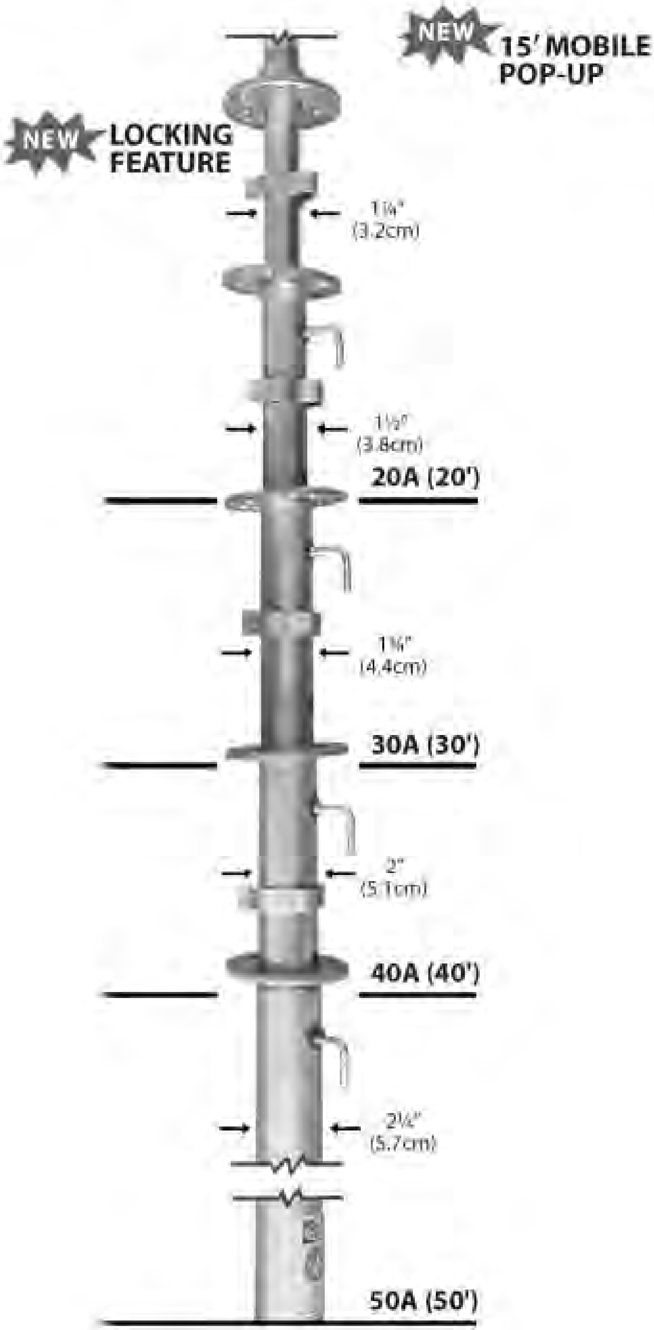
Use a damp sponge or rag to clean the Barometric Pressure smart sensor housing if it gets dirty or needs to be cleaned. Under no circumstances should the unit be immersed in water or any other cleaning solvent. Do not open the sensor as there are no user serviceable parts inside. The electronics are sensitive to light. Do not remove the black label over the sensor. The sensor will give inaccurate measurements if exposed to light.

Verifying Sensor Accuracy

It is recommended that you check the accuracy of the Barometric Pressure smart sensor annually. The Barometric Pressure smart sensor cannot be re-calibrated. Onset uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it may be damaged and should be replaced. If you are unsure of the smart sensor's accuracy, you can send the smart sensor back to Onset for re-certification. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending it.

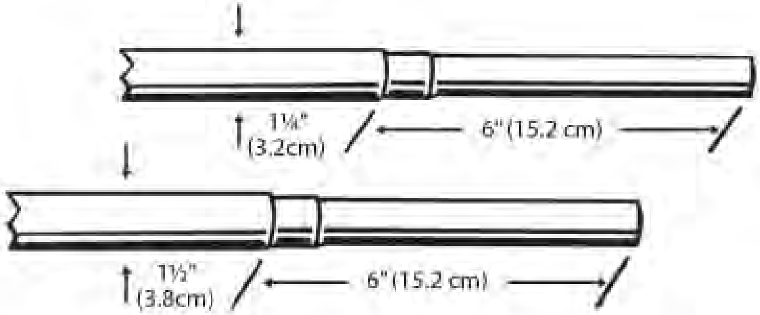
Delhi Pop-Ups

- High strength galvanized steel tubing.
- Precision flared and swaged for smooth fit.
- 16 gauge top section, balance 18 gauge.
- Snap lock for easy installation.
- Chafe resistant floating guy rings.
- Various bases available -- see installation hardware section.



Delhi "Pre-Galvanized" Masting

- Induction welded, galvanized coating.
- Several gauges available.
- High strength steel.
- Precision locking swaged ends.



1.25/18g/5's
5' (1.52 m), 3.2 lbs (1.45 kg)

1.25/18g/10's
10' (3.05 m), 6.4 lbs (2.9 kg)

1.25/16g/5's
5' (1.52 m), 4 lbs (1.81 kg)

1.25/16g/10's
10' (3.05 m), 8 lbs (3.63 kg)

1.5/16g/5's
5'(1.52 m), 4.9 lbs (2.22 kg)

1.5/16g/10's
10'(3.05 m), 9.8 lbs (4.45 kg)

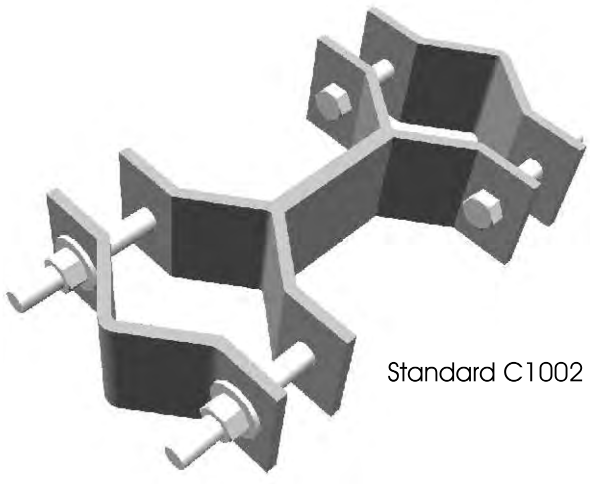
1.66/14g/3's
3' (0.91 m), 4.3 lbs (1.95 kg)

1.66/14g/8' w
8' (2.44 m), 11.3 lbs (5.2 kg)
With weldment for anti-twist ground installation

DM Mast 1.5/16g/8', 7.5 lbs (3.4 kg)

Custom masting also available.

C1002



Standard C1002

ORDERING INFORMATION

PART#	DESCRIPTION
C1002	Parallel Clamp
C1002A	Parallel Clamp (Large)
C1002W-3	3 Foot Wall Mount
C1002W-6	6 Foot Wall Mount
C1002W-10	10 Foot Wall Mount

MECHANICAL SPECIFICATIONS

HEIGHT	2.5" (64 mm)
WIDTH	6.5" (165 mm)
WEIGHT	5 lbs. (2.3 kg)

Weight does not include pipe extensions.

C1002W-3

MOUNTING INFORMATION

All C1002 clamps come with galvanized mounting bracket with two clamping plates w/stainless steel hardware.

C1002 fits from 1.5-3.5" Diameter or angle.
To fit 0-1.50", reverse plate(s).

C1002A fits from 1.5-4.5" Diameter or angle.

Reverse clamp plates to fit 0-1.50".

The C1002 provides a non-penetrating clamp using a center bracket with two clamping plates. Stainless steel hardware is used to bolt the assembly together. Will mount a 1.5-3.5" Diameter mast (1.5-4.5" diameter for C1002A). C1002W series has been designed to provide a penetrating wall mount for a 3, 6 or 10 foot 1 ½"Sched. aluminum pipe.

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EMAIL: sales@bluewaveantenna.com WEBSITE: www.bluewaveantenna.com TOLL FREE: 1.888.334.9244

Appendix-VIII:

Report evaluating and ranking SLR predictive models

Use of Remote Sensing for

Seasonal Load Restriction (SLR) Application & Removal

COOPERATIVE AGREEMENT No. RITA RS-11-H-UMDA

Between

University of Massachusetts Dartmouth

and

U.S. DEPARTMENT OF TRANSPORTATION

RESEARCH AND INNOVATIVE TECHNOLOGY AMINISTRATION (RITA)

Report on Task #9a:

Evaluation of Predictive Models & Protocols for SLR Timing

Prepared by

Christopher S. Cabral, UMass Dartmouth Graduate Research Assistant

Heather J. Miller, PhD, P.E., UMass Dartmouth

Richard Berg, PhD, and Robert Eaton, P.E., Frost Associates

Maureen Kestler, USDA Forest Service

August 27 2013

Disclaimer

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Abstract

Federal and State Departments of Transportation spend huge sums of money each year in an effort to preserve and maintain roadways across the nation. In particular, low-volume roads are the most susceptible to damage from trafficking, especially during the spring thaw seasons. The thawing process causes the pavement structure to lose strength and stiffness, and thus increases its vulnerability to damage. Since these low volume roads are typically not designed to support traffic loading with the decrease of strength during the spring thaw, seasonal load restriction (SLR) policies that limit the axle loads of heavy trucks during the thaw-weakened period have been implemented in many countries in an effort to minimize costly roadway damage. Historically, there have been various methods used for posting spring load restrictions and many agencies still address the question of how to schedule SLRs. This Task 9a Report describes numerous existing prediction models and protocols which can be useful in posting SLRs, presents the procedures for creating site-specific prediction models, and analyzes the effectiveness of individual models in comparison to measured data collected from nine test sites in New Hampshire over several years.

Ultimately, the recommendations from this research will be incorporated into a decision support system (DSS) which is currently under development. Based upon the analyses conducted, it is recommended that the State DOTs consider use of the MnDOT cumulative thawing Index (CTI) criterion (CTI = 25 ^{o}F-day) for SLR application. The USFS/Berg method is equally suitable (and tends to yield almost identical SLR start dates as the MnDOT method); however it is somewhat more cumbersome to initially set up and write computer code for. Both methods are slightly conservative, applying the SLR just slightly before subsurface thawing and pavement weakening was observed at the test sites. In terms of SLR removal, the analyses conducted for this project suggest that a period of 8 weeks duration (56 days), as suggested by both MnDOT (2009) and Bradley et al. (2012), appears to provide a reasonably conservative "outer limit" guideline for SLR removal. It is likely that, in many instances, the SLRs could safely be removed in less than 8 weeks; however additional mechanistic study is recommended for the future in order to establish a less conservative criterion in terms of some easily computed parameter (such as a CTI threshold).

Regarding frost-thaw prediction models, both the Modified Freeze-Thaw Index Model and the Modified Model 158 show much promise. Frost-thaw patterns were reasonably estimated at most of the nine test sites using both models, although they both tended to be conservative in estimating end-of-thaw dates, with estimated end-of-thaw dates falling after measured dates in many instances. It is important to note that the Freeze-Thaw Index Model works best when calibrated on a site-specific basis. Such calibration requires a fair amount of time and money to install subsurface temperature sensors and to conduct the regression analyses. An advantage of the Modified Model 158 is that it does not require site specific calibration; however pavement layer thicknesses must be determined, and values for thermal properties of those layers must be assumed. An advantage of both models is that the only atmospheric weather data required as input is air temperature, which is easily obtained from various sources over the internet. The DSS for this project will initially employ the Modified Freeze-Thaw Index Model; however it will be set up in a modular fashion so that the Modified Model 158 (or any other model) may later be incorporated. A separate "Task 9b Report" will soon be provided which will describe the necessary computer code written to incorporate the Modified Freeze-Thaw Index Model onto the DSS.

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1. Introduction

Federal and State Departments of Transportation (DOT) spend huge sums of money each year in an effort to preserve and maintain roadways across the nation. In particular, low volume roads are the most difficult to sustain. There are thousands of miles of low volume roads across the country, which are essential to the transportation network. These types of roads are incredibly important for many reasons, including the movement of commercial goods from remote resource areas to markets. Even though these roads are a necessity for any sort of travel outside of major cities, they are not constructed to handle the magnitude and frequency of traffic that major highways experience. Low volume roads lying in seasonal frost areas are especially vulnerable to damage from heavy traffic loading during the spring-thaw period. During the winter freeze, the pavement structure freezes from the top down. Similarly, during the spring thaw, the pavement thaws from the surface down, as well as from the bottom up, although bottom up thawing generally occurs at a slower rate. When the thawing or melting of the pavement structure occurs, moisture is trapped in the upper layers of the roadway by the impermeable underlying frozen soil. The asphalt surface then rests on a weak saturated thawing layer and the pavement structure no longer is able to effectively support traffic loading. Heavier vehicles can cause damage to roads in this condition causing DOTs a lot of time and money to repair. As an effort to minimize costly roadway damage, seasonal load restriction (SLR) policies have been implemented in many countries that limit the axle loads of heavy trucks during the spring thaw period.

Spring load restrictions were first introduced by the Minnesota Department of Transportation (MnDOT) in 1937. These restrictions are now implemented in a number of cold region countries outside the United States including Canada, France, Finland, and Sweden (Levinson et al, 2005). Maine SLR policy prevents vehicles with a gross weight over 23,000 pounds to travel over posted roads. Emergency and maintenance vehicles and vehicles transporting perishable goods are exempt. Certain vehicles that surpass 23,000 pounds can apply for an exemption certificate (MaineDOT, 2008).

These vehicle weight restrictions can be very frustrating to businesses. For instance, logging trucks carry incredibly large loads from the wood obtained from remote areas and they rely on these low volume roads for transportation. When the load restrictions are applied, logging companies have to reroute their trucks to avoid the posted roads if they still are to carry the heavy loads intended. If the companies want to maintain the same routes for their trucks, the amount of wood they can carry per trip is considerably diminished. Either alternative the business takes, the company has to pay much more money for gas as well as the truck drivers for the extra time on the road. SLR policies are detrimental to commerce and cause businesses to become less efficient. This ultimately affects manufacturers and retailers because they may have shipments of their commodities less frequently. SLRs clearly have many economic impacts. Businesses would favor that SLRs were imposed for the shortest amount of time possible, while DOTs would prefer longer durations of the restrictions to protect and preserve their roads. The challenge in SLR application is to protect the infrastructure and minimize roadway maintenance costs, but also to allow commerce to flow as much as possible during spring thaw and strength recovery periods, which typically last 6-8 weeks.

Setting dates for SLRs has been and still is a debatable topic for Departments of Transportation lying in seasonal frost areas. DOT officials have historically used a variety of different criteria for applying the spring load restrictions. SLRs have been set by predetermined annual dates that may not be suitable for every thawing season. Subjective inspections and observations of the roads by state DOT officials have also been used for making SLR posting decisions. If officials noticed excessive moisture seeping from the pavement cracks or a soft side shoulder, then the SLR would be applied. Falling Weight Deflectometer tests (FWD) have occasionally been used for posting load restrictions. The FWD is a large sophisticated pavement testing device, which is typically trailer-mounted. It applies a dynamic impulse load to the road surface, simulating a moving wheel load and measures the corresponding pavement deflections. The FWD deflection measurements can be run through complicated software and back calculations performed to determine the elastic moduli of the layers in the pavement structure. SLRs can be posted when increased deflections (and thus decreased modulus values) are observed. The setbacks to FWD tests are the expensive and cumbersome equipment used to measure pavement deflections as well as the need to redirect traffic around the test location. Light weight and handheld Portable FWDs or PFWDs have recently become available, but are still tedious and require frequent measurements during the freezing and thawing seasons in order to be useful. Also, these lighter weight FWDs are only effective on unsurfaced roadways or roadways with relatively thin pavement surfaces.

The main reason for applying these spring load restrictions is to minimize roadway damage and maintenance costs, but when relying on the FWD testing or observational methods to post spring load restrictions, the state DOT's are already subjecting the roads to some measure of damage before the SLRs are even applied. In order to prevent roadway damage and create optimal load postings during spring thaw, state DOTs are investigating alternative methods for posting SLRs. Currently, some transportation agencies are investing in the use of subsurface instrumentation to monitor the freeze-thaw profiles of the pavement structure. Some agencies are also investigating the use of thresholds based on air freezing and thawing indices to post SLRs. And recently, some agencies are investigating predictive models which can estimate the subsurface frost-thaw profiles to schedule SLRs.

Therefore, the overall goal of this research was to utilize data from nine test sites in New Hampshire to evaluate the effectiveness of several different SLR timing protocols and frost-thaw depth prediction models. Ultimately, the recommendations from this research will be incorporated into a decision support system (DSS) which is currently under development with funding provided by the U.S. Department of Transportation Research and Innovative Technology Administration (RITA). The UMass Dartmouth "RITA Research team," is working in collaboration with the New Hampshire Department of Transportation, Maine Department of Transportation and USDA Forest Service to develop a web-based system to monitor roadway conditions in real time during the spring thaw period with the use of commercial remote sensing and spatial information (CRS&SI) technology. In addition to real time monitoring of subsurface temperature and moisture regimes, the system will incorporate one or more of the protocols/models evaluated in this study for use in applying and removing SLRs in northern New England. The following section of this report discusses the various models evaluated. A description of the test sites and instrumentation is provided in Section 3, and the remaining sections present results of the analyses conducted and conclusions regarding the use of various model and protocols for making SLR timing decisions.

2. Background

2.1 SLR Application Methods Based on Air Temperature Indices

Every transportation department has its own methodology for posting spring load restrictions. There is no national unified system for scheduling SLRs. Typically; the SLRs are determined locally by DOT District Engineers. Whether it is a visual inspection or a science-based decision, it is ultimately their call. For example, Maine DOT has historically relied on inspectional methods (i.e., when water is observed pumping through cracks in the roadway) to post SLRs. They now take air temperature indices into consideration for scheduling SLRs because of the discovered correlation between air temperature indices and pavement strength during spring thaw. Many other transportation agencies across the world are also investigating this sort of methodology. Four methods for setting SLRs application dates based upon air temperature indices were evaluated for this research project.

2.1.1 Mahoney et al. (1986)

The method for applying SLRs proposed by Mahoney et al. (1986) suggests using daily average air temperatures to determine when the spring load restrictions should be posted. This method assumes that the pavement structure begins to thaw when the daily average air temperature increases to 29 degrees Fahrenheit. The thawing season begins once the daily average air temperature reaches the 29 degree datum for "several days" The first step in identifying the SLR start date is computing the cumulative degree days (*CDD*) using Equation 1.

$$CDD = \sum_{i=1}^{N} (T_{avg,i} - 29) \bullet \Delta t \qquad [1]$$

Where

N = Number of cumulative days
$T_{avg,i}$ = Corresponding day's average air temperature (degrees Fahrenheit)
Δt= Period between consecutive points (1 day)

The *CDD* values begin accumulating once the average daily temperatures remain above 29 degrees F and if the computed *CDD* becomes negative, the *CDD* is reset to zero. Mahoney et al. (1986) recommend that thin pavements should have the SLR applied on the day where the *CDD* reaches 10 °F-days and must have the SLR applied on the day where the thawing index reaches 40 °F-days. Thick pavements should have the SLR applied on the day where the thawing index reaches 25 °F-days and must have the SLR applied on the day where the thawing index reaches 50 °F-days. In theory, the "should" date correlates to when the upper thaw front reaches the bottom of the base layer and the "must" date correlates to when the front reaches 4" below the bottom of the base. Pavements are considered thin if the bituminous wearing surface is 2 inches or less and the base course is 6 inches or less. Pavements are considered thick if the wearing surface and base course are over 2 and 6 inches, respectively (Mahoney et al. 1986; Yesiller et al. 1996).

2.1.2 Minnesota Department of Transportation (MnDOT)

When determining the start dates for spring load restrictions, the Minnesota Department of Transportation (MnDOT) uses a methodology similar to that suggested by Mahoney et al. (1986). MnDOT has relied on the use of empirical correlations between the freezing and thawing indices and pavement frost-thaw profiles when setting SLRs. The cumulative thawing index (*CTI*) is the running total of each day's thawing index starting from a value of 0 F degree-days during the winter freeze. The daily thawing index is the amount the daily average temperature is above the reference temperature for that day's date. (Huen et al., 2006; Baïz et al., 2008). For days in which freezing occurs, the *CTI* is reduced by one half of that day's freezing index (the *CTI* may be reduced to a minimum value of zero). The daily freezing index is the amount the daily average temperature is below freezing and does not incorporate the reference temperatures. Because each day is either a thawing day or a freezing day; when the daily thawing index is a positive number the daily freezing index is set to zero, when the daily freezing index is a positive number the daily thawing index is set to zero. MnDOT (2009) recommends applying the spring load restriction when the *CTI* surpasses 25°F-days. The *CTI* is calculated using Equation 2, using the variable reference temperatures provided in Table 1.

$$CTI_n = \sum_{i=1}^{n} \left(\textit{Daily Thawing Index} - 0.5 \times \textit{Daily Freezing Index} \right) \qquad [2]$$

Case 1: Significant thawing has not yet occurred

$$\text{When } \left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right) < 0^{o} F \text{ and } CTI_{n-1} > 0.5 \times \left(32^{o} F - \frac{T_{\max} + T_{\min}}{2} \right),$$

$$\text{Then: } DTI = 0^{o} F - day \text{, and } DFI = \left(32^{o} F - \frac{T_{\max} + T_{\min}}{2} \right)$$

Case 2: Pavement structure is thawing

$$\text{When } \left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right) > 0^{o} F,$$

$$\text{Then: } DTI = \left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right) \text{, and } DFI = 0^{o} F - day$$

Where:

CTI_n = cumulative thawing index calculated over n days (°F-days)
CTI_{n-1} = cumulative thawing index for the previous day (°F-days)
DFI, DTI = daily freezing and thawing indices, respectively (°F-day)
T_{max}, T_{min} = daily maximum and minimum temperatures, respectively (°F)
T_{ref} = reference air temperature (°F), from Table 1

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

Table 1 - Reference Temperatures for *CTI* Calculations

Date	Corresponding Reference Temperature (°F)
January 1 – January 31	32.0
February 1 – February 7	29.3
February 8 – February 14	28.4
February 15 – February 21	27.5
February 22 – February 28	26.6
March 1 – March 7	25.7
March 8 – March 14	24.8
March 15 – March 21	23.9
March 22 – March 28	23.0
March 29 – April 4	22.1
April 5 – April 11	21.2
April 12 – April 18	20.3
April 19 – April 25	19.4
April 26 – May 2	18.5
May 3 – May 9	17.6
May 10 – May 16	16.7
May 17 – May 23	15.8
May 24 – May 30	14.9
June 1 – December 31	32.0

In the *CTI* equation, the freezing index is multiplied by a refreeze factor of 0.5 to account for the partial phase change of water from a liquid to semi-solid during temporary refreeze events. The reference temperatures are used to account for the increasing intensity of the sun during the spring thaw period. This factor is included in the *CTI* equation with a reference temperature depression of 2.7°F during the first week of February followed by a 0.9°F depression every week until the end of the thawing season (MnDOT, 2009).

2.1.3 United States Forest Services USFS/Berg Method

The USFS/Berg Method provides and alternative approach to applying spring load restrictions, which takes into account the influence of pavement surface temperatures. This method assumes that both average daily air temperatures and average daily pavement surface follow sinusoidal functions, according to Equation 3. This method requires an initial trial and error fit for the air temperature sinusoid based upon 20 years of average daily air temperature data from a weather station located near the candidate site.

$$T_t = MAAT + Amp * Sin\left(\left(\frac{2\Pi}{P}\right) * (t - Lag)\right) \quad [3]$$

Where,

T_t = sinusoidal temperature on Julian day, t
P = sinusoidal period (365 days)
MAAT = 20-year mean annual air temperature
Amp = amplitude of the temperature sinusoid
Lag = time lag of the temperature sinusoid

The trial and error procedure for determining the amplitude of the air sinusoid is accomplished in an Excel spreadsheet using a recommended value of 100 days for the time lag. Then, the following empirical correlations are relied upon to estimate the pavement surface temperature sinusoid.

$$SFI = n_f\,(AFI) \quad [4]$$

$$STI = n_t\,(ATI) \quad [5]$$

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

Berg et al. (2006) recommend using $n_f = 0.5$ and $n_t = 1.7$. Additional details regarding the methodology for establishing the pavement surface sinusoidal temperature function are described by Berg et al. (2006) and Kestler et al. (2007). 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). That difference is then added to the measured average daily air temperature to approximate the actual pavement surface temperature. The daily thawing index (*DTI*) computation is started on February 14 according to Equation 6.

$$DTI = Pavement\ Surface\ Temp - 32^o\,F \qquad [6]$$

The *DTI* is then used for the computation of a cumulative thawing index (*CTI*) using Equation 7.

$$CTI = \sum_{i=1}^{N}(DTI_i) \qquad [7]$$

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

2.1.4 Manitoba Department of Infrastructure and Transportation (MDIT)

Prior to 2012, Manitoba utilized fixed start dates to apply load restrictions and they typically were in effect for 10 weeks. With the changes in Canada's regional climate, these fixed dates were no longer appropriate for every season. In 2008, the Manitoba Department of Infrastructure and Transportation (MDIT) sought out the use of more rational methods for posting roads in order to more reliably manage their SLR policies. MDIT installed instrumentation at several sites in southern Manitoba that measure roadbed temperatures and moisture contents. The data from these sensors as well as the *CTI* were compared to the weekly measured deflections from FWD surveys during spring thaw. MDIT uses traditional methods for calculating the *CTI*, but has their own computations for reference temperatures (Bradley et al.; 2012).

$$CTI = \sum Daily\ Thawing\ \ Index = \sum\left(T_{ref} + \frac{T_{\max} + T_{\min}}{2}\right) \qquad [8]$$

Where,

T_{ref} = 1.7^{o}C starting March 1 and increases by 0.06°C per day until May 31 (0°C from June through February in the following year)
If $(T_{max} + T_{min})/2 < 0$, then the Daily Thawing Index = $[T_{ref} + (T_{max} + T_{min})/4]$
If *CTI* < 0, *CTI* is reset to 0 (i.e., *CTI* is never negative).

The measured FWD data obtained at the MDIT test sites was compared to the computed *CTI* values to determine if there were any relationships between the *CTI* and the pavement strength. The MDIT researchers noticed a strong correlation between the two and computed an average *CTI* value of 15^{o}C-days when the pavement strength had begun to weaken due to spring thaw. Based on the results of this analysis, MDIT developed new SLR policies based on the *CTI*. The SLR will start when *CTI* reaches 15^{o}C-days (27^{o}F-days), but not earlier than March 11.

2.2 SLR Removal Methods Based Upon Air Temperature Indices

2.2.1 Mahoney et al.(1986)

Mahoney et al, (1986) suggest two alternative methods for lifting spring load restrictions. Both of the SLR removal methods are functions of the air freezing index *(AFI*) for the immediate past winter and are further explained in the following sections. In order to calculate the air freezing index, cumulative degree day (*CDD*) calculations begin prior to when the average daily air temperatures drop below freezing and continue through the spring.. Similar to Equation 1, the formula for the cumulative degree days needed for the AFI calculation is shown in Equation 9 (Steurer & Crandell 1995).

$$CDD = \sum_{i=1}^{n} (T_{avg,i} - 32) \times \Delta t \qquad [9]$$

After the *CDD* is computed for the freeze-thaw season, maximum and minimum *CDD* values are recorded. The air freezing index is then equal to the difference between these maximum and minimum *CDD* values; Equation 10.

$$AFI = CDD_{\max} - CDD_{\min} \qquad [10]$$

With the air freezing index established, Mahoney et al. (1986) suggest that the SLRs can be lifted using empirical correlations for duration (Equations 11 or 12) or for removal date based upon a thawing index (*TI*) threshold (Equation 13 or 14).

2.2.1.1 Duration

This method computes the number of days the restrictions remain after the Mahoney et al. SLR application date is posted. This duration can be determined by Equation 11; or by Equation 12, which is an approximation of Equation 11:

$$Duration = 22.62 + 0.011(AFI) \qquad [11]$$

$$Duration = 25 + 0.01(AFI) \qquad [12]$$

2.2.1.2 Date

The Mahoney et al. spring load restriction removal date is the day corresponding to when the cumulative thawing index reaches the threshold value determined from either Equation 13 or Equation 14 (which is an approximation of Equation 13): The thawing index is calculated using Equation 1 and once its value surpasses the threshold computed through Equations 13 or 14, the SLR should be lifted.

$$TI = 4.154 + 0.259(AFI) \qquad [13]$$

$$TI = 0.3(AFI) \qquad [14]$$

2.2.2 Manitoba Department of Infrastructure and Transportation (MDIT)

In their research, MDIT correlated pavement strength recovery (as indicated by FWD deflections) with three other parameters: measurements of thaw depth, moisture content, and *CTI*. Using Equation 8, the *CTI* was tabulated when: the FWD peak deflections substantially recovered to summer levels, when moisture contents in the upper 1 m of the pavement structure stabilized at summer levels, and when thawing penetrated to a depth of 1.2 m. Based on the results of this analysis, MDIT developed the following new SLR policy: the SLR will end on the earliest of 8 weeks (56 day duration), when the *CTI* reaches 350^{o}C-days (630^{o}F-days), or May 31.

2.3 Frost-Thaw Prediction Models

Many transportation agencies are now considering the use of predictive models to estimate frost-thaw profiles. If accurate, the models can be used to set SLR application dates (i.e., when the pavement structure starts thawing). In theory, the SLR should remain in place at least until thawing is complete, or until thawing has reached sufficient depth that excess moisture can drain from the base and upper subgrade layers. These models can rely on a variety of inputs that may include air temperature data and other atmospheric weather data, pavement layers thicknesses, as well as thermal and other material properties of the pavement structure.

2.3.1 University of Waterloo Model

In 2005, research at the University of Waterloo, Ontario, began investigating the relationship between depths of frost and thaw beneath the road and air temperatures. They installed subsurface instrumentation to monitor the temperatures beneath the roadway at two test locations in Ontario. At both test sites Road Weather Information Systems (RWIS) were available to measure atmospheric weather data, such as air temperature, humidity, precipitation, etc. The ultimate goal of this research was to create a localized model which could predict frost depths based upon average air temperature data. In order to create this model, freezing and thawing temperature indices were plotted against the measured frost and thaw depths. Equations 15 and 16 are used for computing freezing and thawing indices, respectively. The freezing index is calculated once the daily average temperatures drop below freezing. Computations for the thawing index begin once the daily average temperatures are warming up and above freezing.

$$FI = \sum (0^{o}C - T_{avg,i}) \qquad [15]$$

$$TI = \sum (T_{avg,i} - T_{ref}) \quad [16]$$

Where,

FI = daily freezing index (^oC-days)
TI = daily thawing index (^oC-days)
$T_{avg,i}$ = average air temperature for day i (^oC)
T_{ref} = reference temperature (^oC)

The reference temperature is used to account for the difference between air and pavement surface temperatures. Mean air temperatures were plotted against the corresponding pavement surface temperatures over a 3 month period. The data showed a 5.31 ^oC lag difference between the two and this value became the fixed reference temperature for the localized prediction model, as shown in Equation 17.

$$TI = \sum (T_{avg,i} + 5.31) \quad [17]$$

The cumulative freezing and thawing indices are then equal to the summation of the daily freezing and thawing indices, respectively, and are reset to zero if negative.

$$CTI_n = \sum_{i=1}^{n} TI_n \quad [18a]$$

$$CFI_n = \sum_{i=1}^{n} FI_n \quad [18b]$$

Where,

CFI_n, CTI_n = cumulative freezing and thawing index for day n (^oC-days)
FI_n, TI_n = freezing and thawing index for day n (^oC)

The researchers developed a preliminary model relating the depth of frost penetration to the square root of the *CFI* and discovered a linear relationship with a coefficient of determination of 98% (Huen et al., 2006; Tighe et al., 2007):

$$FD = 5.537\sqrt{CFI} \quad [19]$$

Where,

FD = frost depth (cm below pavement surface)

This freeze-thaw index prediction model was used as a supplemental tool to understand the state of the Ontario highways and assisted transportation engineers in their scheduling of SLR applications and removals (Huen et al., 2006). At the time of that publication, only one season of data was collected for the prediction model. This season may have been colder or warmer than an average season and may not have provided a good average representation of a freeze-thaw index model. They concluded that further studies should be done over more freeze-thaw cycles in order to create a model that would more reasonably estimate frost depths.

In 2006-2007 the State of Maine DOT built upon the work originally conducted at the University of Waterloo, as well as work conducted by the Minnesota Department of Transportation. Maine DOT estimated frost depths using the same methodology, but incorporated the reference temperatures listed in Table 1 (rather than 5.31 ^{o}C). They compared those estimated depths with frost depths measured via frost tubes at four test sites in Maine. The Maine DOT concluded that the estimated frost depths correlated very well with measured frost depths at three of their four test sites (Marquis, 2008). As a follow-up to their work, investigators at UMass Dartmouth used the same methodology that was used in the Maine DOT study to estimate frost depths at nine test sites established for the NH DOT/FS SLR study (Miller et al., 2012). The results of that investigation suggested that the freeze-thaw index model shows much promise as a tool that could assist transportation agencies in deciding when to place and remove SLRs. However, the investigators concluded that calibrating the model on a site-specific basis might enable more accurate estimates of frost-thaw profiles. This site-specific calibration ("Modified Freeze-Thaw Index Model") is described in Section 4.2.

2.3.2 US 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 was originally developed for use with arctic and subarctic construction. Model 158 was based on the Modified Berggren equation, originally developed in the 1950's (Joint Departments of the Army and the Air Force USA, 1988), which uses air temperature indices as well as pavement material properties to integrate heat flow in the calculation of frost depth. The US Army Corps of Engineers Model 158 equation is:

$$X = -\frac{d}{2} + \left(\frac{d}{2} + \frac{86{,}400 k I_{sf}}{L + c(v_o + I_{sf} / 2t)} \right)^{1/2} \qquad [20]$$

Where,

X = depth of frost (m)
k = thermal conductivity (W/m^{o}C))
I_{sf} = seasonal surface-freezing index (^{o}C-days)
L = latent heat (MJ/m^{3})
d = thickness of the surface asphalt layer (m)
c = volumetric heat capacity (MJ/m^{3o}C)
v_o = average pavement surface temperature year-round (^{o}C)
t = annually length of time below freezing (days)
86,400 = amount of seconds in a day for dimensional consistency (sec/day)

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 use of modern computers now allows for the Model 158 to predict daily frost depths, by using the parameter I_{sf} on a daily basis rather than for an entire season (Orr and Irwin, 2006). The daily surface-freezing index is equal to the daily air freezing index computed in the traditional manner as per Equation 15, but multiplied by a factor to adjust air-freezing to surface freezing temperatures. I_{sf} is still a cumulative value summed on a daily basis and cannot be less than zero.

The Model 158 equation requires layer thicknesses and material properties of the pavement structure. The thermal properties necessary for the model are thermal conductivity (k), heat capacity (c), and latent heat (L). Thermal conductivity is a measure of a material's ability to conduct heat, which is the rate at which heat transfers 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 helps account for the change in energy during a phase transition (i.e. water transitioning from liquid to ice). These properties are material specific and change with the depth of frost penetration. Recommended input and thermal property values for use with this model are provided in Section 4.3.

2.3.3 Enhanced Integrated Climatic Model (EICM)

As a part of the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG), the Enhanced Integrated Climatic Module (EICM) is a module which 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. 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, C., and Houston, W., 2008). This software stores multiple seasons of hourly atmospheric weather data from weather stations across the US. The designer can utilize the historic database or import their own weather data to estimate depths of frost and thaw penetration over the winter-spring period. The climatic inputs required are: air temperature, precipitation, wind speed, percent sunshine, relative humidity, and groundwater table depth. If there are gaps in the data, the software interpolates to fill in any missing values. 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 soil strength parameters. The software provides default values for properties like thermal conductivity and specific gravity, and even the grain size distributions for different soil types.

There have been many studies investigating the validity of the EICM by state Departments of Transportation, the Transportation Research Board (TRB), the National Cooperative Highway Research Program (NCHRP), and other transportation agencies. These studies compared EICM computed data to measured pavement parameters such as temperature and moisture content profiles, and frost-thaw depths. Results of a New Jersey Department of Transportation study did not indicate a high correlation between field-measured values and EICM-predicted temperature and moisture profiles through various pavement structures (Ahmed et al., 2005). An Ohio study also found that EICM predicted temperature profiles did not match measured field data, but the range of values computed by the model can be considered within an acceptable range. This research found that there was not a good relationship between the modeled and measured frost-thaw depths in the bounded base material sections (such as cement or asphalt stabilized base layers), but there was a noticeable relationship for unbounded base material layers (Liang, 2006).

The EICM is an advanced, complex, and state-of-the-art program that has recently been gaining a lot of attention from many transportation agencies. Therefore, it was originally proposed to investigate the EICM in this study. Unfortunately, new licensing agreements have become extremely costly (about $5,000 per year), so this software was not generally available for use on this project.

3. Test Sites and Instrumentation

This research is based on the data collected from 9 test sites in northern New Hampshire, over a period of 5 years. The list of all the sites and their locations are provided in Table 2. Figures 1 and 2 are images taken from Google Maps of the test site locations zoomed in and out, respectively.

Table 2 - Test Site Abbreviations and Coordinates

Site Name		Elevation (ft)	Latitude	Longitude
K-1	Kancamagus/Rt. 112	1,243	N43.99	W71.33
K-2	Kancamagus/Rt. 112	1,243	N43.99	W71.33
K-3	Kancamagus/Rt. 112	1,243	N43.99	W71.33
LT	Lake Tarleton	1,371	N43.98	W71.97
NGR	North Groton Road	1,499	N43.75	W71.86
RUM	Rumney Shed	525	N43.79	W71.83
SLR	Stinson Lake Road	1,416	N43.88	W71.80
WF	Warren Flats/Rt. 25 C	791	N43.93	W71.91
WS	Wentworth Shed	862	N43.89	W71.90

The Kancamagus/Rt. 112 site is comprised of three test sections located within a thousand foot stretch of roadway. During 2005, this strip of roadway was rehabilitated using 3 different methods. K-1 was reconstructed using conventional (box cut) methods, K-2 using full depth reclamation (FDR) with cement, and K-3 using FDR without any stabilization. Additional details regarding the reconstruction and initial establishment of these test sites are provided by Miller et al. (2007).

In 2006, those three Kancamagus test sections were combined with six additional sites for a research project sponsored by the New Hampshire Department of Transportation (NH DOT) and USDA Forest Service (FS). The NH DOT and FS installed the following subsurface instrumentation at the nine test sections:

- Frost tubes, to determine the state of the ground (frozen/unfrozen)
- Tubes that held six to nine “Hobo” temperature data loggers
- Observation wells (OWs), to determine groundwater depth

All of those instruments were located in the right wheel path, about 2.5 ft from the white line marking the edge of the travel lane. They are spaced 5 ft from each other along a line that runs parallel to the roadway centerline. One frost tube was installed in each test section to a depth of 6 ft. for measuring frost/thaw penetration. A frost tube consists of two concentric plastic pipes installed vertically in the ground with a protective cover. The outer pipe acts as protection for the inner pipe, which is removable. The inner pipe is filled with water and dye. When the dye freezes, its color changes; when it thaws, it returns to its original color. Depths to the top and bottom of the frozen layer were

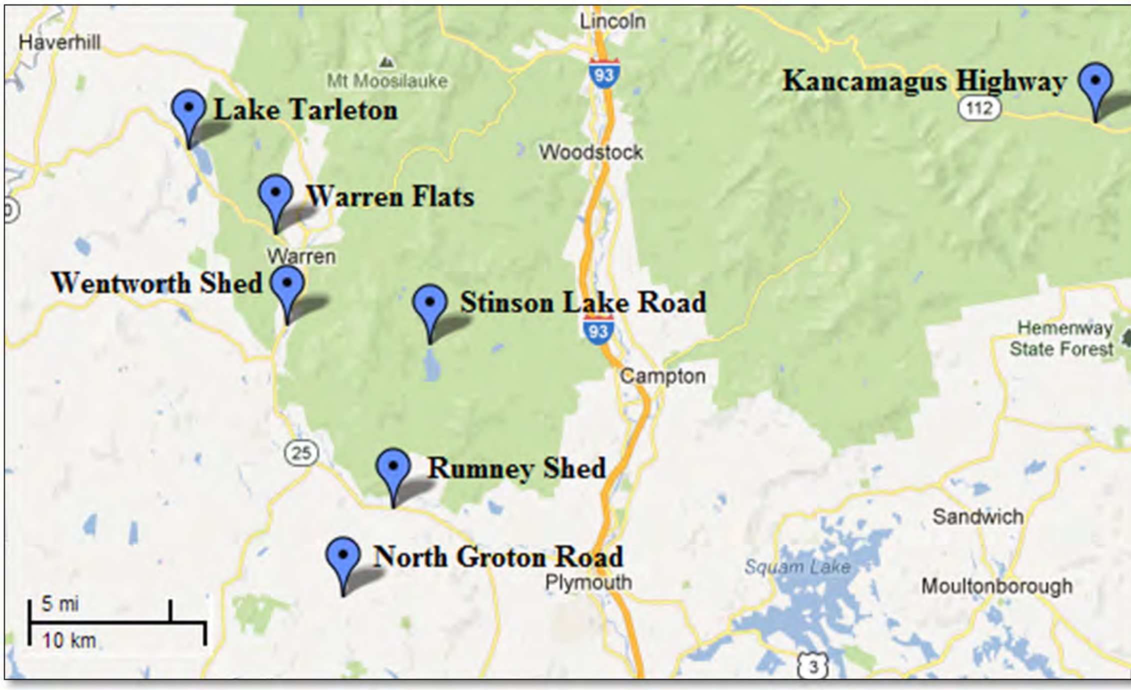

Figure 1 - New Hampshire Test Sites, Zoom In (Google, 2013)

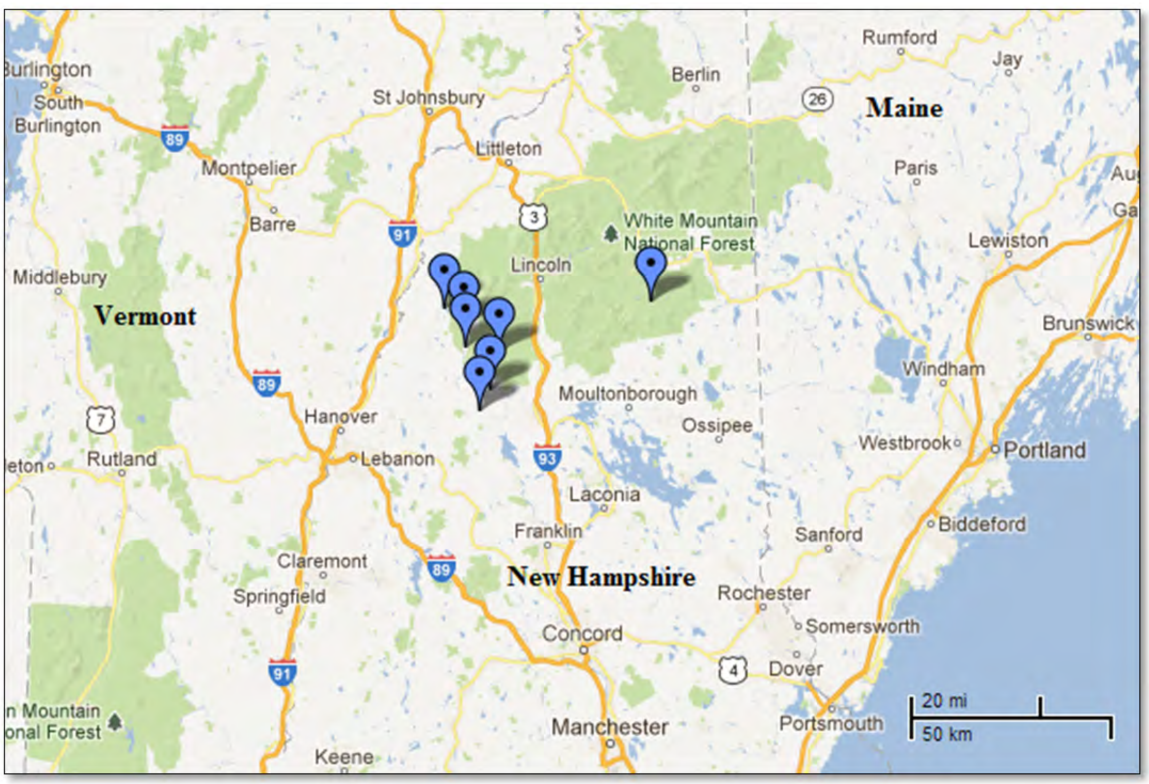

Figure 2 - New Hampshire Test Sites, Zoom Out (Google, 2013)

established based upon the color change, which is associated with the freezing/thawing of the soil surrounding the outer pipe.

In each test section a tube was installed to a depth of 7 ft. which originally held six temperature data loggers. The data loggers were spaced at depths of approximately 6, 12, 18, 30, 54, and 78 inches beneath the surface. The following year, 3 additional HOBO sensors were added to each of the sites, then enabling measurements at depths of about 6, 12, 18, 24, 30, 36, 42, 54, and 78 inches. The data loggers recorded and stored hourly temperature readings. Those data were typically downloaded at the end of each spring thaw period. In order to account for the effects of roadway heaving, the actual depths of the sensors below the pavement surface were measured at the end of spring. The HOBO sensors were calibrated in a 32 ^{o}F ice bath so that freezing temperature offsets could be accounted for in any analyses.

The frost tubes and OWs were monitored weekly to bi-weekly, and the Hobos were programmed to record subsurface temperatures hourly. Additionally, a weather station was installed above ground at each site, which recorded a number of atmospheric weather parameters once per hour. Details regarding the test sites, instrumentation, and monitoring are discussed by Eaton et al. (2009).

During instrument installation at each of the 9 test sites (with the exception of K-2), soil samples were collected to classify pavement base, sub-base and subgrade soils. Sieve analyses were run on all of the samples to determine the percentages of gravel, sand, and fines. Hydrometer tests were performed on samples with a high amount of fines to determine the grain size distribution (GSD) of those fines. The GSD data allowed for each of the samples to be classified in the Unified Soil Classification System (USCS). The entire set of GSD and soil classification data are tabulated in Appendix A. Additionally, a “generalized soil descriptor” was designated for each of the sites and can be found in Table 3. Any site where the majority of samples contained more than 50% fine sand and silt was given the generalized soil descriptor “Fine.” Any site where the majority of samples contained more than 50% medium to coarse sand and gravel was given the descriptor “Coarse.” And sites which had a wide variety of soils ranging from silt to gravel were given the soil descriptor “F-C” (Miller et al., 2012). Note: since there were no samples obtained from K-2, the generalized soil descriptor designated for this site was the same as K-1 and K-3.

Data from the frost tubes, HOBO temperature data loggers, observation wells, and atmospheric weather station were provided to the UMass research team by the NHDOT. After the hourly HOBO data was collected, the daily average temperatures were computed, and freezing temperature offsets added/subtracted from each reading. The daily average temperatures were input into an excel spreadsheet and the depths of frost and thaw were computed using linear interpolation between subsurface sensors and 32^{o}F as the freezing point (refer to Table 4 as an example). The daily frost and thaw depths were then tabulated for the duration of the freeze-thaw season and were plotted versus time in days as shown in Figure 3.

Table 3 - Test Site Soil Descriptors

Site	Soil Descriptor
K-1	Coarse
K-2	Coarse
K-3	Coarse
RUM	F-C
WS	F-C
LT	F-C
NGR	Fine
SLR	Fine
WF	Fine

Table 4 - Measured Frost-Thaw Depths at Lake Tarleton 2009-2010

Date	Sensor Depth (in)									Thaw Depth	Frost Depth
	5	11	17	23	29	35	41	53	77		
03/06/10	33.4	31.9	31.0	30.2	30.4	30.7	31.4	36.0	39.0	9.2	41.40
03/07/10	35.6	32.3	31.2	30.3	30.6	30.8	31.4	35.9	38.8	11.2	41.29
03/08/10	38.0	33.6	31.7	30.4	30.6	30.8	31.4	35.9	38.8	14.8	41.29
03/09/10	36.3	34.0	32.3	30.6	30.6	30.8	31.4	35.9	38.8	16.7	41.29
03/10/10	34.5	33.1	32.1	30.6	30.8	31.0	31.6	35.9	38.8	16.2	40.87
03/11/10	34.9	33.0	32.1	30.8	30.8	31.0	31.6	35.9	38.7	16.1	40.81
03/12/10	38.4	35.2	33.1	30.9	30.9	31.1	31.6	35.9	38.6	18.7	40.77
03/13/10	38.3	35.2	33.4	31.0	31.0	31.2	31.8	35.9	38.6	19.3	40.35
03/14/10	37.8	35.8	33.9	31.2	31.1	31.2	31.8	35.9	38.6	20.0	40.28
03/15/10	38.7	35.8	33.8	31.5	31.3	31.3	31.8	35.9	38.6	20.4	40.28
03/16/10	40.7	36.3	34.0	31.6	31.4	31.4	31.8	35.9	38.6	20.7	40.28
03/17/10	43.0	38.3	35.3	31.9	31.6	31.6	31.9	35.9	38.5	21.5	39.97
03/18/10	44.4	39.5	36.1	32.6	31.9	31.7	32.0	35.9	38.4	26.5	39.38
03/19/10	47.0	41.0	37.1	33.4	32.2	31.9	32.2	35.9	38.4	31.9	35.52
03/20/10	47.8	42.3	38.3	34.5	33.0	32.3	32.5	36.1	38.4		

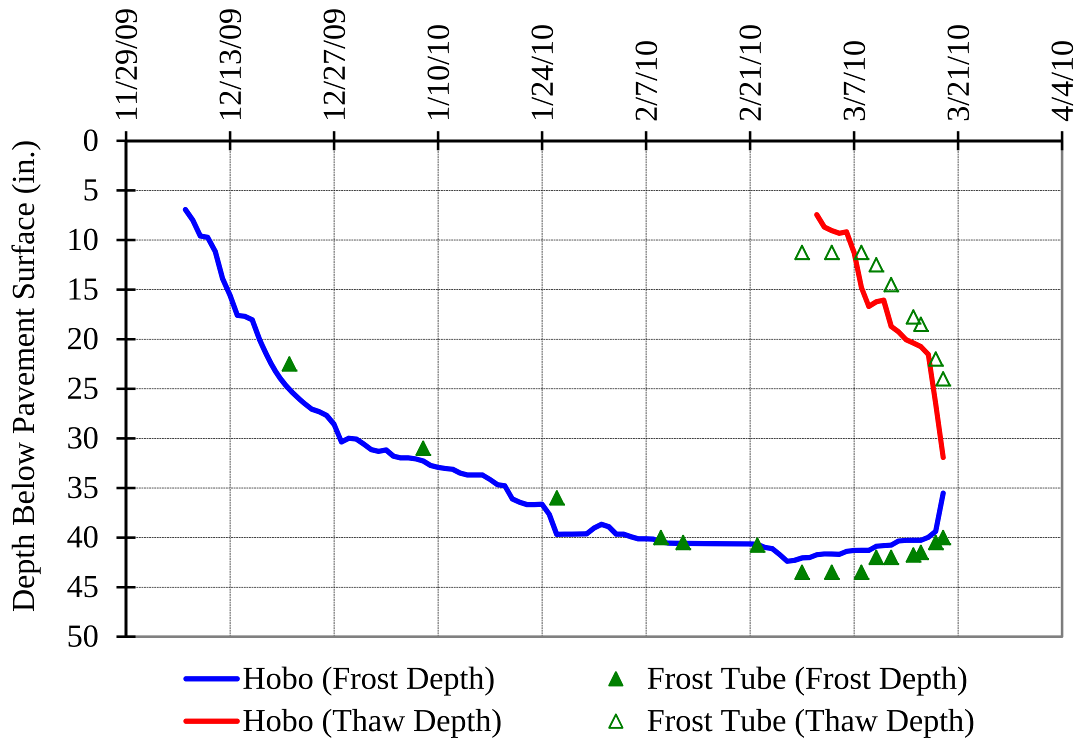

Figure 3 - Measured Frost-Thaw Depths at Lake Tarleton 2009-2010

In addition to collecting data from subsurface instrumentation, the NHDOT performed FWD tests on a weekly-biweekly basis at all of the sites (excluding Wentworth Shed), during the 2007-2008 and 2008-2009 seasons. Adjusted center deflections (ACD) were computed from the raw FWD data, and were used to evaluate changes in pavement stiffness during the spring thaw periods.

4. Data Analysis

4.1 General

The research described herein evaluates several of the methods for scheduling spring load restrictions and predicting frost-thaw depths that were described in Section 2 (Background) using the data collected from the nine NH test sites described in Section 3. In Sections 4.2, 4.3 and 4.4, three freeze-thaw prediction models will be used in their original forms and/or slightly modified forms to estimate frost-thaw profiles and compare them to the measured frost-thaw depths determined from the site instrumentation. Section 4.2 also includes a description of procedures used to develop and calibrate site-specific freeze-thaw prediction models. In Section 4.5, various protocols or thresholds recommended for applying and removing SLRs are evaluated by comparing the SLR threshold dates with measured frost-thaw profiles and FWD data.

Atmospheric weather data required for the prediction models and SLR timing protocols was generally obtained from the weather stations that were installed at each of the test sites. However, occasionally there were gaps because the site weather stations periodically failed to collect data. In those cases, gaps were filled in with data obtained from nearby weather stations. Missing data from the western NH sites were filled with information from the Plymouth State University Weather Station (PSU, 1997) and the gaps in data from the Kancamagus sites were filled using data from a Remote Automated Weather Station (RAWS) in the White Mountains, NH (WRCC, 1986).

4.2 Modified Freeze-Thaw Index Model

The procedures outlined in the development of the Waterloo Model provided a good basis for developing site specific freeze-thaw index models at the New Hampshire test sites. The research from the University of Waterloo observed a somewhat linear trend between their measured thaw depths and square root of the *CTI*. They developed an equation for estimating the depth of thaw, which was equal to a constant/coefficient multiplied by the square root of *CTI*. The purpose of this section of the research is to define both cumulative freezing and thawing indices and compare them to measured frost and thaw depths, respectively. Creating freeze-thaw index models (with only air temperature data as input) that can accurately estimate depths of frost and thaw at each of the nine test sites are the end goals.

Measured depths of frost and thaw were collected using subsurface temperature sensors and frost tubes. As previously described in the Section 3, the data was manipulated in a spreadsheet using linear interpolation to produce daily frost-thaw depths. Next, the cumulative freezing and thawing indices were computed. The *CFI* was determined using the traditional calculations as shown in Equations 21 and 22. Several methods could have been used to compute *CTI*, but the procedures and reference temperatures outlined by MnDOT provided the best output.

$$Daily\ \ Freezing\ \ Index = \left(32^o\,F - \frac{T_{\max} + T_{\min}}{2} \right) \qquad [21]$$

$$CFI_n = \sum_{i=1}^{n} (Daily\ \ Freezing\ \ Index) \qquad [22]$$

If $CFI_{n\text{-}1} + \left(32^o\,F - \frac{T_{\max} + T_{\min}}{2} \right) < 0$°F-day

Then, $CFI_n = 0^o\,F - day$

Where: CFI_n = cumulative freezing index calculated over *n* days (°F-day)
CFI_{n-1} = cumulative freezing index for the previous day (°F-day)
T_{max} = Maximum daily air temperature (°F)
T_{min} = Minimum daily air temperature (°F)

$$CTI_n = \sum_{i=1}^{n} \left(\ Daily\ Thawing\ Index - 0.5 \times \ Daily\ Freezing\ Index \ \right) \qquad [23]$$

Case 1: Significant thawing has not yet occurred

When $\left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right) < 0^o\,F$ and $CTI_{n-1} > 0.5 \times \left(32^o\,F - \frac{T_{\max} + T_{\min}}{2} \right)$,

Then: $DTI = 0^o\,F - day$, and $DFI = \left(32^o\,F - \frac{T_{\max} + T_{\min}}{2} \right)$

Case 2: Pavement structure is thawing

When $\left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right) > 0^o\,F$,

Then: $DTI = \left(\frac{T_{\max} + T_{\min}}{2} - T_{ref} \right)$, and $DFI = 0^o\,F - day$

Where:
CTI_n = cumulative thawing index calculated over *n* days (°F-days)
$CTI_{n\text{-}1}$ = cumulative thawing index for the previous day (°F-days)
DFI, *DTI* = daily freezing and thawing indices, respectively (°F-day)
T_{max}, T_{min} = daily maximum and minimum temperatures, respectively (°F)
T_{ref} = reference air temperature (°F), from Table 1 (MnDOT, 2009)

For each site and season, the measured frost-thaw depths and corresponding *CFI* and *CTI* were tabulated for each day and input into scatter plot. The square root of the *CFI* was plotted on the x-axis with the measured frost depth on the y-axis. Similarly, the square root of the *CTI* was plotted on the x-axis with the measured thaw depth on the y-axis. The data plots appeared to show a linear relationship as noted in similar model analyses from other studies. Best-fit linear trend lines with zero y-intercepts were determined for the data with the format of $y=mx$, or:

$$FD = C_F \sqrt{CFI} \qquad [24]$$

$$TD = C_T \sqrt{CTI} \qquad [25]$$

Where,

FD = frost depth (in)
TD = thaw depth (in)
C_F = frost coefficient or slope of the frost trend line
C_T = thaw coefficient or slope of the thaw trend line

The R^2 values for all of the linear regressions were tabulated to evaluate the accuracy of the trend lines. As shown in Equations 24 and 25, the frost and thaw coefficients are equal to the slopes of these best fit lines. Refer to Figures 4 and 5.

The daily frost and thaw depths can be estimated using Equations 24 and 25, the C_F and C_T coefficients determined from Figures 4 and 5, and the square roots of *CFI* and *CTI*, respectively, calculated as per MnDOT (2009). See Figure 6 for the graphical comparison of the measured versus model data for the Lake Tarleton site for the 2009-2010 season.

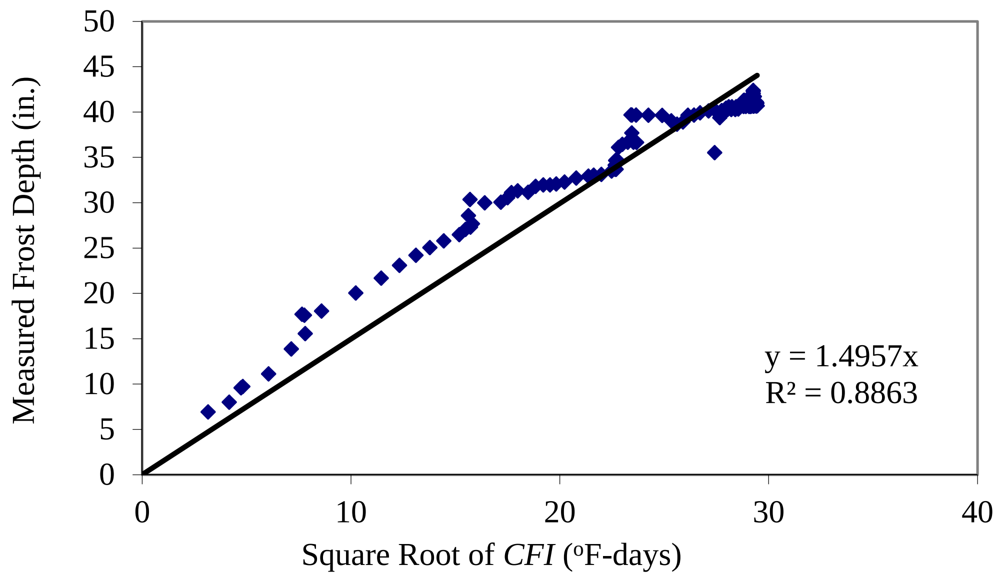

Figure 4 - LT 2009-2010 Linear Regression for Frost Coefficient

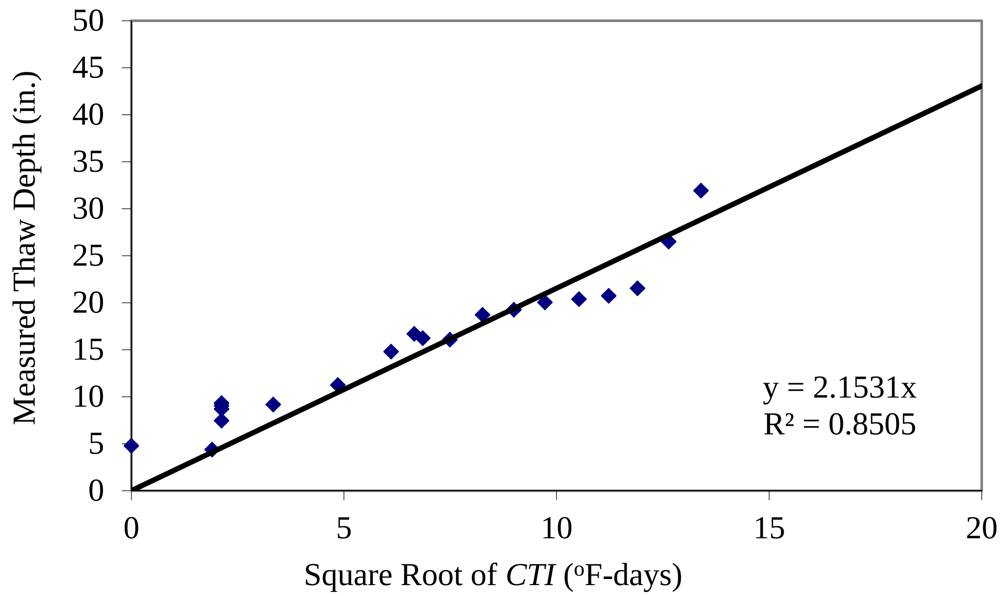

Figure 5 - LT 2009-2010 Linear Regression for Thaw Coefficient

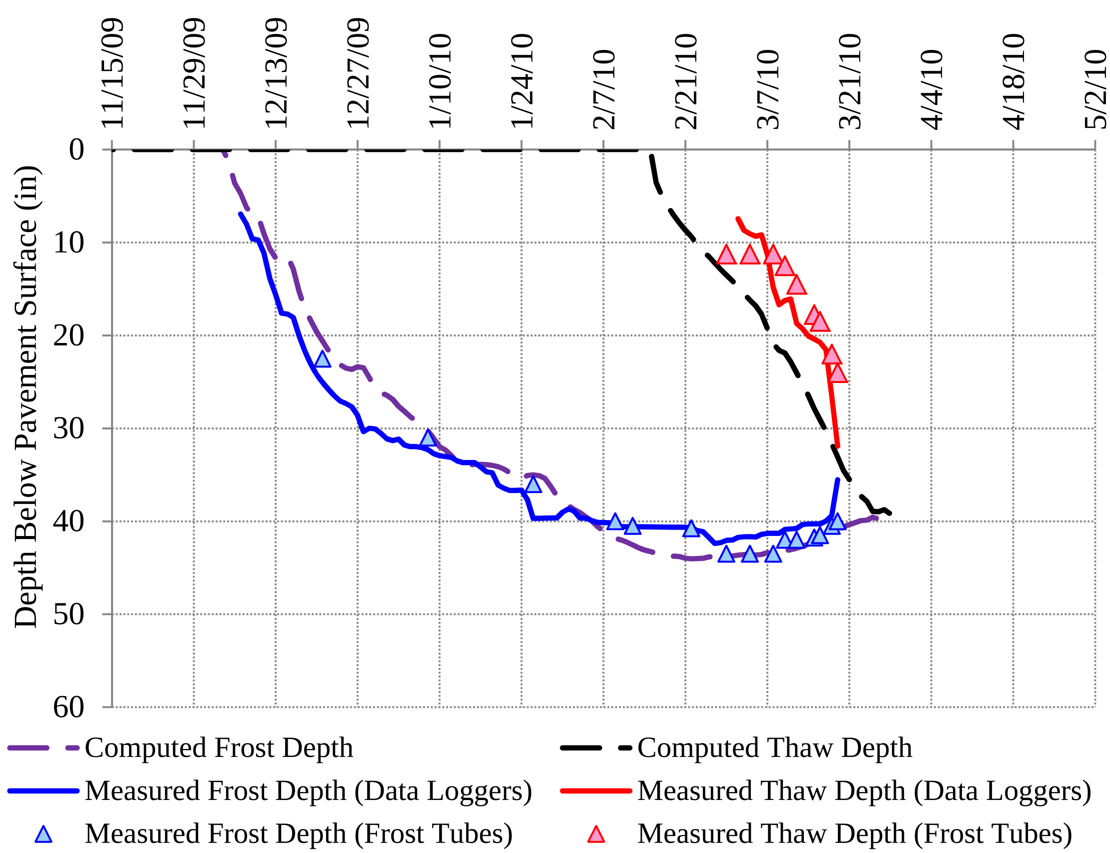

Figure 6 - LT 2009-2010 Modified Freeze-Thaw Index Model Calculated vs. Measured Frost-Thaw Depths

For each site and year, the models were predicting frost and thaw depths quite accurately. But, the point of this study is not to have a bunch of different models that fit nicely to each site for individual years. The purpose is to create and calibrate a model that will fit relatively well to each site for all years. To do so, all of the historic data from 2007 to 2010 (measured frost-thaw depths and *CFI* and *CTI*) was compiled into site-specific tables. Using the same charts as shown in Figures 5 and 6, measured frost and thaw depths for the 3 years were plotted against the corresponding values for *CFI* and *CTI*, respectively. Best fit trend lines were generated for the nine plots (one for each site) with the same $y=mx$ format. Site specific C_F and C_T values were determined from the slopes of the frost and thaw charts, respectively. Because the regression data for sites K-2 and K-3 were very similar, those two data sets were combined for the 3-year regression analysis.

After the site-specific data was compiled and regressed, a few calibrations were performed to optimize the model. The two calibrations made to all the models consisted of omitting measured thaw depths when the computed *CTI* equaled zero and frost depth "end tails" that occurred from rapid bottom up thawing. Since data from those observations seemed rather unreasonable, they were eliminated from the linear regressions and determinations of frost-thaw coefficients. Refer to Figures 7 through 10 for examples of these calibrations and how they impact C_F and C_T and their corresponding R^2 values.

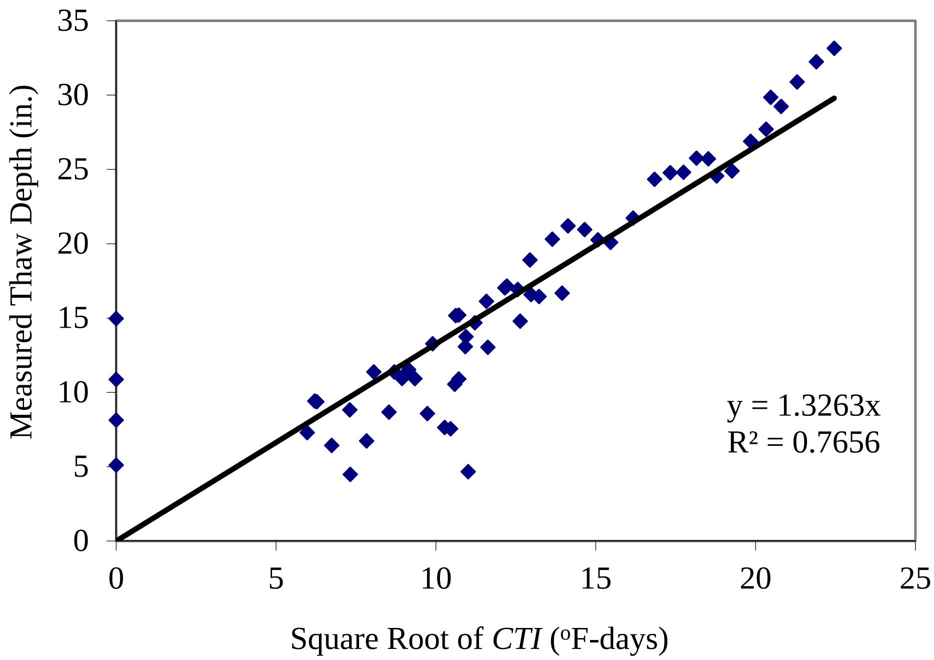

Figure 7 - NGR 2007-2010 Compiled Thaw Data (Before Calibration)

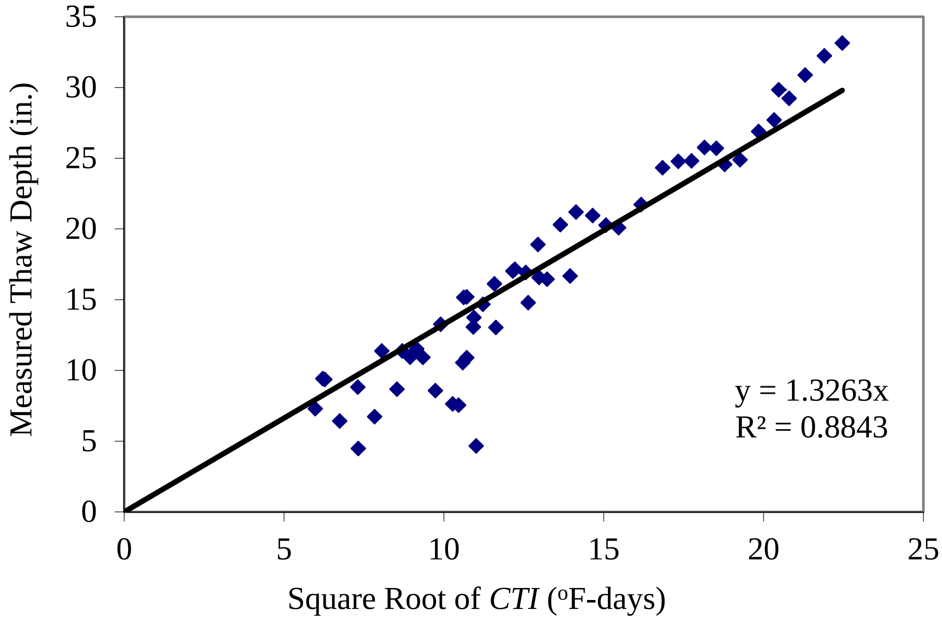

Figure 8 - NGR 2007-2010 Compiled Thaw Data (After Calibration)

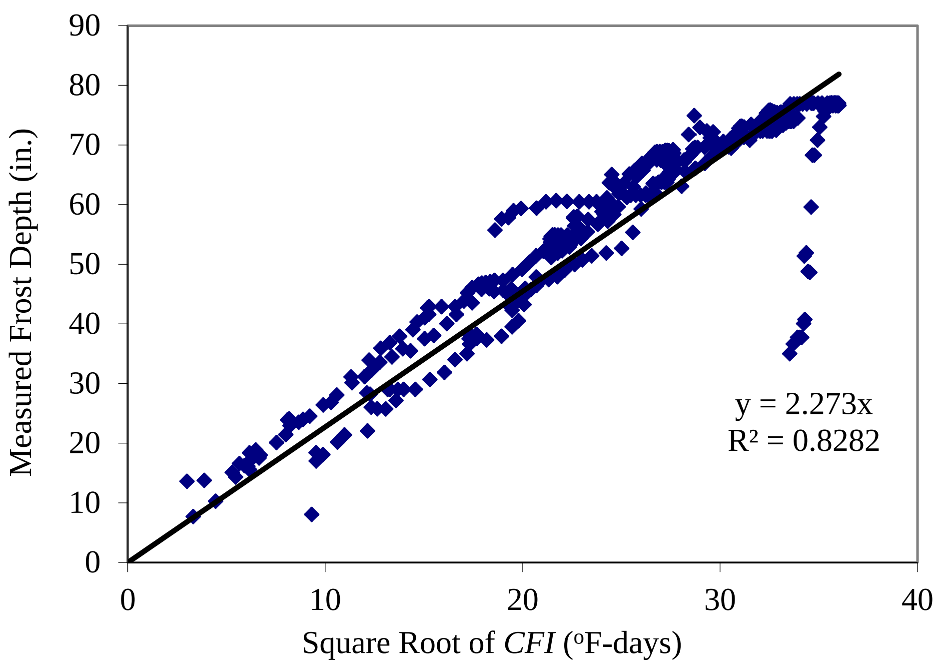

Figure 9 - K-1 2007-2010 Compiled Frost Data (Before Calibration)

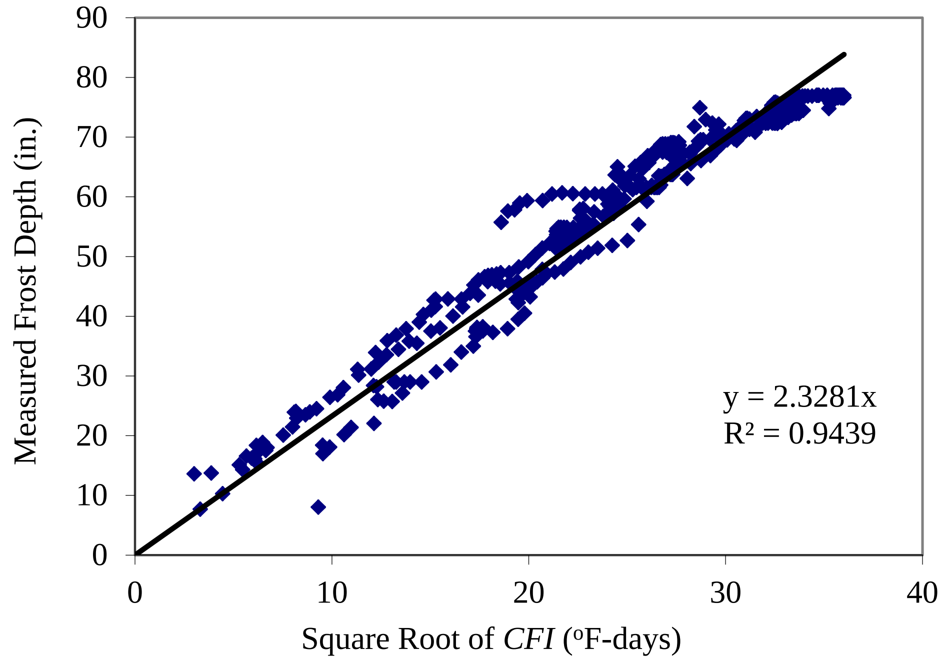

Figure 10 - K-1 2007-2010 Compiled Frost Data (After Calibration)

After the above calibrations were performed, the C_F and C_T values were tabulated (See Table 5) for all test locations. Those site-specific coefficients were then used in Equations 24 to 25 to predict the depths of frost and thaw penetration for the 2010-2011 and 2011-2012 seasons.

In general, the calibrated models tended to reasonably estimate frost and thaw depths with a zero y-intercept, with the exception of the thaw depths at the three Kancamagus Highway sites. The R^2 coefficient was improved significantly at these sites by allowing for a non-zero intercept (Figures 11 and 12). This might suggest that a thermal lag phenomenon existed at those sites. In other words, there appeared to be a time lag between when positive *CTI* values began to accumulate and when subsurface thawing actually began. This may be due, in part, to the fact that ice remains at 32°F during a phase change to liquid even though heat is being added (Miller et al, 2012). The road orientation runs east to west at the test site location with evergreen trees on both sides. Therefore, lack of sunshine may have also contributed to this phenomenon.

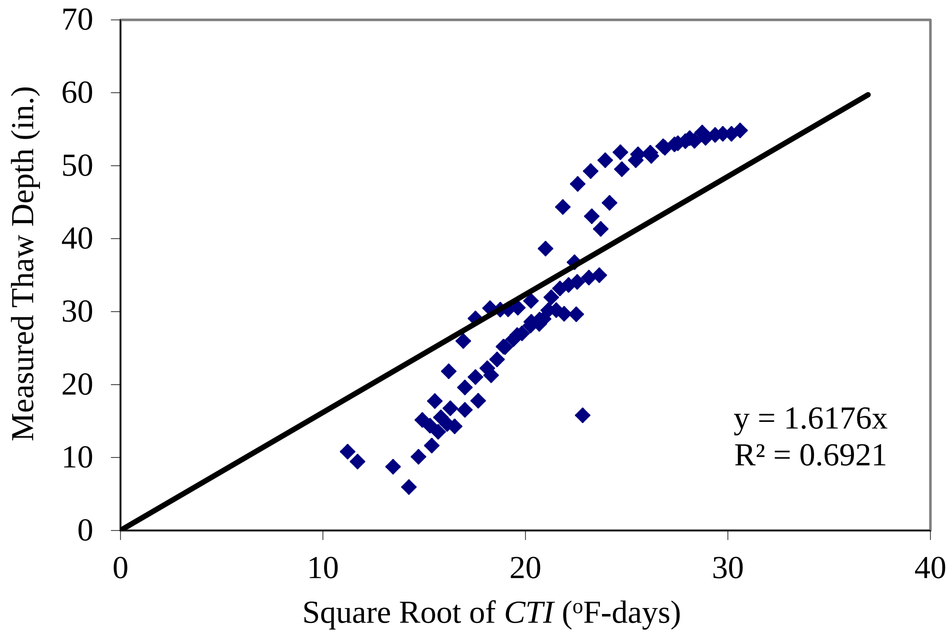

Figure 11 - K-1 Thaw Data with Zero Y-Intercept

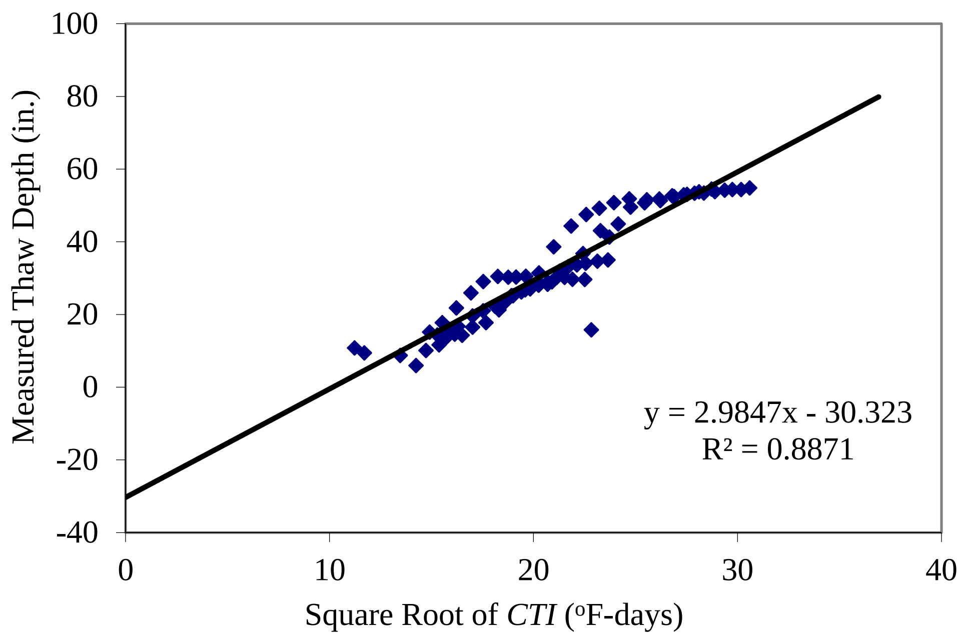

Figure 12 - K-1 Thaw Data with Non Zero Y-Intercept

Therefore, Equations 26 and 27 are the recommended thaw depth equations for the Kancamagus sites. The resulting R^2 coefficients were 0.89 and 0.83, respectively, for those modified regressions. At all other sites, changing the regression analysis from a zero intercept to a non-zero intercept did not significantly affect the R^2 coefficients.

Table 5 - Site-Specific Frost and Thaw Coefficients (with Zero Y-Intercepts)

Site	Years	C_F	R^2	C_T	R^2
K-1	2007-2010	2.33	0.94	1.62	0.69
K-2 & K-3	2007-2010	1.86	0.94	1.73	0.77
LT	2007-2010	1.36	0.79	1.39	0.83
NGR	2007-2010	1.20	0.91	1.33	0.88
RUM	2007-2010	1.31	0.94	1.89	0.79
SLR	2007-2010	1.18	0.76	1.34	0.38
WF	2007-2010	0.90	0.75	1.79	0.82
WS	2007-2010	1.72	0.92	1.55	0.38

For K-1: $TD = 2.98\sqrt{CTI} - 30.32$ [26]

For K-2 & K-3: $TD = 2.29\sqrt{CTI} - 10.55$ [27]

The Warren Flats (WF) site was overlaid with 14 inches of asphalt stabilized base course and 4 inches of new asphalt concrete pavement during the summer of 2010. Subsequently, the model at this site did not accurately predict depths of frost and thaw for 2010-2011 and 2011-2012. Therefore, the WF model was recalibrated solely using the measured data from 2010-2012 since data collected prior to the reconstruction would not truly apply to the new pavement structure. Equations 28 and 29 are the updated WF frost and thaw equations, with R^2 values of 0.72 and 0.67, respectively. Similar to the Kancamagus sites, the thaw depth equation had a significantly better fit with a non-zero y-intercept.

$$FD = 1.49\sqrt{CFI} \qquad [28]$$

$$TD = 3.35\sqrt{CTI} - 9.35 \qquad [29]$$

As noted, the Modified Freeze-Thaw Index Model reasonably predicted frost-thaw profiles recorded during the 2010-2011 and 2011-2012 seasons. An example of measured frost-thaw depths and those predicted from the model at the K-3 site is shown in Figure 13. Plots of measured versus predicted frost-thaw penetration for all nine test sites are provided in Appendix B. Further discussion of the accuracy of this freeze-thaw index model is discussed in Section 5.3.

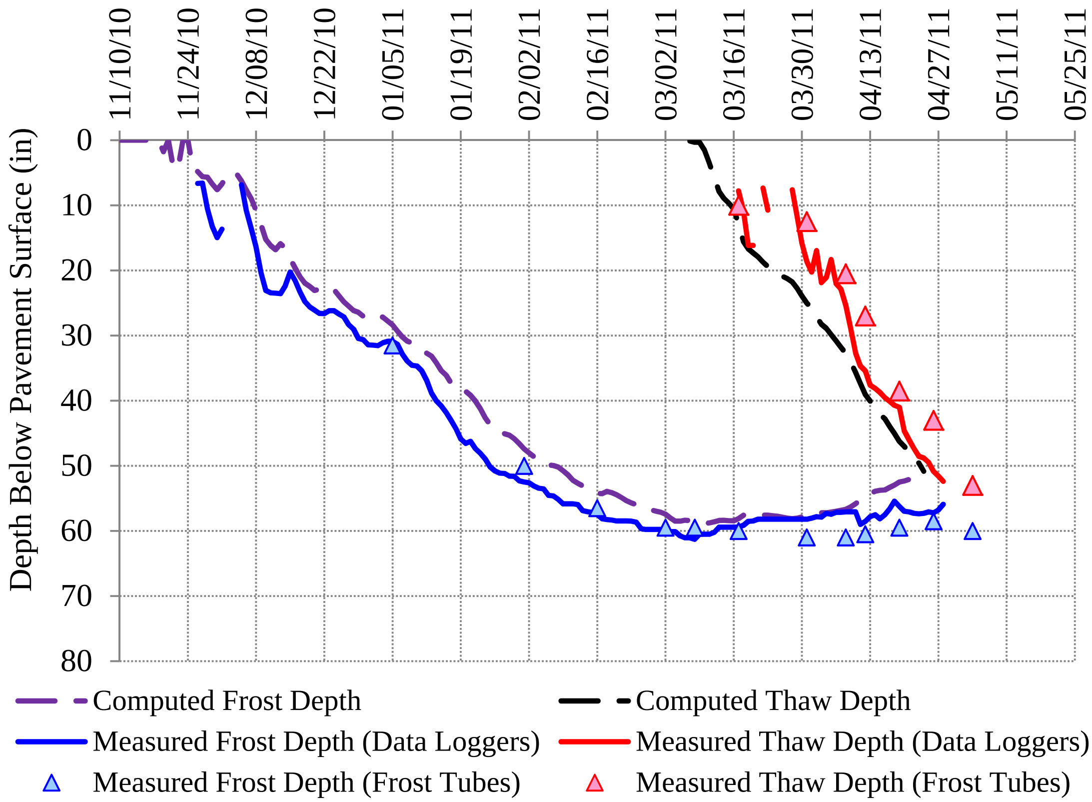

Figure 13 - K-3 2010-2011 Modified Freeze-Thaw Index Model Calculated vs. Measured Frost-Thaw Depths

4.3 Modified Model 158

One of the first steps for investigating this model was researching values of thermal properties for layers in the pavement structure. Recommended values for the properties vary from reference to reference and they are a function of many parameters. The research by Kersten (1949) suggests that factors such as density, temperature, and moisture content have to be considered for determining the thermal properties of a soil. Numerous tests were conducted to see how each of these variables influences the values of thermal conductivity and heat capacity on various soil types. Results of this research suggest that thermal conductivity increases with an increase in density, and decreases with a decrease in density. Heat capacity did not seem to change with an increase or decrease in density. The research also suggested that an increase in moisture content increased thermal conductivity and heat capacity. Similarly, a decrease in moisture content resulted in a decrease in thermal conductivity and heat capacity. Kersten also found that temperature does have an effect on thermal conductivity of soils, but is dependent on moisture content. The thermal conductivity of a soil with low moisture content will decrease as the temperature decreases. The thermal conductivity of a soil with high moisture content will decrease as temperature decreases until the freezing point. Then as temperature continues to decrease below freezing, the thermal conductivity will steadily increase. Each of these variables affects the changes in thermal properties differently for various soil types.

Kersten (1949) developed equations for approximating thermal conductivity and heat capacity based upon variables such as density, moisture content, and temperature. However, since those parameters were not recorded at the test sites, it would be impossible to provide exact values for these thermal properties. By comparing the recommendations provided by Kersten (1949) with recommended thermal properties provided in numerous other references (Orr, D., and Irwin, L., 2006, Andersland, O., and Branko, L., 1994, Joint Departments of the Army and the Air Force USA, 1988 and Cortez et. al, 2000), the following values for thermal properties were selected for use in this research.

Table 6 - Recommended Thermal Properties

Layer	n_f	n_t	k	c	L
	unit-less	unit-less	W/(m°C)	MJ/(m^3 °C)	MJ/m^3
Asphalt	0.8	2.0	1.4	1.8	0.0
Base - Subbase	0.9	2.0	2.0	1.8	50.0
Subgrade	0.9	2.0	2.5	1.8	100.0

Only 7 of the 9 sites were included in the analysis of this model (K-2 and K-3 were excluded). Computing frost-thaw depths during the initial runs of the Modified Model 158 clearly showed that the model was unable to estimate depths of frost and thaw as deep as observed at the Kancamagus sites; thus it was decided to solely use the K-1 site in this analysis. The pavement structure layers were generalized into asphalt, base-subbase, and subgrade. Using the boring logs and grain size distribution data, the thicknesses were determined for these layers at each of the sites. Table 7 lists these thicknesses as well as some basic soil descriptions. The subgrade thickness is not listed because it is theoretically infinite for this analysis. The last two constant variables are t, the seasonal length of time below freezing (days), and v_o, the average annual surface temperature (^oC). Values used for these parameters were 140 days and 12 degrees Celsius, respectively. These two values were obtained from the ModBerg Computer Model (Cortez et al., 2000). This program utilizes a database of temperature data from over a 20-year collection period at numerous locations, several of which are near the NH sites in this study.

Table 7 - Generalized Pavement Layers and Thicknesses

Site	Pavement Thickness (in)	Layer 2	Layer 2 Thickness (in)	Layer 3
K-1	4.0	C-F Sand & Gravel (Fill)	34.0	M-F Sand
LT	9.0	C-F Sand (Fill)	54.0	M-F Silty Sand
NGR	8.4	Silty F. Sand (Fill)	33.6	F Sand (Till)
RUM	3.6	Fill	50.4	Outwash
SLR	9.6	C-F Sand & Gravel (Fill)	26.4	F Sand (Outwash & Till)
WF	9.6	C-F Sand, some Silt	8.4	F Sand (Glacial-Fluvial)
WS	2.4	C-F Sand (Fill)	27.6	C-F Sand & Gravel (Outwash)

Even though the original Model 158 frost depth equation was developed to compute the maximum seasonal depth of frost, modern computerized spreadsheets can allow for estimates of daily frost depths, thus being a potential tool for posting SLRs. See Equations 30 and 31 for the Modified Model 158 equations.

$$X_f = -\frac{d}{2} + \left(\left(\frac{d}{2} \right)^2 + \frac{86{,}400 k I_{sf}}{L + c(v_o + I_{sf} / 2t)} \right) \qquad [30]$$

$$X_t = -\frac{d}{2} + \left(\left(\frac{d}{2} \right)^2 + \frac{86{,}400 k I_{st}}{L + c(v_o + I_{st} / 2t)} \right) \qquad [31]$$

Where:

X_f = depth of frost (m)
X_t = depth of thaw (m)
k = thermal conductivity (W/m^{o}C))
I_{sf} = surface-freezing index (^{o}C-days)
I_{st} = surface-thawing index (^{o}C-days)
L = latent heat (MJ/m^3)
d = thickness of the surface asphalt layer (m)
c = volumetric heat capacity (MJ/m^{3o}C)
v_o = average pavement surface temperature year-round (^{o}C)
t = annual length of time below freezing (days)

The cumulative freezing and thawing indices were computed as per MnDOT and the steps to do so are provided in the previous subsection. The only difference for computing air temperature indices in this model are the units. The *CFI* and *CTI* are converted to degree Celsius days and then multiplied by weighted average values for n_f and n_t based on the depth of frost from the previous day to determine I_{sf} and I_{st}, respectively. Equation 32 shows how to compute the weighted averages of the thermal properties from Table 6, which are used in the I_{sf}, I_{st} , and frost-thaw depth calculations. Calculations for I_{sf} and I_{st} are presented in Equations 33 and 34, respectively

$$\text{Weighted Average, } P = \frac{p_1 d_1 + p_2 d_2 + p_3 d_3}{X_{n-1}} \qquad [32]$$

Where,

P = weighted average value for a thermal property
p_1, p_2, p_3 = thermal 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 (mm). i.e. if the thicknesses of the asphalt and base-subbase layers are 150 and 600 mm, respectively, and the frost depth from the previous day is 1000 mm, then d_1 = 150 mm, d_2 = 600 mm, and d_3 = 250 mm
X_{n-1} = total depth of frost penetration from the previous day (mm)

$$(I_{sf})_n = n_f (CFI_n) \qquad [33]$$

$$(I_{st})_n = n_t (CTI_n) \qquad [34]$$

Where,

n_f = weighted average n_f
n_t = weighted average n_t
$(I_{sf})_n$ = cumulative surface freezing temperature index for day n (^{o}C-days)
$(I_{st})_n$ = cumulative surface thawing temperature index for day n (^{o}C-days)
CFI_n = cumulative freezing index calculated over n days using Equations 21-22 (°C-days)
CTI_n = cumulative thawing index calculated over n days using Equation 23 (°C-days)

The Modified Model 158 estimated fairly reasonable frost-thaw profiles for all the sites (using Equations 30 and 31), with the exception of the Kancamagus site. K-1 tended to be an anomaly and the model computed depths of frost much shallower than what was measured. An example of the Modified Model 158 output is shown in Figure 14.

Plots of measured versus model profiles for all test sites (except for K-2 and K-3) from 2007-2012 are provided in Appendix C. Further discussion of the accuracy of this model is included in Section 5.3.

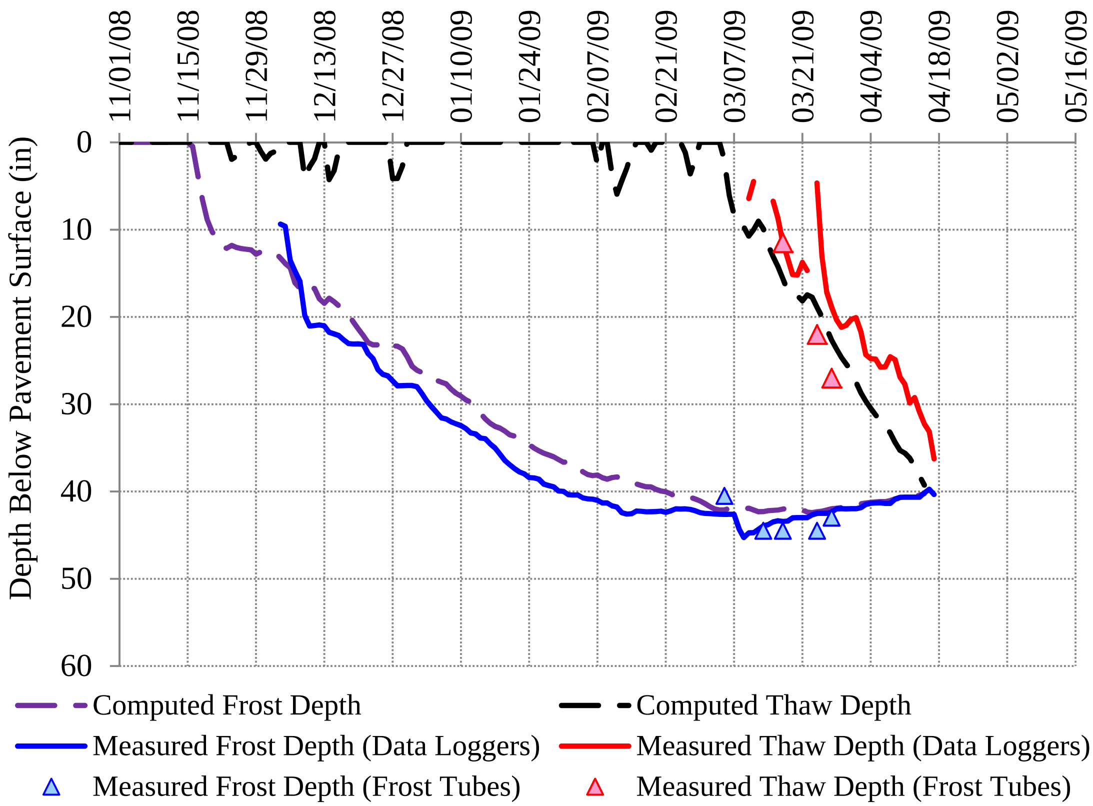

Figure 14 - NGR 2008-2009 Modified Model 158 Calculated vs. Measured Frost-Thaw Depths

4.4 Enhanced Integrated Climatic Model (EICM)

The goal of this model evaluation was to predict frost and thaw depths using a stand-alone version of the EICM and compare those with measured frost-thaw profiles. Unfortunately, the stand-alone EICM version 3.0 failed to run on computers with newer operating systems/newer versions of Windows. As noted in Section 2, the EICM is now integrated as a module in the DarWin ME software (based on the AASHTO Mechanistic-Empirical Pavement Design Guide), however licensing agreements have become extremely costly (about $5,000 per year), so this software was not available for use on this project.

In the early stages of this research project, a research colleague, Richard Berg, was able to run the EICM on an older computer and shared his model predictions for the 2008-2009 season at two of the three Kancamagus sites (K-1 and K-2) and Rumney Shed. The measured frost-thaw profiles for those sites during that season were overlaid on the predicted data; those plots are included in Appendix D, and results of that limited analysis are discussed in Section 5.3.

4.5 SLR Application and Removal Methods Based on "Trigger Thresholds"

For this analysis, SLR application and removal dates computed using methods described in Sections 2.1 and 2.2 were compared with measured frost-thaw profiles. Additionally, since FWD center deflection provides a preliminary assessment of weak zones, the SLR trigger dates were compared with the FWD temperature adjusted center deflection (ACD) plots for the 2008 and 2009 spring thaw periods. An example is shown in Figure 15, and a complete set of plots for all sites is included in Appendix E.

In terms of SLR application dates, the following three methods were directly applied to the NH test sites without any modification:

1. Mahoney et al. (1986) as described in Section 2.1.1
2. MnDOT (2009), as described in Section 2.1.2
3. USFS/Berg et. al (2006), as described in Section 2.1.3

For the first method, it is noted that the nine test sites all fit the "thick" pavement criteria which calls for SLR application dates corresponding to when the cumulative degree days (CDD, computed with Equation 1) surpassed 25 °F-days (Mahoney et al., 1986). A fourth method, discussed in Section 2.1.4 (Bradley et al., 2012), is very similar to the MnDOT method, with the exception of the reference temperature used in the CTI computation. Because the NH test sites used in this study were closer in latitude to Minnesota than to Manitoba, it was decided not to utilize the method suggested in Section 2.1.4. SLR application dates from the three methods analyzed are presented in Tables 8 and 9.

Table 8 - Spring 2008 SLR Application Dates

2007-2008	SLR Application Dates		
Site	USFS/Berg	MnDOT	Mahoney et al
K-1	3/15/08	3/15/08	4/5/08
K-2	3/15/08	3/15/08	4/5/08
K-3	3/15/08	3/15/08	4/5/08
LT	3/7/08	3/7/08	3/19/08
NGR	3/7/08	3/7/08	3/19/08
RUM	3/7/08	3/7/08	3/19/08
SLR	3/7/08	3/7/08	3/19/08
WF	3/7/08	3/7/08	3/19/08
WS	3/7/08	3/7/08	3/19/08

Table 9 - Spring 2009 SLR Application Dates

2008-2009	SLR Application Dates		
Site	USFS/Berg	MnDOT	Mahoney et al.
K-1	3/8/09	3/7/09	3/8/09
K-2	3/8/09	3/7/09	3/8/09
K-3	3/8/09	3/7/09	3/8/09
LT	3/8/09	3/9/09	3/8/09
NGR	3/8/09	3/8/09	3/10/09
RUM	3/8/09	3/8/09	3/9/09
SLR	3/8/09	3/8/09	3/28/09
WF	3/8/09	3/8/09	3/28/09
WS	3/8/09	3/8/09	3/9/09

In terms of SLR removal dates, the investigators on this project initially evaluated the approach suggested by Mahoney et al. (1986) for computing the duration of the SLR. This method suggested that during the 2008 spring thaw, the SLR should remain in place for 37 days at the three Kancamagus Highway sites and 33 days at the remaining six test sites. In 2009, the suggested duration was 38 days at the three Kancamagus Highway sites and between 38 and 40 days at the remaining six test sites. SLR removal dates were also determined according to the following thresholds:

1. Remove SLR: CTI Threshold as per Mahoney et al. (1986)
2. Remove SLR: CTI > 630 °F-days (CTI computed using Equation 23)
3. Remove SLR: 56 day duration after MnDOT Apply SLR date

SLR removal dates from the three methods analyzed are presented in Tables 10 and 11.

Table 10 - Spring 2008 End of Thaw vs. SLR Removal Dates

Spring 2008	End Thaw	SLR Removal Dates		
Site	Hobo Measured	Mahoney et al. (1986)	CTI > 630 ^{o}F-days	56 Day Duration (after MnDOT CTI > 25 ^{o}F-days)
K-1	04/30/08	04/26/08	04/24/08	05/10/08
K-2	04/12/08	04/26/08	04/24/08	05/10/08
K-3	04/25/08	04/26/08	04/24/08	05/10/08
LT	04/09/08	04/19/08	04/21/08	05/02/08
NGR	04/01/08	04/19/08	04/21/08	05/02/08
RUM	03/27/08	04/19/08	04/21/08	05/02/08
SLR	04/01/08	04/19/08	04/21/08	05/02/08
WF	04/03/08	04/19/08	04/21/08	05/02/08
WS	03/21/08	04/19/08	04/21/08	05/02/08

Table 11 - Spring 2009 End of Thaw vs. SLR Removal Dates

Spring 2009	End Thaw	SLR Removal Dates		
Site	Hobo Measured	Mahoney et al. (1986)	CTI > 630 ^{o}F-days	56 Day Duration (after MnDOT CTI > 25 ^{o}F-days)
K-1	04/18/09	4/25/09	04/22/09	05/02/09
K-2	04/17/09	4/25/09	04/22/09	05/02/09
K-3	04/26/09	4/25/09	04/22/09	05/02/09
LT	04/17/09	4/25/09	04/22/09	05/03/09
NGR	04/16/09	4/25/09	04/22/09	05/03/09
RUM	04/11/09	4/23/09	04/21/09	05/03/09
SLR	03/28/09	5/1/09	04/25/09	05/03/09
WF	03/27/09	5/1/09	04/25/09	05/03/09
WS	03/22/09	4/22/09	04/20/09	05/03/09

These SLR removal dates were superimposed on the ACD plots (as shown in Figure 15) and the results qualitatively evaluated in terms of where the dates fell with respect to thaw weakening and recovery (as indicated by the ACD values). Results of the analysis are presented in Section 5.

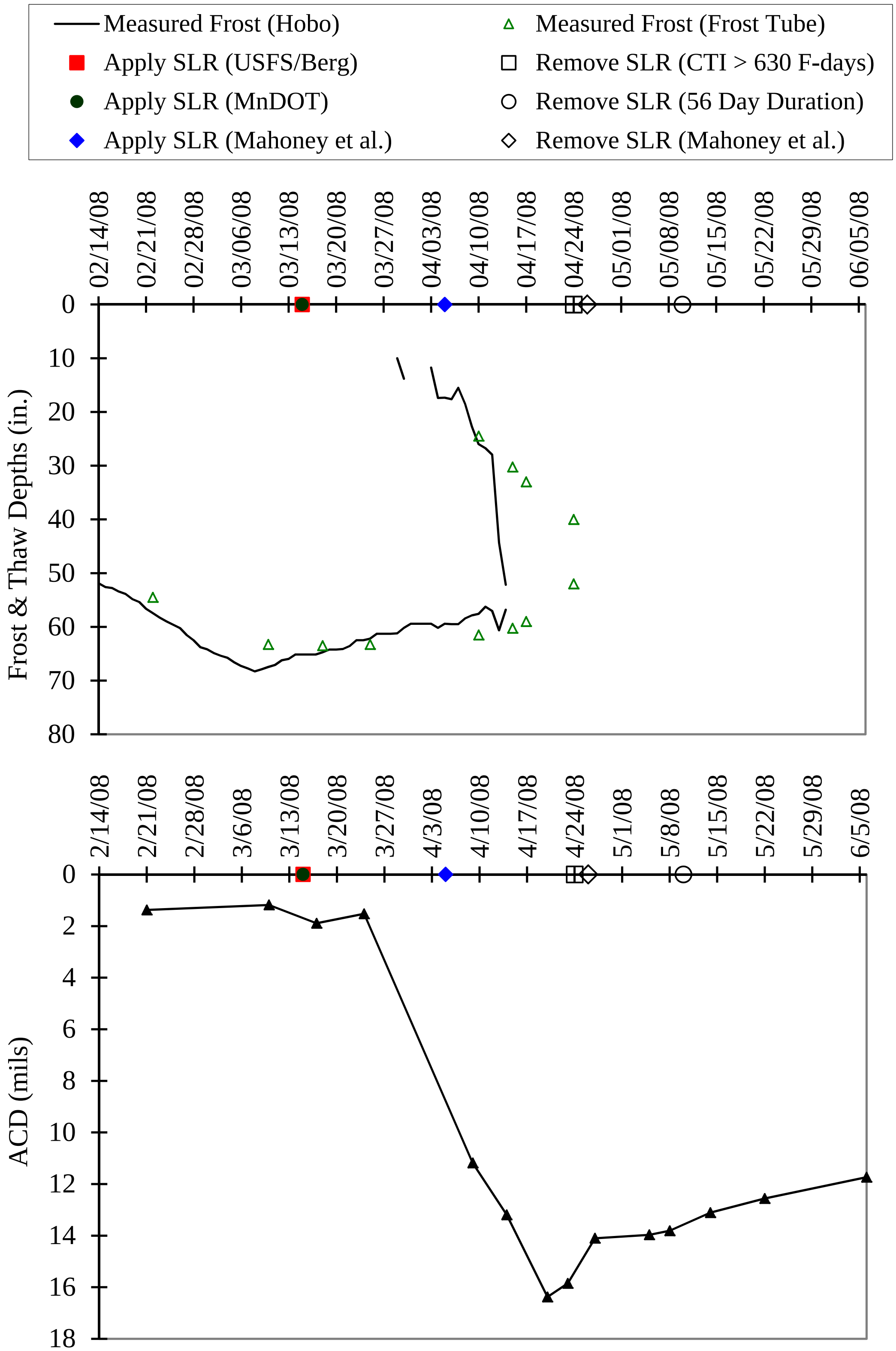

Figure 15 - K-2 Spring 2008 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

5. Discussion

5.1 SLR Application Methods Based on "Trigger Thresholds"

The SLR application dates provided in Tables 8 and 9 were compared to frost-thaw profiles, ACD data, and the dates generated by the other application methods in this study. In terms of SLR application dates, the USFS/Berg method and the MnDOT method yielded very similar results. For 14 of the 18 determinations, both methods yielded exactly the same SLR application date. For 4 of the determinations, the MnDOT method yielded an application date that differed by 1 day from the USFS method.

On the other hand, the method outlined by Mahoney et al. (1986) tended to be much less conservative than both the USFS/Berg and MnDOT methods, yielding SLR application dates up to 21 days later than those estimated by the latter two methods. The largest discrepancies existed during spring 2008 (for both eastern and western NH sites) and at the WF and SLR sites in spring 2009. At all sites other than WF and SLR sites, the Mahoney et al. criteria yielded SLR application dates that were within 2 days of the dates suggested by the USFS and MnDOT methods in spring 2009.

Many studies agree that the SLR application date should be set just prior to the start of the complete thawing event. Research from this study and many others concur that the pavement structure starts to become the most vulnerable to damage during the onset of thaw. Overall, the USFS/Berg and MnDOT methods were fairly accurate in setting SLR application dates yielding an average date of approximately 7 days prior to measured hobo thaw depths (when a thaw depth surpassed the first temperature sensor). Both methods did have SLR application dates 3 weeks prior to measured thawing on two instances. Besides those two occurrences, the USFS/Berg and MnDOT methods produced SLR application dates ranging from 13 days prior to and 4 days after measured thawing. The Mahoney et al. trigger dates tended to be less accurate and less conservative; yielding an average SLR application date approximately 3 days after interpolated HOBO thaw depths were recorded, with a range of 21 days prior to and 21 after measured thawing. All of these figures for the 2007-2008 and 2008-2009 seasons can be found in Appendix E. Since the USFS/Berg and MnDOT methods computed nearly identical start dates, the data points for the two frequently overlap.

With regard to ACD data, the USFS/Berg and MnDOT methods were conservative and consistent in setting SLR application dates prior to significant pavement deflections (with the exception of Rumney Shed 2008 thawing season, where both methods yielded SLR application dates after large pavement deflections were measured). The SLR dates acquired through the Mahoney et al. criteria were consistently late and set after significant pavement deformation was measured in the 2008 thawing season. During Spring 2009, the SLR application dates using the Mahoney et al. procedures varied from setting premature SLR dates to very late dates relative to the ACD data and proved to be unreliable. Since the ACD data is collected weekly and not continuously, the exact difference between when the pavement and its sub layers significantly became weaker from thawing and SLR application dates cannot be quantified.

5.2 SLR Removal Methods Based on "Trigger Thresholds"

SLR end dates calculated using the discussed removal methods are provided in Tables 10 and 11 and compared to ACD data and the end of thaw. Regarding the end of thaw, the SLR removal Date method suggested by Mahoney et al. (1986) yielded removal dates ranging from 4 days prior to and 35 days after the measured end of thaw. The SLR removal Duration method suggested by Mahoney et al. (1986) yielded removal dates ranging from 11 days prior to and 41 days after the measured end of thaw. These two SLR removal dates never yielded identical dates in this study and ranged from 2-16 days apart with the earlier of the two. Over these two seasons, the Mahoney et al., MDIT, and 8 week duration criteria for lifting the SLRs generated end dates on average 14.9, 13.5, and 25.0 days post measured HOBO ends of thaw, respectively.

When examining the ACD plots with respect to the completion of thawing (whether indicated by frost tubes or by Hobo temperature data loggers), in spring of 2008 it generally appeared that significant stiffness recovery had occurred at most sites by the time thawing was complete; however there was also some residual recovery that continued for several days or weeks after the subsoil was completely thawed at many of the sites. It is assumed that any residual increases in stiffness (i.e., decrease in ACD values) was due to dissipation of excess moisture in the sub-soils, which continued to occur gradually after the ice lens melted completely. In spring of 2009, the ACD plots were somewhat more erratic, and at several sites, recovery to a "steady-state" condition was not clearly indicated by the ACD plots. This may be due, in part, to excessive cracking of the asphalt pavement layer that occurred at several of the test sites during the late winter and early spring that year. If the deflection sensors of the FWD apparatus were located near cracks in the asphalt, the resulting FWD test data would be adversely affected. (Miller et al, 2013). Refer to Tables 12 and 13 for site observations between the ACD data and the end of thaw (EOT).

Regarding the SLR removal dates and roadway stiffness, the data was qualitatively analyzed compared to ACD data as shown in Table 14. The status of the pavement structure was categorized into three groups derived from the ACD data; thaw-weakened, during recovery, and significant recovery. "Thaw-weakened" referred to when the adjusted center deflections were at their peak, while "during recovery" related to deflections still progressively decreasing. "Significant recovery" was considered to be when the ACD showed stabilization of the pavement deflections and leveled out. The condition of the roadway corresponding to each of the SLR removal methods are displayed in Table 14 (with the exception of WS since no FWD tests performed at that site). During the 2009 spring thaw, there were two sites (K-2 and LT) where FWD deflections increased and there was no measured recovery, thus only 6 of the 8 sites were included in the analysis for that year. As shown in Figure 16, the Mahoney et al. (1986) and CTI threshold of 630 ^{o}F-days SLR removal methods were considered to fall within the thaw-weakened period, and the 8 week duration method after significant recovery. As displayed in Figure 17, all three SLR removal methods were considered to be within the significant recovery zone, although the 630 ^{o}F-days threshold was somewhat of a borderline case.

Table 12 - Spring 2008 End of Thaw vs. ACD Data

Site	Observations from Spring 2008
K-1	EOT 1 week after peak deflections, few days-week before significant recovery
K-2	EOT 1 week before peak deflections, 2-3 weeks before significant recovery
K-3	EOT on peak deflections, 2-3 weeks before significant recovery
LT	EOT few days-week before peak deflections, 1.5 weeks before significant recovery
NGR	EOT 1.5 weeks before peak deflections, 2-3 weeks before significant recovery
RUM	EOT 2 weeks before peak deflections, 3 weeks before significant recovery
SLR	EOT 1 week before peak deflections, 2-3 weeks before significant recovery
WF	EOT few days before peak deflections, 3 weeks before significant recovery

Table 13 - Spring 2009 End of Thaw vs. ACD Data

Site	Observations from Spring 2009
K-1	EOT 1 week before peak deflections, 2 weeks before significant recovery
K-2	EOT on peak deflections, FWD data does not show recovery
K-3	EOT 3 weeks after peak deflections, on significant recovery
LT	EOT on peak deflections, FWD data does not show recovery
NGR	EOT 3 weeks after peak deflections, on significant recovery
RUM	EOT 1-2 weeks after peak deflections, 1 week before significant recovery
SLR	EOT 3 weeks before peak deflections, 4 weeks before significant recovery
WF	EOT 1-2 weeks after peak deflections, 4 weeks before significant recovery

SLR removal method numbers for Table 14:

1. Remove SLR: CTI Threshold as per Mahoney et al. (1986)
2. Remove SLR: CTI > 630 °F-days (CTI computed using Equation 23)
3. Remove SLR: 56 day duration after MnDOT Apply SLR date

Table 14 - ACD Data vs. SLR Removal Dates

SLR Removal occurred during the following periods:	2008: No. of Occurrences			2009: No. of Occurrences		
	Remove SLR (1)	Remove SLR (2)	Remove SLR (3)	Remove SLR (1)	Remove SLR (2)	Remove SLR (3)
Thaw-weakened	2	2	0	1	2	0
During Recovery	2	1	0	2	1	3
Significant Recovery	4	5	8	3	3	3

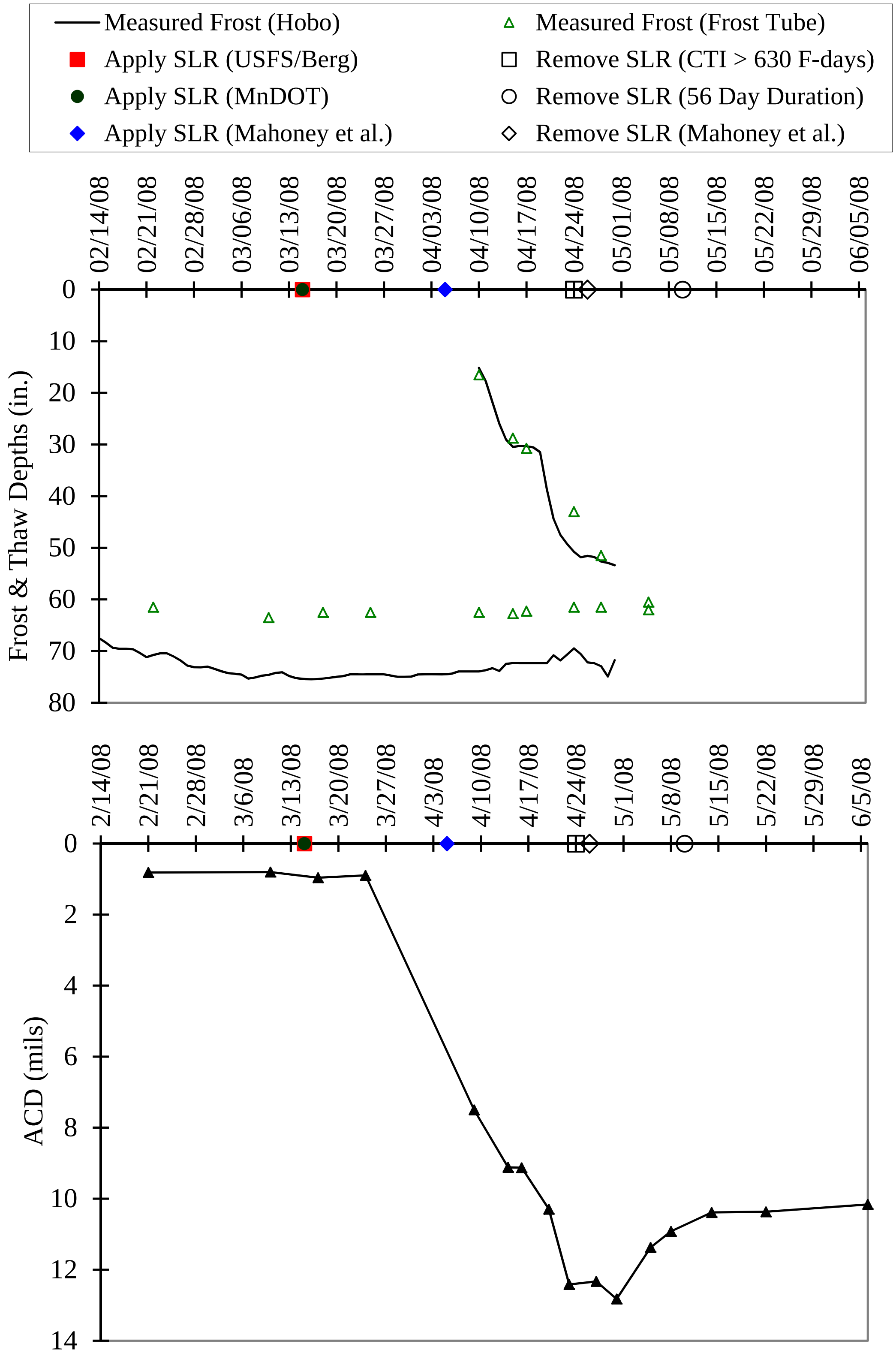

Figure 16 - K-1 Spring 2008 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

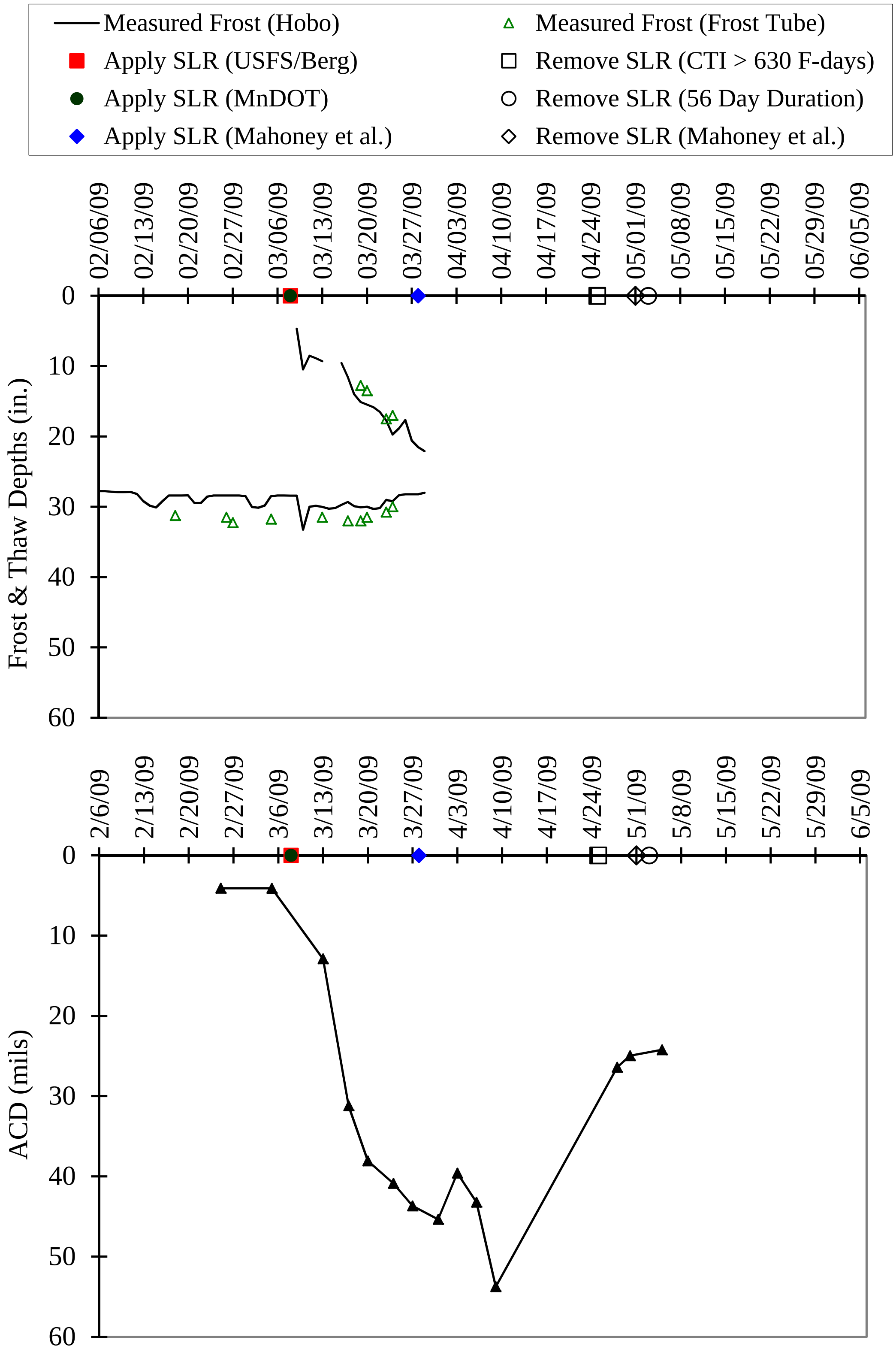

Figure 17 - WF Spring 2009 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

The 8 week duration tended to be the most conservative of the methods yielding SLR removal dates when there was significant measured recovery on 11 out of the 14 instances, with only 3 occurrences while the pavement stiffness was still recovering. The Mahoney et al. criteria generated removal dates when the ACD data had shown significant recovery on only half of the occurrences with 4 and 3 occurrences during recovery and the thaw weakened state, respectively. The criteria of removing the load restrictions when the *CTI* surpassed 630 ^{o}F-days yielded dates on 8 out of the 14 instances after significant recovery with 2 and 4 occurrences during recovery and the thaw weakened state, respectively. An effort to identify trends between *CTI* and the stabilization of ACD data, similar to that of MDIT, and discover criteria to lift the SLR prior to the 8 week duration was unsuccessful. When looking at approximate timings for when the pavement stiffness showed leveling out to summer levels, *CTI* values ranged from 400 to 1300 ^{o}F-days and a threshold could not be identified for suggesting when to lift the load restrictions. Similarly, looking at thawing patterns compared to when the pavement strength showed significant recovery, no trends could be identified. The range of end of thaw occurred on significant recovery to 4 weeks prior to significant recovery.

Results of a MnDOT study in 2000 investigating improved guidelines for posting spring load restrictions (Ovik et al, 2000) concluded that eight weeks is required for the pavement base and subgrade layers to regain sufficient strength to support heavy truck loads, thus the SLR period should be fixed at 8 weeks, and that additional research would be required to modify this duration period. The results of this research tend to agree with the findings of MnDOT. See Appendix E for all of the SLR trigger dates versus measured frost-thaw depths and ACD data for the 2007-2008 and 2008-2009 seasons.

5.3 Frost-Thaw Prediction Models

All three prediction models in this study were fairly successful in estimating depths of frost and thaw penetration compared to the measured data. Originally, the models were evaluated using four “points of interest” to determine their accuracy. These “points of interest” were: start of freezing, seasonal maximum frost depth, start of thawing, and end of thawing. The differences or similarities between the predicted and measured data for these “points of interest” can validate the accuracy of the model. It was later determined that 3 of these 4 points of interest would not have been appropriate for evaluating the models’ accuracy for several reasons. There were discrepancies between the dates for measured versus modeled onset of freezing and thawing because frost and thaw penetration would have to surpass the depth of the temperature sensor closest to the surface (approximately 6”) before a measured frost or thaw depth could be reported. The measured start of freezing and thawing dates constantly occurred later than the calculated dates for this reason and tabulating the differences between them would not be a proper tool to evaluate the models. As shown in Figure 18, there is a large discrepancy between the measured and modeled starts of thawing, but the model reasonably tracks the frost-thaw patterns.

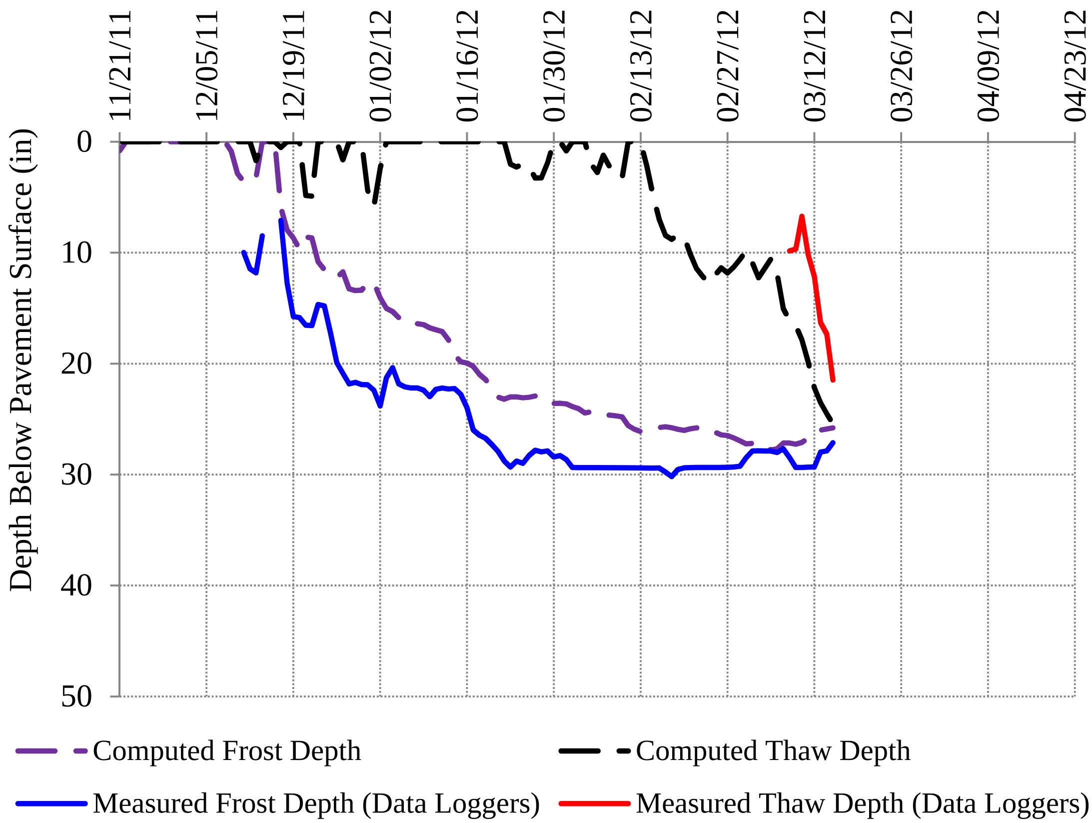

Figure 18 - SLR 2011-2012 Modified Model 158 vs. Measured Frost-Thaw Depths

The other “point of interest” intended to evaluate the accuracy of the models was the end of thaw. There were frequent discrepancies between the measured ends of thaw for suggested by the temperature data loggers and frost tubes, which made it difficult and impossible at times to judge the accuracy of the modeled output. Refer to Figure 19 as an example of this phenomenon, and how tabulating the differences between the HOBO interpolated end of thaw to the modeled end of thaw would not be able to sufficiently evaluate the accuracy of the model regarding this parameter.

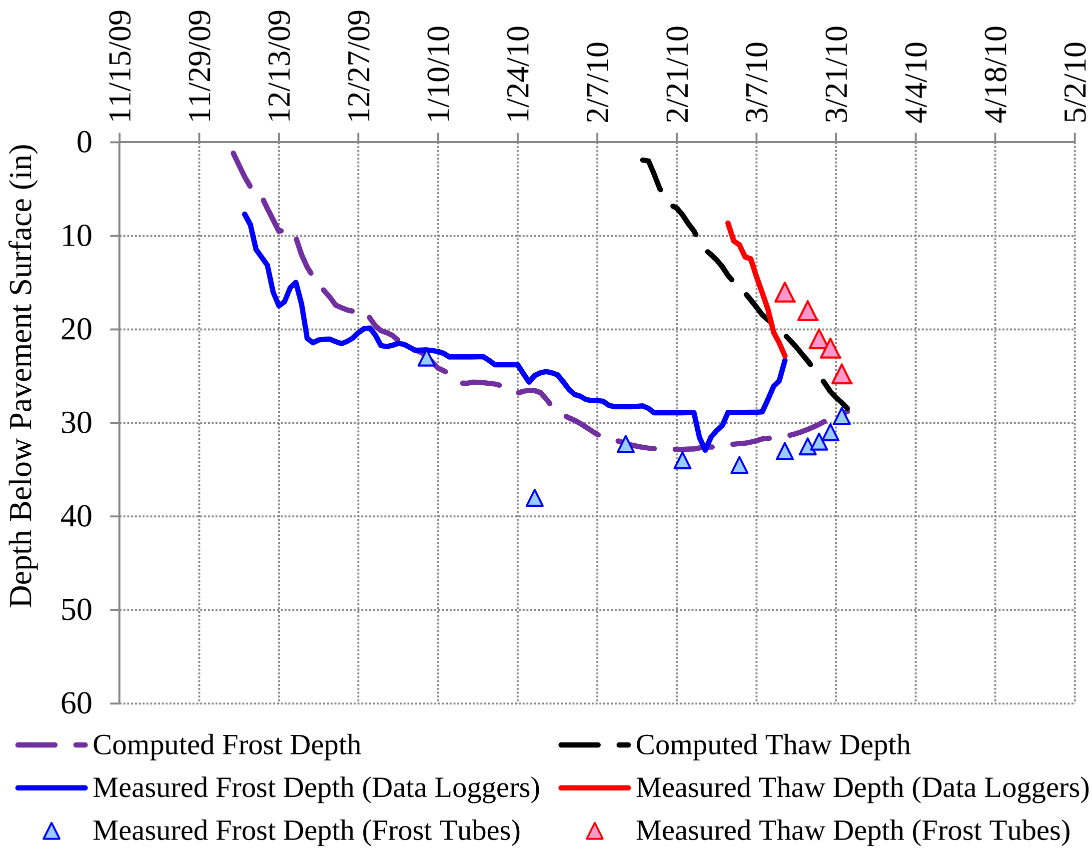

Figure 19 - NGR 2009-2010 Modified Freeze-Thaw Index Model

However, the measured and modeled seasonal maximum frost depth was still a "point of interest" that could assist in the validation of the models' accuracy. The measured and modeled values of maximum frost depth s are provided in Tables 15 through 19. The seasonal average differences are provided as well. The models correspond to these numerical formats in the following tables.

1. Modified Freeze-Thaw Index Model
2. Modified Model 158
3. EICM

Some of the mean differences between modeled and measured depths of frost could have been skewed for several reasons. For example, large downward frost depth spikes were observed due to large interpolation depths during every season at Rumney Shed. At the K-1 site there were two instances when the measured frost depths surpassed the lowest temperature sensor so the modeled maximum frost depth values were not fairly evaluated (2008-2009 and 2010-2011). The largest deviation of the model from the measured max frost depth was at Wentworth Shed 2008-2009. This was one of the coldest of the seasons in this study and max frost depths measured at all sites were deeper than average, with the modeled data following this trend as well. The recorded max depth from the temperature sensors at this site was 30.7 inches, while the frost tubes measured a maximum of 60.75 inches of frost penetration which more agree with the modeled values. This season's data was omitted from the calibration of the WS Freeze-Thaw Index Model because of the unusual shallow HOBO interpolated frost depths.

Regarding the Modified Freeze-Thaw Index Model and seasonal maximum frost depths, this model was successful in estimating values close to that were measured. During the 2007-2008 season, the model estimated maximum frost penetration 9.9 inches shallower to 5.3 inches deeper than the measured max depths, with a mean difference of 1.8 inches shallower than measured values. During the 2008-2009 season, the model estimated max frost depths 7.9 inches shallower to 6.9 inches deeper than the measured max depths (with WS 2008-2009 data omitted), with a mean difference of 0.7 inches deeper than measured values. During the 2009-2010 season, the model computed max frost penetration 5.5 inches shallower to 1.3 inches deeper than the measured max depths, with a mean difference of 1.9 inches shallower than measured values. Including the recalibrated WF model, the modeled max frost depths were on average 4.0 and 4.5 inches shallower than measured values for the 2010-2011 and 2011-2012 seasons, respectively.

Excluding the anomaly K-1 site from the evaluation, the Modified Model 158 reasonably calculated max frost depth values close to that were measured. During the 2007-2008 season, the model on average estimated maximum frost penetration 15.6 inches shallower to 1.3 inches deeper than the measured max depths, with a mean difference of 5.6 inches shallower than measured values. During the 2008-2009 season (omitting WS), the model estimated max frost depths14.0 inches shallower to 9.9 inches deeper than the measured max depths, with a mean difference of 2.8 inches deeper than measured values. During the 2009-2010 season, the model computed max frost penetration 11.1 inches shallower to 5.4 inches deeper than the measured max depths, with a mean difference of 0.1 inches shallower than measured values. Including the recalibrated WF model, the modeled max frost depths were on average 8.2 and 7.0 inches shallower than measured values for the 2010-2011 and 2011-2012 seasons, respectively.

The EICM calculated maximum depths of frost quite close to that measured in the field, with the exception at the K-2 site. Because of the limited data obtained through the EICM, definitive conclusions regarding the accuracy of this model cannot be made.

Table 15 - 2007-2008 Seasonal Maximum Frost Depths

Site	K-1	K-2	K-3	LT	NGR	RUM	SLR	WF	WS	Avg (+/-)
Measured	75.4	68.3	57.8	38.1	33.9	47.3	37.4	30.7	51.8	
1	79.1	63.1	63.1	38.9	34.3	37.4	33.7	25.7	49.1	
(+/-)	3.7	-5.2	5.3	0.8	0.4	-9.9	-3.7	-5.0	-2.7	-1.8
2	39.5	-	-	35.7	33.7	32.7	35.6	32.0	36.2	
(+/-)	-35.9	-	-	-2.4	-0.2	-14.6	-1.8	1.3	-15.6	-5.6

Table 16 - 2008-2009 Seasonal Maximum Frost Depths

Site	K-1	K-2	K-3	LT	NGR	RUM	SLR	WF	WS	Avg (+/-)
Measured	77.0	74.4	62.5	45.3	45.3	54.6	42.2	33.3	30.7	
1	83.9	67.0	67.0	49.5	44.3	46.7	46.3	35.2	61.9	
(+/-)	6.9	-7.4	4.5	4.2	-1.0	-7.9	4.1	1.9	31.2	0.7
2	41.8	-	-	45.5	42.4	40.6	46.3	43.2	44.2	
(+/-)	-35.2	-	-	0.2	-2.9	-14.0	4.1	9.9	13.5	-0.5
3	80.9	52.6	-	-	-	57.1	-	-	-	
(+/-)	3.9	-21.8	-	-	-	2.5	-	-	-	-5.1

Table 17 - 2009-2010 Seasonal Maximum Frost Depths

Site	K-1	K-2	K-3	LT	NGR	RUM	SLR	WF	WS	Avg (+/-)
Measured	69.2	54.4	53.9	42.4	32.9	41.4	35.4	27.7	46.4	
1	64.6	51.3	51.6	40.0	32.8	35.9	36.4	26.7	47.7	
(+/-)	-4.6	-3.1	-2.3	-2.4	-0.1	-5.5	1.0	-1.0	1.3	-1.9
2	32.7	-	-	36.8	31.0	31.4	37.9	33.1	35.3	
(+/-)	-36.5	-	-	-5.6	-1.9	-10.0	2.5	5.4	-11.1	-3.5

Table 18 - 2010-2011 Seasonal Maximum Frost Depths

Site	K-1	K-2	K-3	LT	NGR	RUM	SLR	WF	WS	Avg (+/-)
Measured	78.0	74.6	61.3	43.8	39.7	50.2	39.6	38.9	62.0	
1	73.7	58.8	58.8	42.9	37.8	41.3	37.2	28.4	54.2	
(+/-)	-4.3	-15.8	-2.5	-0.9	-1.9	-8.9	-2.4	-10.5	-7.8	-6.1
2	37.0	-	-	39.4	36.7	36.0	38.6	35.1	39.4	
(+/-)	-41.0	-	-	-4.4	-3.0	-14.2	-1.0	-3.8	-22.6	-8.2

Table 19 - 2011-2012 Seasonal Maximum Frost Depths

Site	K-1	K-2	K-3	LT	NGR	RUM	SLR	WF	WS	Avg (+/-)
Measured	61.4	46.8	49.0	39.5	25.0	35.6	30.2	35.2	40.3	
1	52.9	42.2	42.2	30.5	26.9	29.3	26.4	20.2	38.5	
(+/-)	-8.5	-4.6	-6.8	-9.0	1.9	-6.3	-3.8	-15.0	-1.8	-6.0
2	27.2	-	-	27.9	27.4	25.8	27.8	25.6	29.5	
(+/-)	-34.2	-	-	-11.6	2.4	-9.8	-2.4	-9.6	-10.8	-7.0

To further evaluate the accuracy of the models, they were qualitatively examined based on how well they individually tracked frost and thaw profiles. For each site and year, the models were given rankings from 1-5 on how successful they were in matching the measured frost-thaw depths. A score of 5 represents a very accurate modeled frost and thaw penetration, while a score of 1 represents very poor modeled frost and thaw penetration. These scores are shown in Table 20 with 1, 2, and 3 referring to the Modified Freeze-Thaw Index Model, Modified Model 158, and EICM, respectively. For each site and season, the models have two scores. The left number corresponds to the qualitative score for how well the model compared to the measured frost depth, while the right number corresponds to the thaw depth score. Since the Modified Model 158 was unable to estimate depths of frost penetration as deep as observed at the K-1 site, the qualitative evaluation of the model at that site was excluded.

Table 20 - Qualitative Frost-Thaw Prediction Model Scoring

2007-2008	1		2		2008-2009	1		2		3	
K-1	5	5	-	-	K-1	5	5	-	-	5	4
K-2	5	5	-	-	K-2	5	5	-	-	3	5
K-3	5	5	-	-	K-3	5	5	-	-	-	-
LT	5	4	4	5	LT	4	5	5	5	-	-
NGR	4	4	5	5	NGR	5	5	5	5	-	-
RUM	5	5	4	4	RUM	5	5	4	5	4	3
SLR	5	4	5	4	SLR	3	2	3	2	-	-
WF	5	4	4	4	WF	4	5	3	3	-	-
WS	4	1	2	2	WS	2	2	3	2	-	-

2009-2010	1		2		2010-2011	1		2		2011-2012	1		2	
K-1	4	5	-	-	K-1	5	5	-	-	K-1	3	5	-	-
K-2	5	5	-	-	K-2	4	5	-	-	K-2	5	5	-	-
K-3	5	5	-	-	K-3	5	5	-	-	K-3	3	4	-	-
LT	4	2	5	4	LT	5	4	5	4	LT	3	5	3	5
NGR	5	4	5	5	NGR	5	4	5	4	NGR	5	5	5	5
RUM	5	5	4	5	RUM	5	4	4	4	RUM	5	5	4	5
SLR	4	3	4	4	SLR	5	4	5	4	SLR	4	5	5	5
WF	5	4	4	3	WF	4	3	4	3	WF	3	3	3	3
WS	2	1	3	3	WS	3	2	2	3	WS	2	3	3	3

As seen in Table 20, all 3 models scored fairly well on the visual evaluation. Since data from the EICM was very limited in this study, it is hard to draw conclusions regarding the model's performance. The Modified Freeze-Thaw Index Model (1) and Modified Model 158 (2) matched the measured data better at some sites than others and better during some years than others. For example, both models scored mostly scored 4s and 5s at the Stinson Lake Road site (SLR) with the exception during the 2008-2009 season when the models failed to track the measured rapid bottom-up and top-down thawing. The models frequently failed to estimate these unusual rapid thawing patterns, which were prevalent at the Wentworth Shed (WS) site, and were responsible for the majority of the lower scores.

For all 5 seasons, the Modified Freeze-Thaw Index Model received average scores for tracking frost and thaw depths of 4.6 and 4.9, respectively, for all of the Kancamagus Highway sites (K-1, K-2, and K-3). Since the Kancamagus sites were omitted from the Modified Model 158 evaluation, their scores were also neglected from the Modified Freeze-Thaw Index Model seasonal average scores used for comparison in Table 20. As can be seen in the Table 21, both models received very similar average scores in the high 3 to 4 range The Modified Freeze-Thaw Index Model tended to track the frost depth a little better than the Modified Model 158, while the Modified Model 158 tended to track the thaw depth slightly better than the Modified Freeze-Thaw Index Model.

Table 21 - Seasonal Average Scores from Qualitative Model Evaluation

	Modified Freeze-Thaw Index Model		Modified Model 158	
Season	Frost Depth	Thaw Depth	Frost Depth	Thaw Depth
2007-2008	4.7	3.7	4.0	4.0
2008-2009	3.8	4.0	3.8	3.7
2009-2010	4.2	3.2	4.2	4.2
2010-2011	4.5	3.5	4.2	3.7
2011-2012	3.7	4.3	3.8	4.3
Total	4.2	3.7	4.0	3.9

Despite the fact that both the Modified Freeze-Thaw Index Model and Modified Model 158 were successful in estimating frost-thaw depths; they each have their own setbacks. The Modified Model 158 struggled to calculate deeper frost penetration as seen at the Kancamagus Highway sites. In order to achieve the most accurate predictions of frost and thaw depths using the Modified Freeze-Thaw Index Model, several years of historical subsurface and air temperature data would be needed to determine the optimal frost and thaw coefficients required for any predictions. Regardless of these setbacks, the Modified Freeze-Thaw Index Model and Modified Model 158 show promise to be helpful tools for transportation agencies to estimate frost-thaw penetration to assist in their judgment for scheduling spring load restrictions.

After the model evaluation, the next step in the research was to identify trends and recommend values of frost and thaw coefficients for use with the Modified Freeze-Thaw Index Model. The frost and thaw coefficients were determined using three years of historical data, and in order to be implemented at locations without historical subsurface data, it would be rather difficult to create an accurate a frost-thaw prediction model. Other studies or transportation agencies looking to approximate depths of frost and thaw, but that do not have access to historic subsurface data to regress and determine site specific values for C_F and C_T, could select values for these coefficients based on parameters such as ground water table depths or predominant soil types. Analysis of some site parameters versus frost and thaw coefficients, as shown in Table 22, were used to observe any trends.

Frost penetration tended to be deepest (and C_F values larger) at sites with coarser soils and deeper groundwater tables (K-1, K-2, K-3, RUM and WS, although soils were mixed at RUM and WS). Frost penetration tended to be shallowest (and C_F values smaller) at the sites with more fine sands and silts and shallow water tables (SLR & WF). The findings of many other studies agree that frost penetration tends to be deeper at sites with finer soils (and shallower for coarser soils), which was the opposite of what was observed in this study. The deepest frost penetration (and higher C_F values) observed at the coarser Kancamagus Highway sites had the most amount of shade from tree coverage. The large amount shade may have contributed to the deeper frost penetration at those sites, thus yielding results conflicting with that of other similar studies. The WF site was “wide open” and tended to get much more exposure to sunlight than most of the other test sites, which may also help to explain the unusually low C_F value (and rather high C_T value). NGR and LT were sort of “intermediate” cases. NGR tended to have relatively shallow frost depths (and a low C_F value) despite a deep groundwater table; however, soils at that site contained a high percentage of fine sand and silt. LT had intermediate frost depths (and an intermediate C_F value). Although the water table depth there was generally fairly shallow, the site soils included a well-graded mix of gravel to silt-sized material (Miller et al, 2012).

Table 22 - Site Parameters used to Identify Trends for C_F and C_T

Site	C_F	C_T	Avg GWT (in)	GWT Descriptor	Elevation (ft)	Soil Descriptor	Avg Max Frost Depth (in)
K-1	2.33	1.62	76.70	Deep	1,243	Coarse	74.5
K-2	1.86	1.73	85.64	Deep	1,243	Coarse	67.9
K-3	1.86	1.73	94.58	Deep	1,243	Coarse	58.9
RUM	1.31	1.89	115.13	Deep	525	F-C	51.1
WS	1.72	1.55	109.25	Deep	862	F-C	47.7
LT	1.36	1.43	33.26	Shallow	1,371	F-C	42.4
NGR	1.2	1.33	97.40	Deep	1,499	Fine	38.0
SLR	1.18	1.34	17.94	Shallow	1,416	Fine	38.7
WF	0.9	1.79	38.98	Shallow	791	Fine	32.7

In general, C_F values ranged from 1.2 to 2.3, with the exception of the WF site, which had a C_F value of 0.9. The analyses in this study suggest that lower C_F values should be used at sites with shallow groundwater tables and/or subsoils with a high percentage of fine sands and silts. For sites with coarser soils and deeper water tables, C_F values nearer to the high end of that range were observed. C_T values ranged from 1.3 to 1.9, but no distinct trends could be identified. Analysis of thaw depth data at the three Kancamagus Highway sites and the reconstructed Warren Flats site suggested that a thermal lag phenomenon may exist at those sites (i.e., there appeared to be a time lag between when positive CTI values began to accumulate and when subsurface thawing actually began). Even though the thaw depth equation with a non-zero y-intercept tended to provide more accurate depths of thaw, an average C_T value computed from the 9 NH test sites of 1.60 should help sufficiently estimate depths of thaw. Coincidentally, in a Maine DOT study, a value of 1.62 was used for both C_F and C_T. The Maine DOT concluded that the frost depths calculated by Equations 24 and 25 (and $C_F = C_T = 1.62$) correlated very well with measured frost depths at three of their four test sites (Marquis, 2008).

6. Conclusions and Recommendations

This report describes three different models for predicting frost-thaw penetration and several methods for posting SLRs based upon weather-based indices. Ultimately, the recommendations from this research will be incorporated into a decision support system (DSS) which is currently under development with funding provided by the U.S. Department of Transportation Research and Innovative Technology Administration (RITA). The UMass Dartmouth "RITA Research team," is working in collaboration with the New Hampshire Department of Transportation, Maine Department of Transportation and USDA Forest Service to develop a web-based system to monitor roadway conditions in real time during the spring thaw period with the use of commercial remote sensing and spatial information (CRS&SI) technology. In addition to real time monitoring of subsurface temperature and moisture regimes, the system will incorporate one or more of the protocols/models evaluated in this study for use in applying and removing SLRs in northern New England.

Based upon the analyses conducted, it is recommended that the State DOTs consider use of the MnDOT method (CTI = 25 ^{o}F-day criterion) for SLR application. The USFS/Berg method is equally suitable (and tends to yield almost identical SLR start dates as the MnDOT method); however it is somewhat more cumbersome to initially set up and write computer code for. Both methods are slightly conservative, applying the SLR just slightly before subsurface thawing and pavement weakening was observed at the test sites. In terms of SLR removal, the analyses conducted for this project suggest that a period of 8 weeks duration (56 days), as suggested by both MnDOT (2009) and Bradley et al. (2012), appears to provide a reasonably conservative "outer limit" guideline for SLR removal. It is likely that, in many instances, the SLRs could safely be removed in less than 8 weeks; however additional mechanistic study is recommended for the future in order to establish a less conservative criterion in terms of some easily computed parameter (such as a CTI threshold).

Regarding frost-thaw prediction models, both the Modified Freeze-Thaw Index Model and the Modified Model 158 show much promise. Frost-thaw patterns were reasonably estimated at most of the nine test sites using the Modified Freeze-Thaw Index Model, although the model tended to be too conservative in estimating end-of-thaw dates, with estimated end-of-thaw dates falling after measured dates in many instances. Suggested ranges of values for frost and thaw coefficients are provided in this report; however it is important to keep in mind that the Freeze-Thaw Index Model works best when calibrated on a site-specific basis. Such calibration requires a fair amount of time and money to install subsurface temperature sensors and to conduct the regression analyses. With the exception of the Kancamagus Highway site (K-1), the Modified Model 158 reasonably predicted depths of frost and thaw at the test locations, but (like the Modified Freeze-Thaw Index Model) often estimated an end of thaw later than measured. On average, the Modified Model 158 estimated end of thaw roughly 2 days closer to measured end of thaw than found using the Modified Freeze-Thaw Index Model. An advantage of the Modified Model 158 is that it does not require site specific calibration; however pavement layer thicknesses must be determined, and values for thermal properties of those layers must be assumed. An advantage of both the Modified Freeze-Thaw Index Model and the Modified Model 158 is that the only atmospheric weather data required as input for the models is air temperature, which is easily obtained from various sources over the internet.

The EICM, on the other hand, requires much more extensive atmospheric weather data as input (as described in Section 2.3.3). The EICM analyses conducted by Dr. Berg during the one year study at 3 test sites managed to reasonably estimate frost-thaw penetration, but due to the excessive cost of the software (and thus the limited data obtained), no legitimate conclusions could be drawn from its evaluation. If this research were to be expanded upon in the future, and sufficient funds were available to purchase the software license, a more detailed analyses using measured data from all test sites and seasons would be recommended.

In summary, readily available measured and forecasted daily air temperature data can be used to effectively estimate and predict near future frost-thaw penetration and SLR timing dates with the methods described herein. The MnDOT method appears to provide a very reliable trigger for SLR application. While a clearly defined criterion for SLR removal has not currently been identified for northern New England, it is hoped that future research, along with more widespread real-time monitoring as initiated under the RITA project, will be helpful in this regard.

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Appendix A - Test Site Grain Size Distribution Data

Table A1 - Test Site Abbreviations and Coordinates

Site Names and Abbreviations		Elevation (ft)	Latitude	Longitude
K-1	Kancamagus Highway/Rt. 112	1,243	N43.99	W71.33
K-2	Kancamagus Highway/Rt. 112	1,243	N43.99	W71.33
K-3	Kancamagus Highway/Rt. 112	1,243	N43.99	W71.33
LT	Lake Tarleton	1,371	N43.98	W71.97
NGR	North Groton Road	1,499	N43.75	W71.86
RUM	Rumney Shed	525	N43.79	W71.83
SLR	Stinson Lake Road	1,416	N43.88	W71.80
WF	Warren Flats/Rt. 25 C	791	N43.93	W71.91
WS	Wentworth Shed	862	N43.89	W71.90

Table A2 - GSD Data (1)

Site	Sample #	Depth (ft)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	% Passing 0.02 mm	% Passing 0.002 mm
Kanc K-1	1	.55-2.5	20	17	12	29	17	4	2	1
	2	2.5-4.5	9	13	10	34	28	6	3	1
	3	4.5-6.5	0	16	10	33	36	5	1	1
	4	6.5-8.5	17	22	11	28	15	7	3	1
	5	8.5-10.5	13	20	18	30	15	5	2	0
Kanc K-3	1	1-3	0	24	16	32	21	8	3	1
	2	3-5	0	10	13	34	28	16	6	2
	3	5-7	0	5	18	51	20	7	3	0
	4	7-9	0	7	9	41	39	3	1	0
	5	9-11	0	0	1	28	56	15	4	1
NGR	0a	.5	28	31	7	15	16	4	-	-
	0b	.5	33	3	4	19	35	6	-	-
	1	2.5-4.5	0	12	9	23	42	15	5	2
	2	4.5-6.5	0	6	9	20	53	12	5	2
	3	6.5-8.5	0	6	7	21	56	10	5	1
	4	8.5-10.5	0	12	9	21	42	15	7	1
SLR	1	.8-2.8	23	13	11	23	23	8	2	0
	2	3-5	0	6	5	23	55	11	4	0
	3	5-7	0	6	4	15	46	30	10	2
	4	7-9	0	14	6	16	40	24	8	1
	5	9-9.9	0	4	5	16	46	28	10	1
LT	1	1-3	15	13	12	26	24	10	9	3
	2	3-5	0	4	13	43	31	8	-	-
	3	5-7	0	22	13	20	29	15	9	5
	4	7-9	0	14	18	23	24	20	13	6
	5	9-11	0	22	14	18	25	21	10	5

(cont. on next page)

Table A2 (cont.)

Site	Sample #	Depth (ft)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	% Passing 0.02 mm	% Passing 0.002 mm
WF	1	1-3	0	14	9	16	28	34	12	3
	2	3-5	0	1	6	14	60	18	3	1
	3	5-7	0	1	4	19	63	14	3	1
	4	7-9	0	0	0	3	52	44	-	-
	5	9-11	0	0	1	11	81	7	1	1
RUM	1	0.3-2.3	7	14	9	21	35	14	9	3
	2	2.5-4.5	0	1	4	21	55	19	15	5
	3	4.5-6.5	39	17	7	11	20	6	4	2
	4	6.5-8.5	33	14	9	12	23	8	4	3
	5	8.5-10.5	0	0	0	1	61	38	9	6
WS	1	.3-1	0	29	11	26	32	2	5	3
	2	2-4	16	34	11	19	15	6	5	3
	3	6-8	24	22	7	18	20	9	5	3
	4	8-10	21	6	4	15	45	8	5	3

Table A3 - GSD Data (2)

Site	Sample #	Depth (ft)	D_{10}	D_{30}	D_{60}	C_u	C_c	USCS	AASHTO
Kanc K-1	1	.55-2.5	0.17	0.66	3.9	22.94	0.66	SP	A-1-B/A-2
	2	2.5-4.5	0.12	0.35	1.40	11.67	0.73	SP-SM	A-1-B/A-2
	3	4.5-6.5	0.11	0.28	0.89	8.09	0.80	SP	A-1-B/A-2
	4	6.5-8.5	0.13	0.70	4.20	32.31	0.90	SP-SM	A-1-B/A-2
	5	8.5-10.5	0.16	0.80	3.30	20.63	1.21	SW	A-1-A/A-2
Kanc K-3	1	1-3	0.11	0.45	2.00	18.87	1.00	SW-SM	A-1-B/A-2
	2	3-5	-	-	-	-	-	SM	A-1-B/A-2
	3	5-7	0.11	0.36	1.20	10.91	0.98	SP-SM	A-1-B/A-2
	4	7-9	0.13	0.29	0.80	6.15	0.81	SP	A-1-B/A-2
	5	9-11	-	-	-	-	-	SM	A-2
NGR	0a	.5	0.18	1.10	11.00	61.11	0.61	GP	A-1-A/A-2
	0b	.5	-	-	-	-	-	SW-SM	A-1-B/A-2
	1	2.5-4.5	-	-	-	-	-	SM	A-2
	2	4.5-6.5	-	-	-	-	-	SM	A-2
	3	6.5-8.5	0.07	0.13	0.32	4.57	0.75	SP-SM	A-2
	4	8.5-10.5	-	-	-	-	-	SM	A-2
SLR	1	.8-2.8	0.10	0.40	3.20	33.68	0.53	SP-SM	A-1-B/A-2
	2	3-5	0.07	0.17	0.26	3.71	1.59	SP-SM	A-2
	3	5-7	-	-	-	-	-	SM	A-2
	4	7-9	-	-	-	-	-	SM	A-2
	5	9-9.9	-	-	-	-	-	SM	A-2
LT	1	1-3	0.032	0.33	2.00	62.50	1.70	SW-SM	A-1-B/A-2
	2	3-5	0.9	0.29	0.85	0.94	0.11	SP-SM	A-1-B/A-2
	3	5-7	N/A	N/A	N/A			SM	A-1-B/A-2
	4	7-9	N/A	N/A	N/A			SM	A-1-B/A-2
	5	9-11	N/A	N/A	N/A			SM	A-1-B/A-2

(cont. on next page)

Table A3 (cont.)

Site	Sample #	Depth (ft)	D_{10}	D_{30}	D_{60}	C_u	C_c	USCS	AASHTO
WF	1	1-3	0.016	0.065	0.39	24.38	0.68	SM	A-2
	2	3-5	0.049	0.105	0.22	4.49	1.02	SM	A-2
	3	5-7	0.06	0.13	0.25	4.17	1.13	SM	A-2
	4	7-9	-	-	-	-	-	SM	A-4/5/6/7
	5	9-11	0.08	0.14	0.21	2.63	1.17	SP-SM	A-3/A-2
RUM	1	0.3-2.3	N/A	N/A	N/A	-	-	SM	A-1-B/A-2
	2	2.5-4.5	N/A	N/A	N/A	-	-	SM	A-2
	3	4.5-6.5	0.11	0.85	18.00	163.64	0.36	SP-SM	A-1-A/A-2
	4	6.5-8.5	0.08	0.34	9.60	118.52	0.15	SP-SM	A-1-B/A-2
	5	8.5-10.5	N/A	N/A	N/A			SM	A-4/5/6/7
WS	1	.3-1	0.14	0.38	2.00	14.29	0.50	SP	A-1-B/A-2
	2	2-4	0	1	7	52	1	SP-SM	A-1-A/A-2
	3	6-8	0.08	0.45	6.60	79.52	0.37	SP-SM	A-1-A/A-2
	4	8-10	0.08	0.20	0.72	8.51	0.63	SP-SM	A-3/A-2

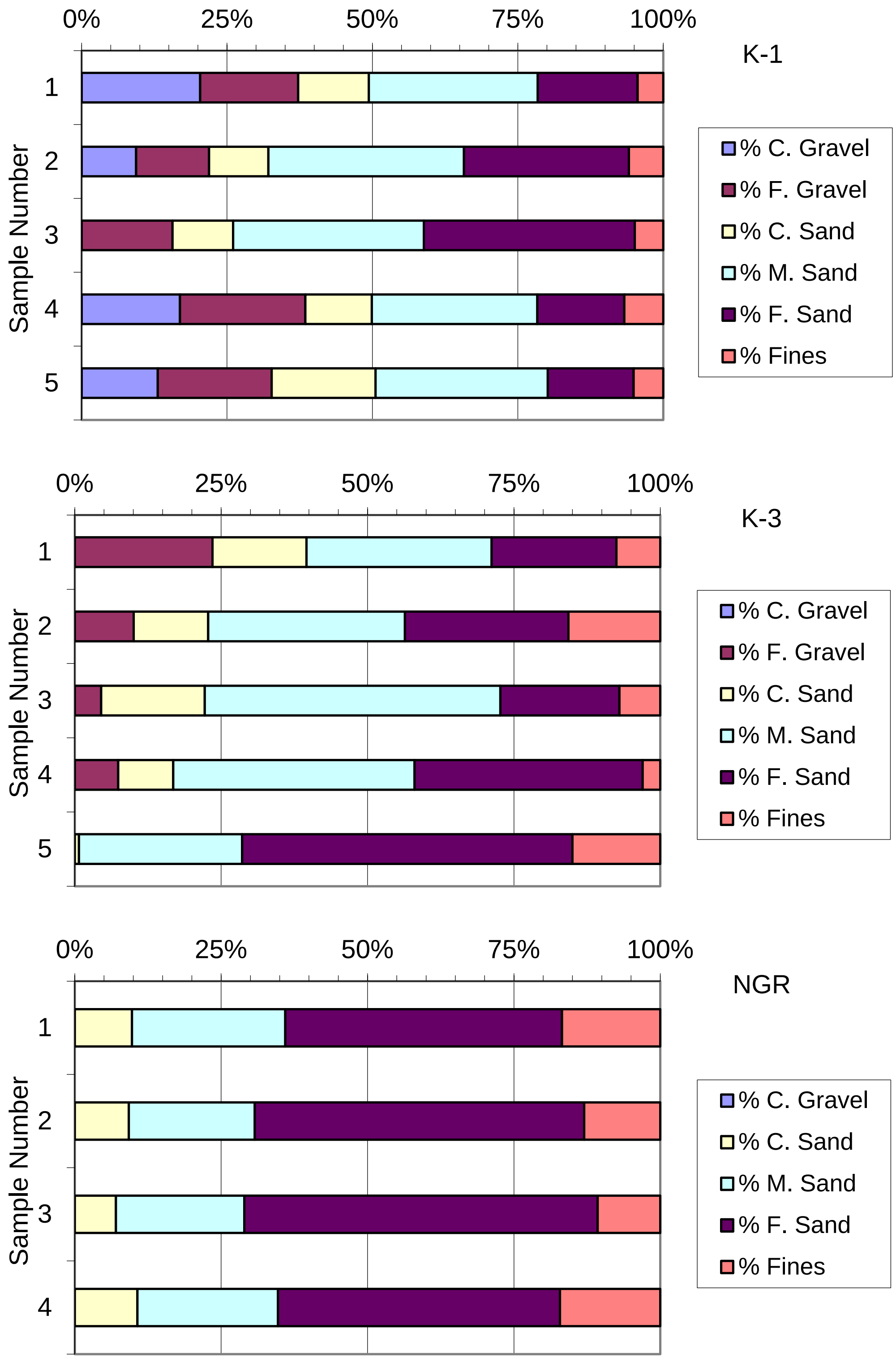


Figure A1 – USCS Soil Classification Percentages at Sites K-1, K-3, and NGR

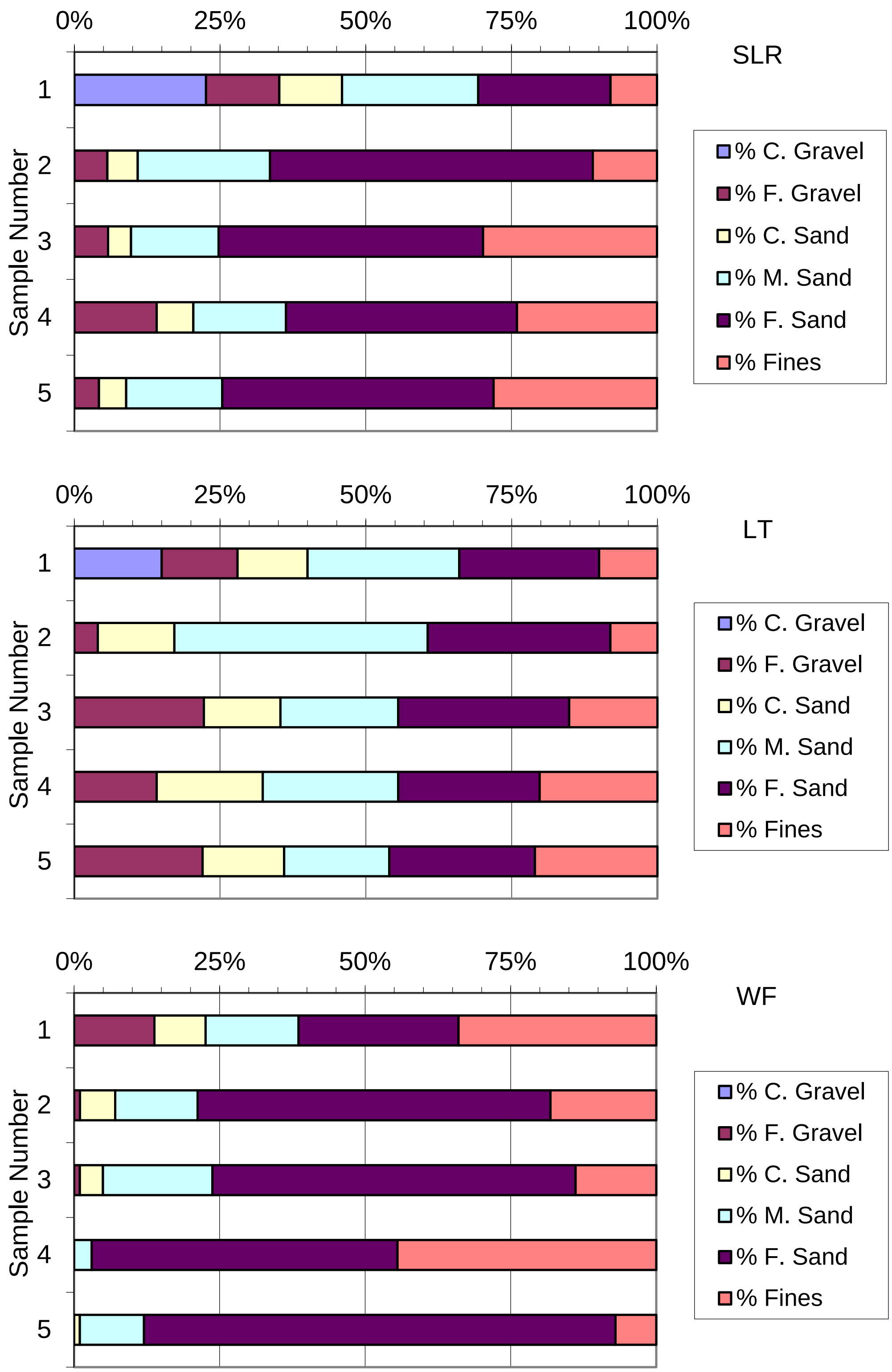
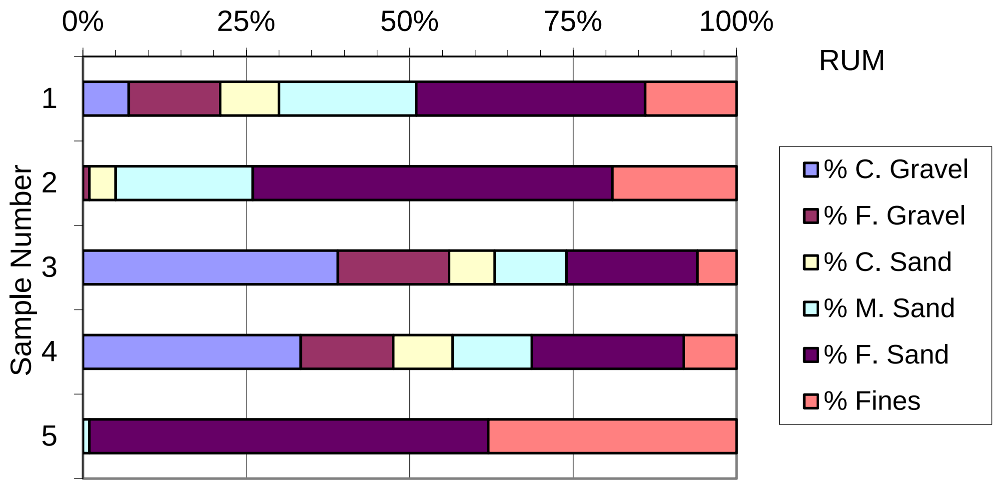


Figure A2 - USCS Soil Classification Percentages at Sites SLR, LT, and WF



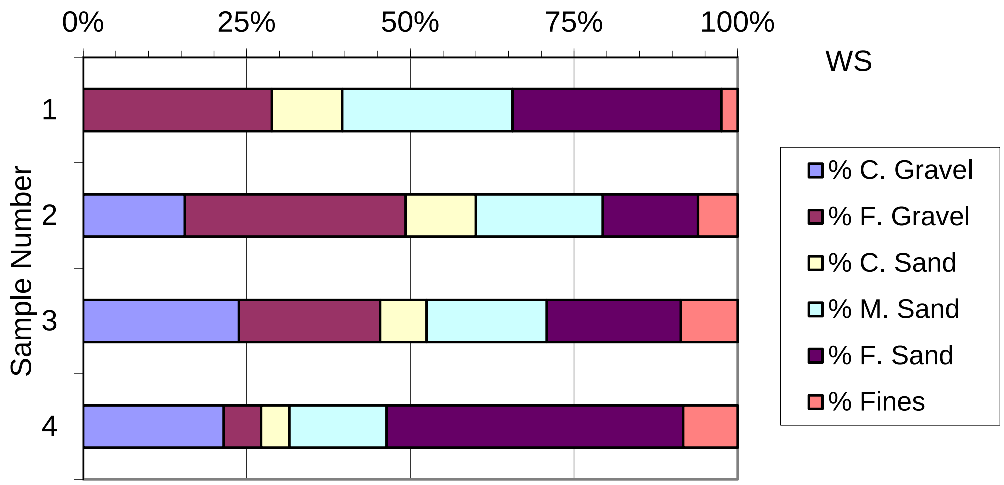


Figure A3 - USCS Soil Classification Percentages at Sites RUM and WS

Appendix B - Modified Freeze-Thaw Index Model Calculated vs. Measured Frost-Thaw Depths

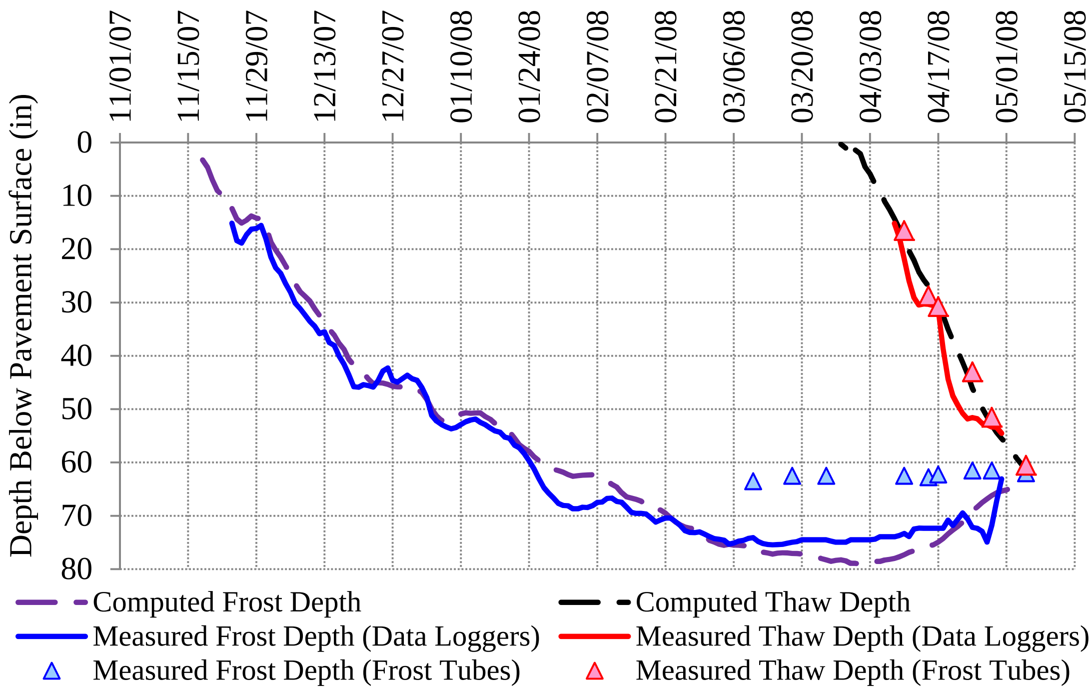


Figure B1 - K-1 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

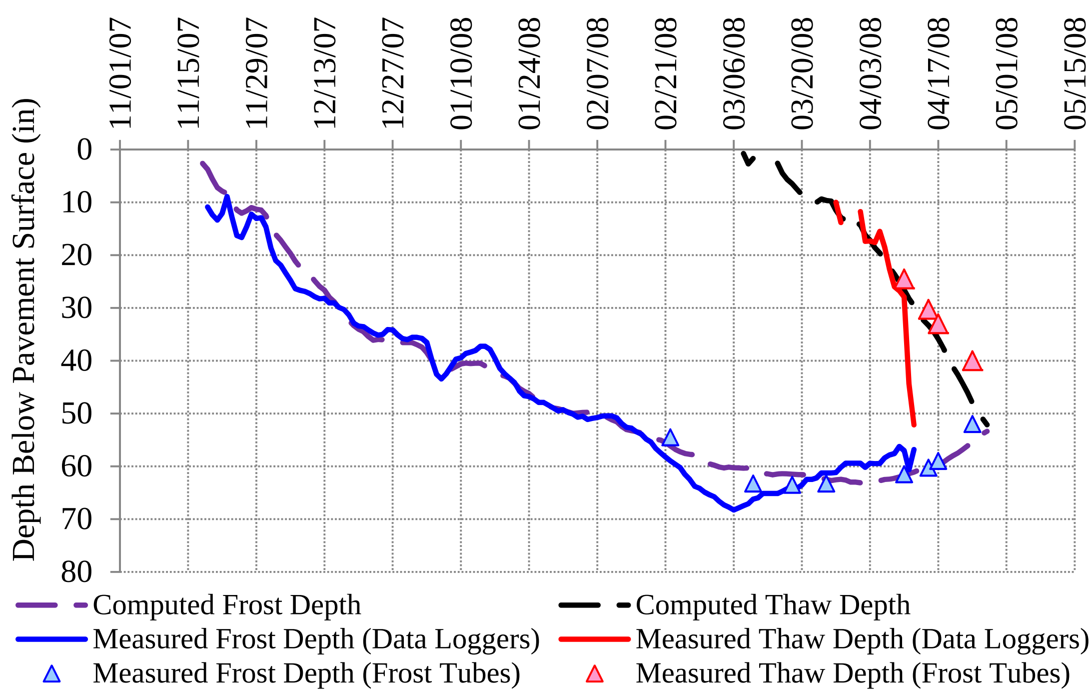


Figure B2 - K-2 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

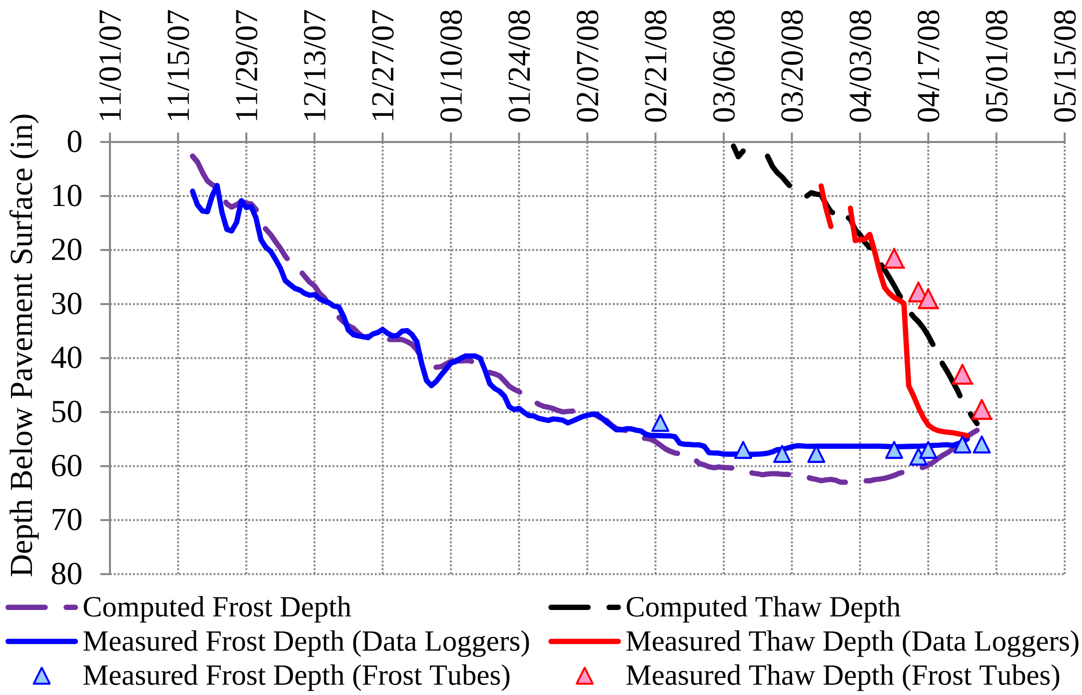


Figure B3 - K-3 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

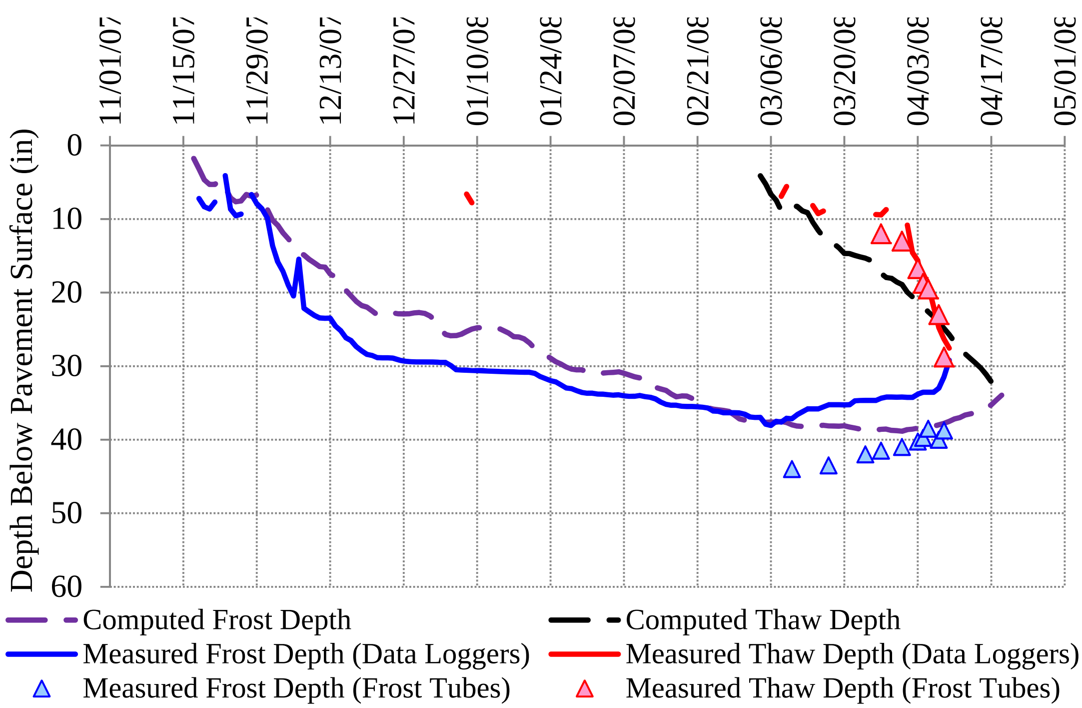


Figure B4 - LT 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

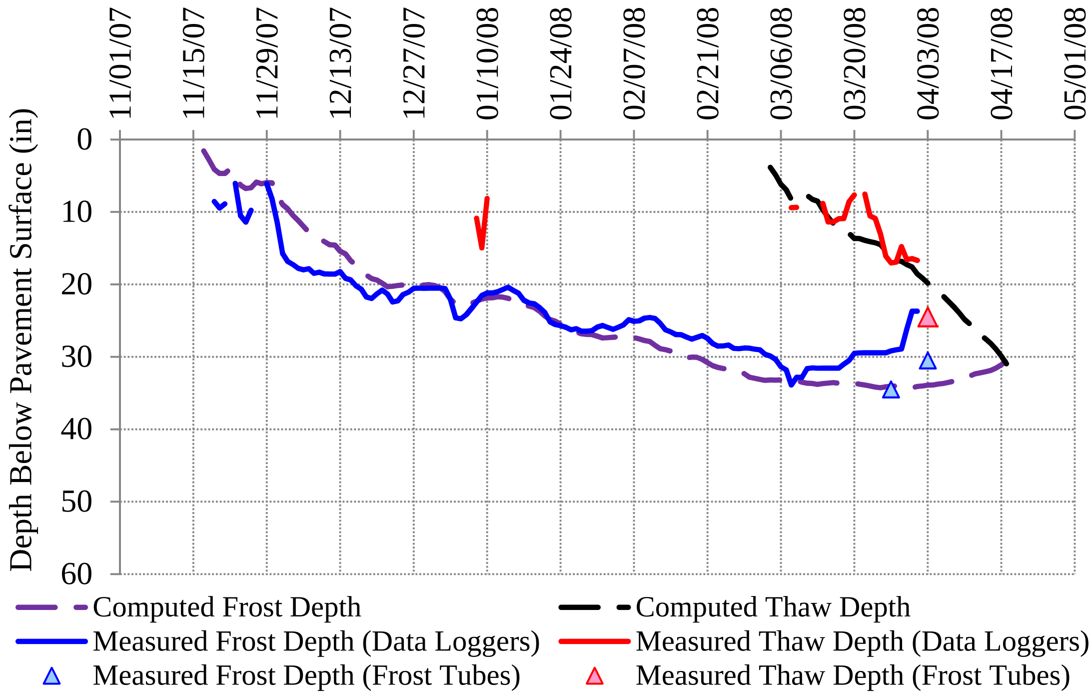


Figure B5 - NGR2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

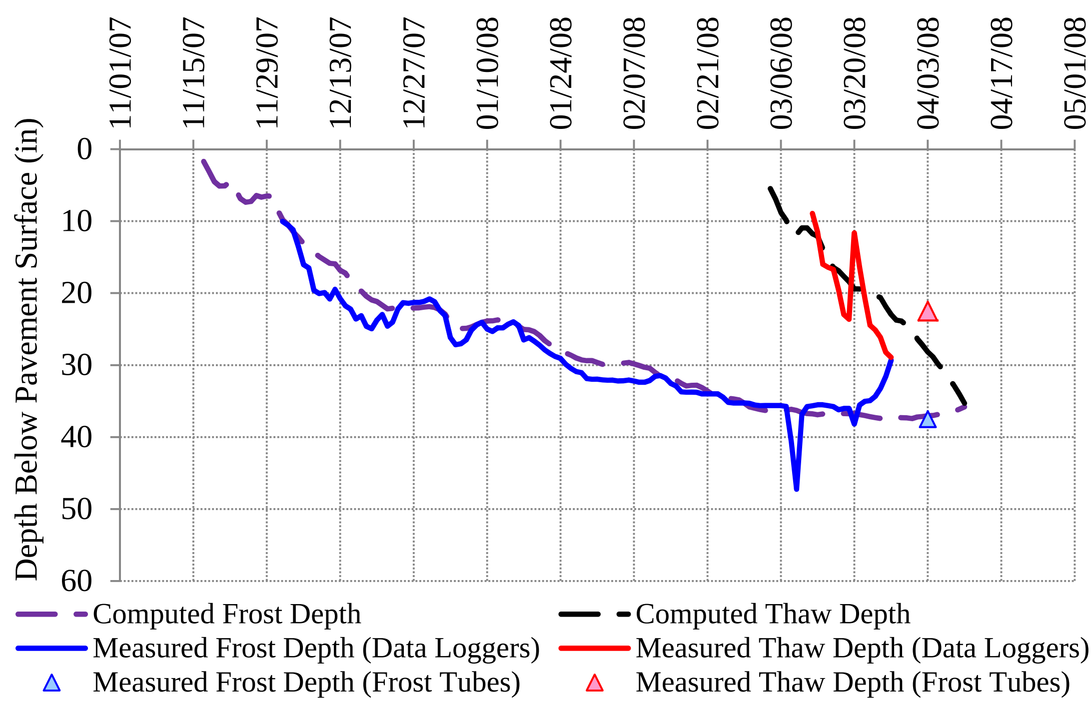


Figure B6 - RUM 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

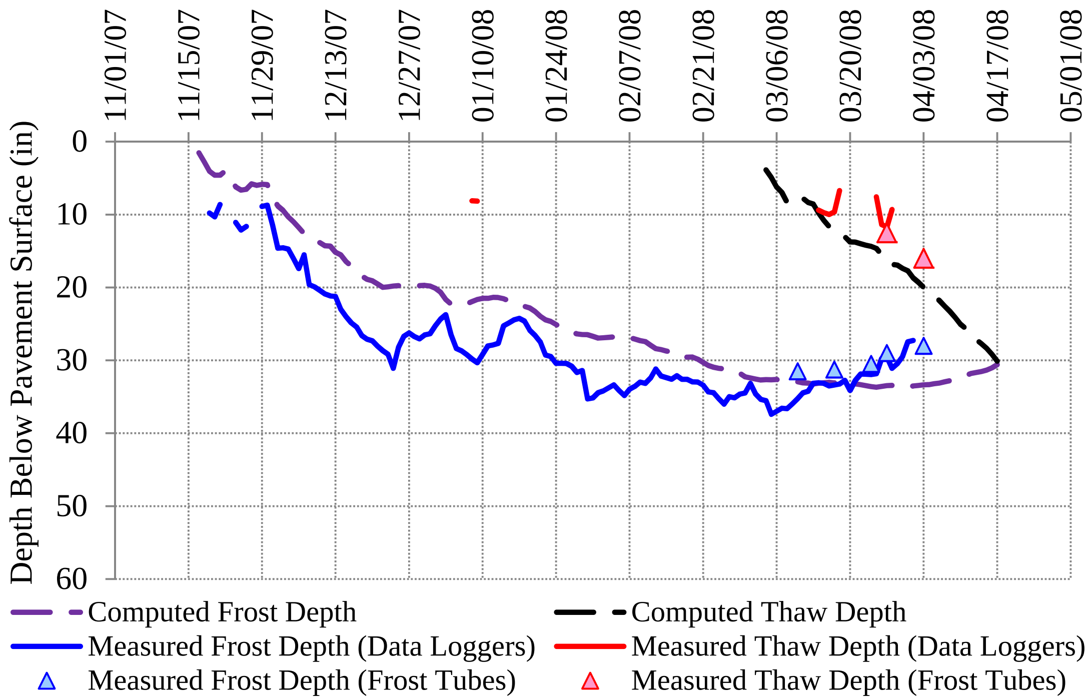


Figure B7 - SLR 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

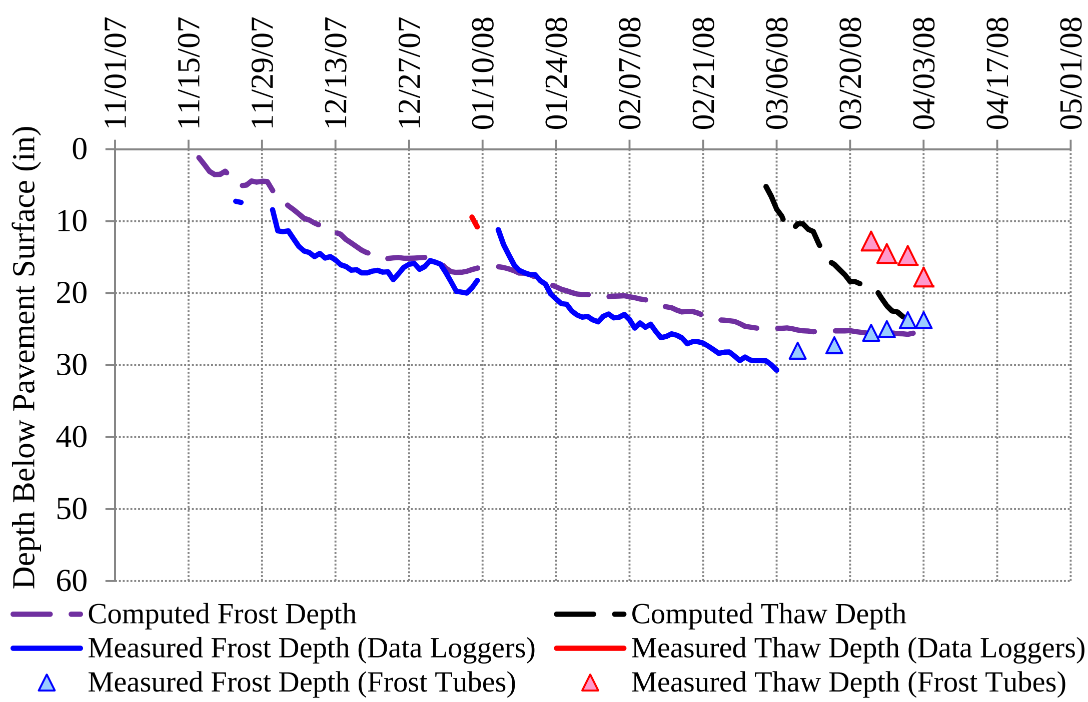


Figure B8 - WF 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

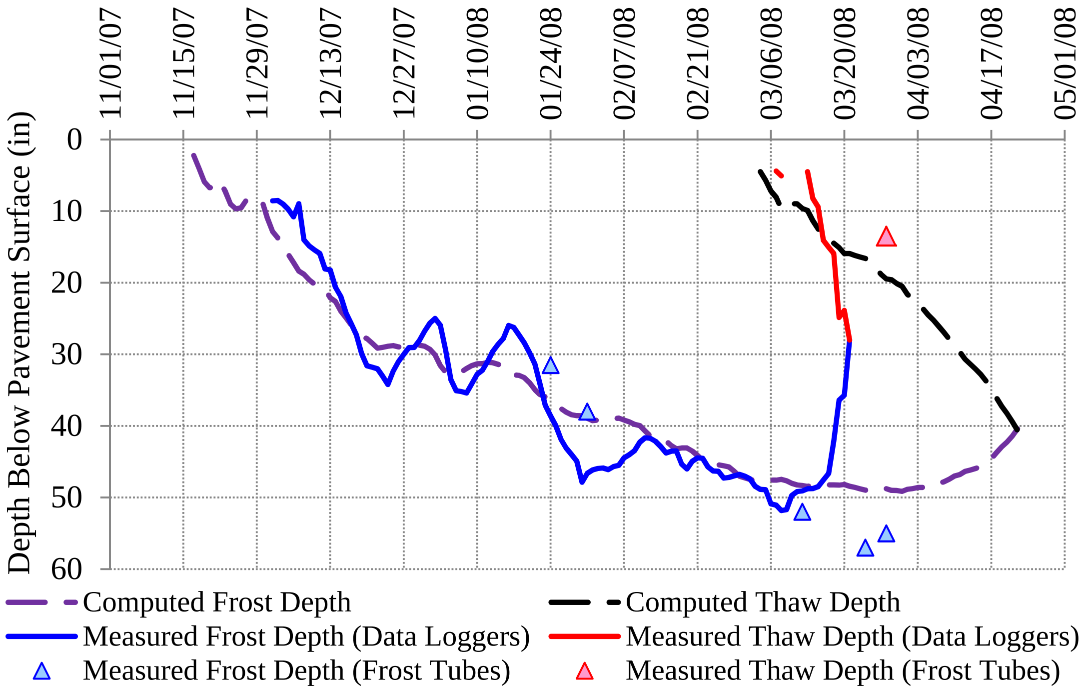


Figure B9 - WS 2007-2008 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

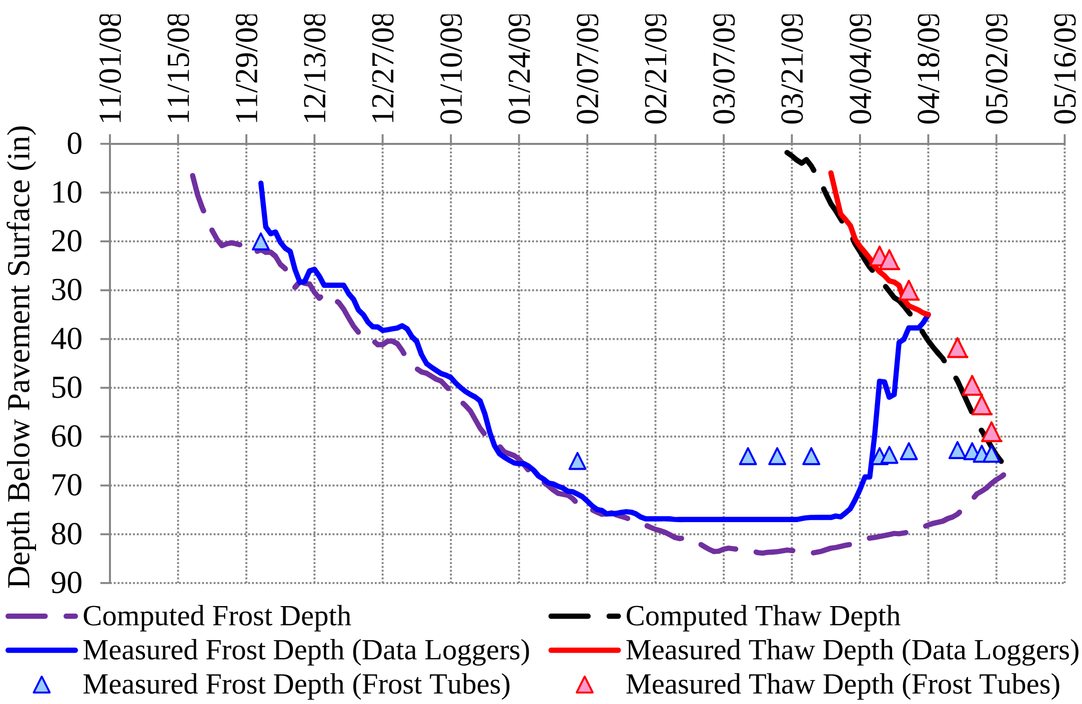


Figure B10 - K-1 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

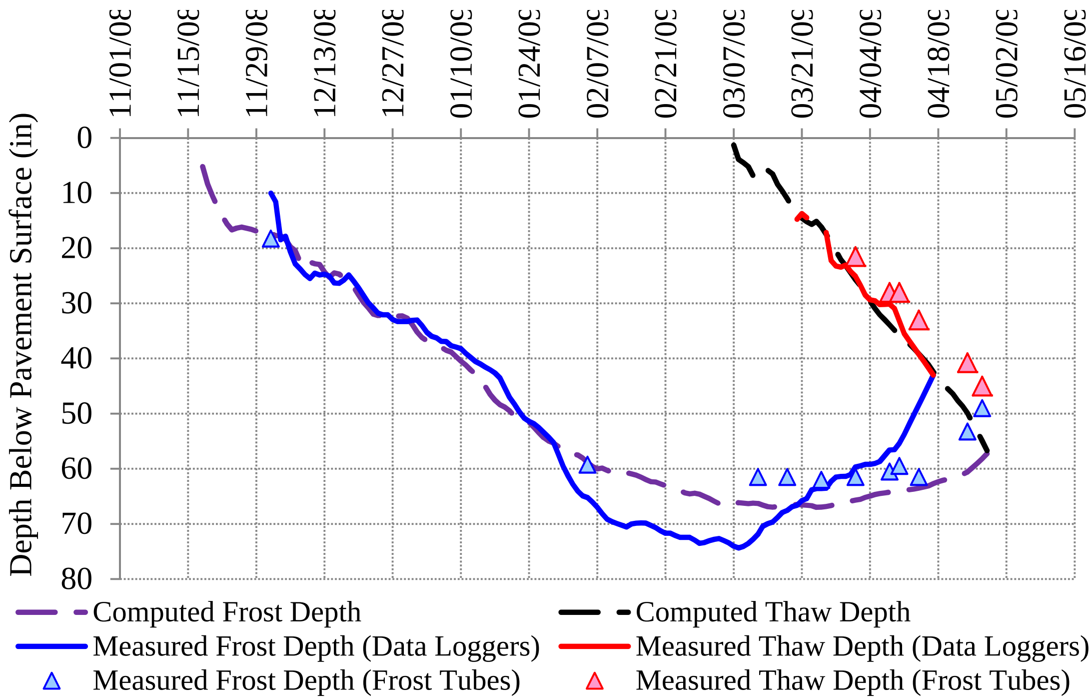


Figure B11 - K-2 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

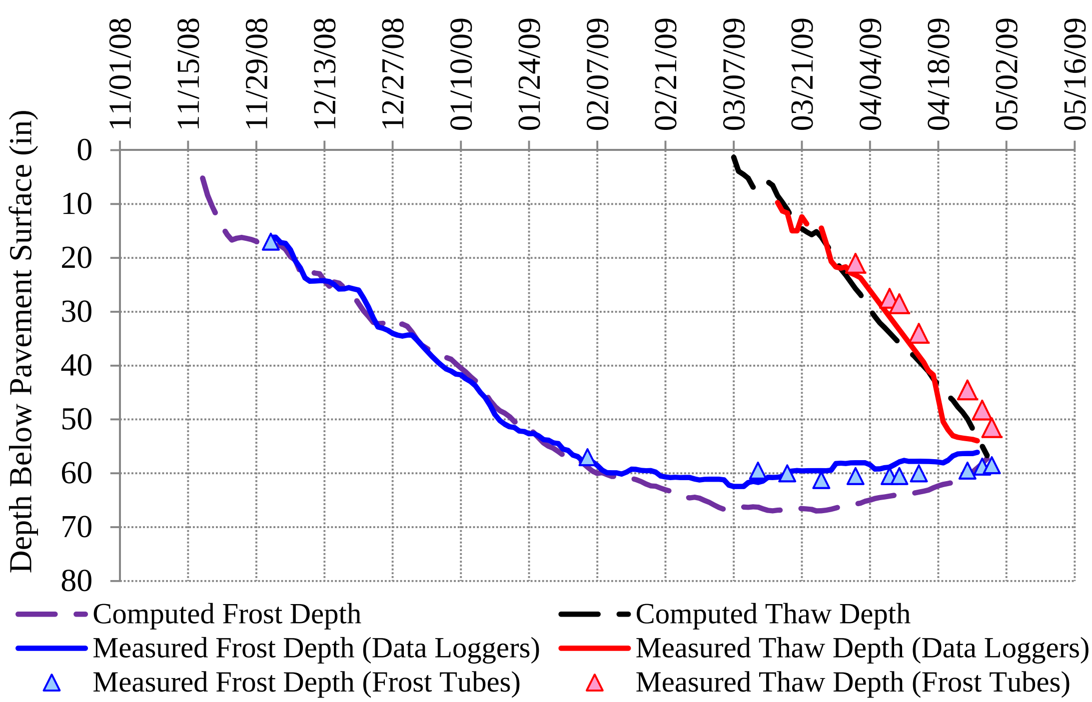


Figure B12 - K-3 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

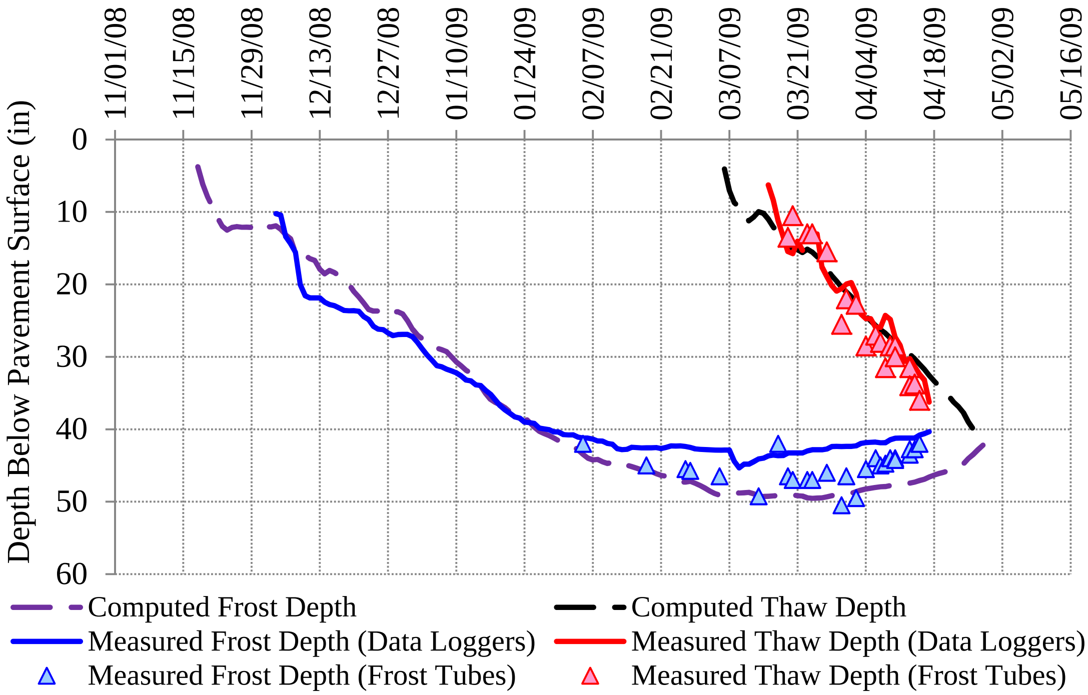


Figure B13 - LT 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

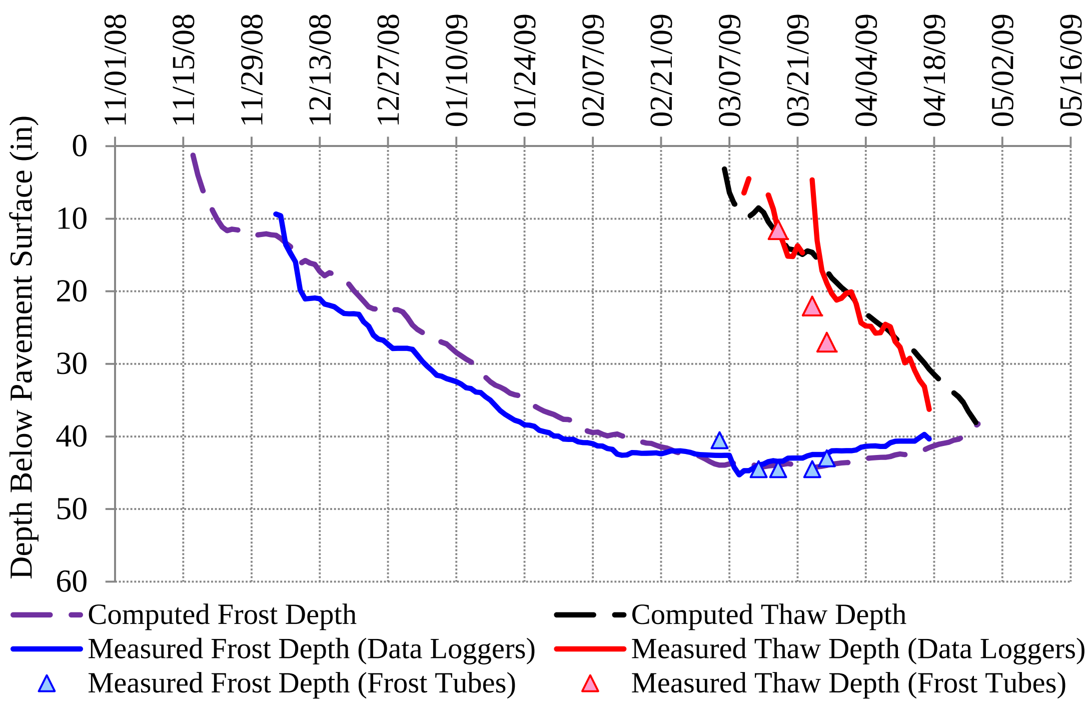


Figure B14 - NGR 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

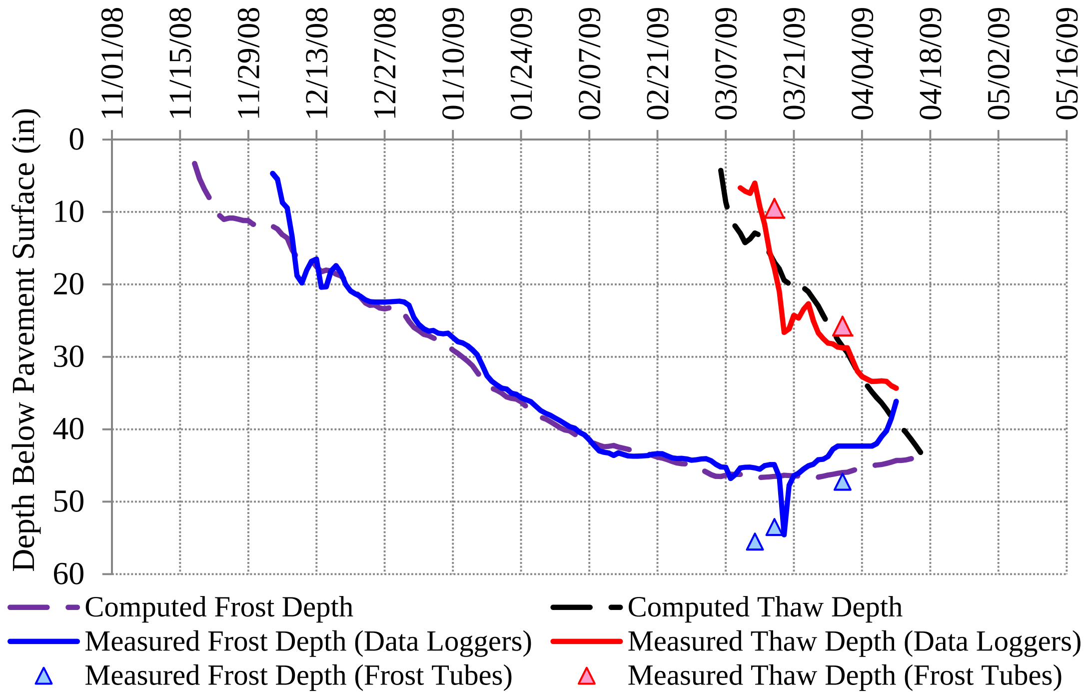


Figure B15 - RUM 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

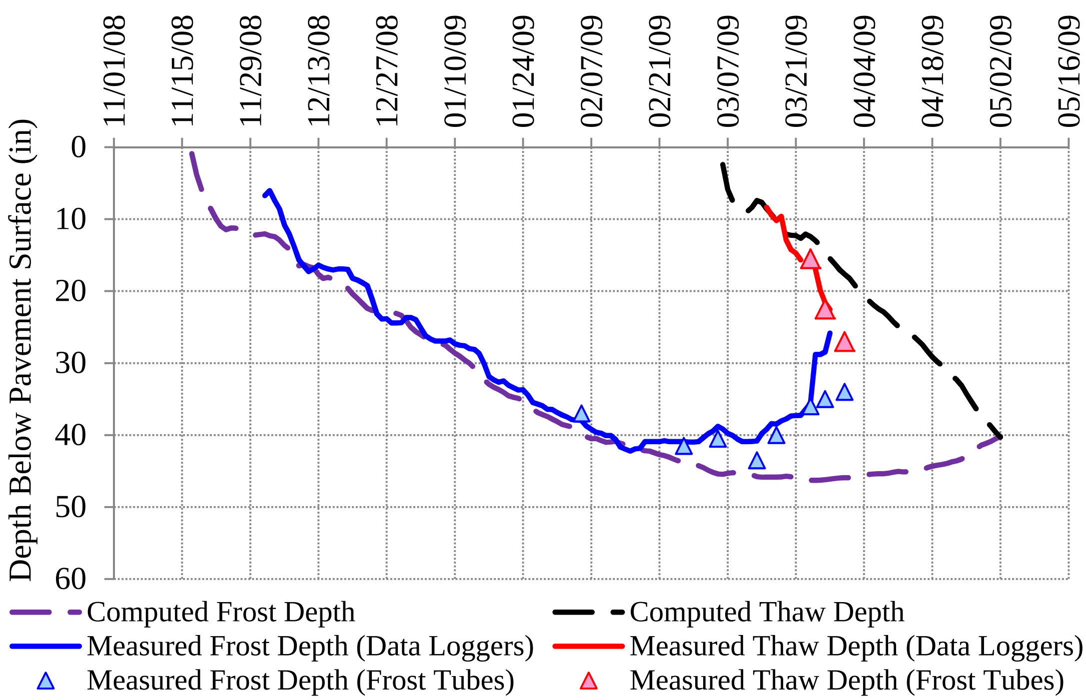


Figure B16 - SLR 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

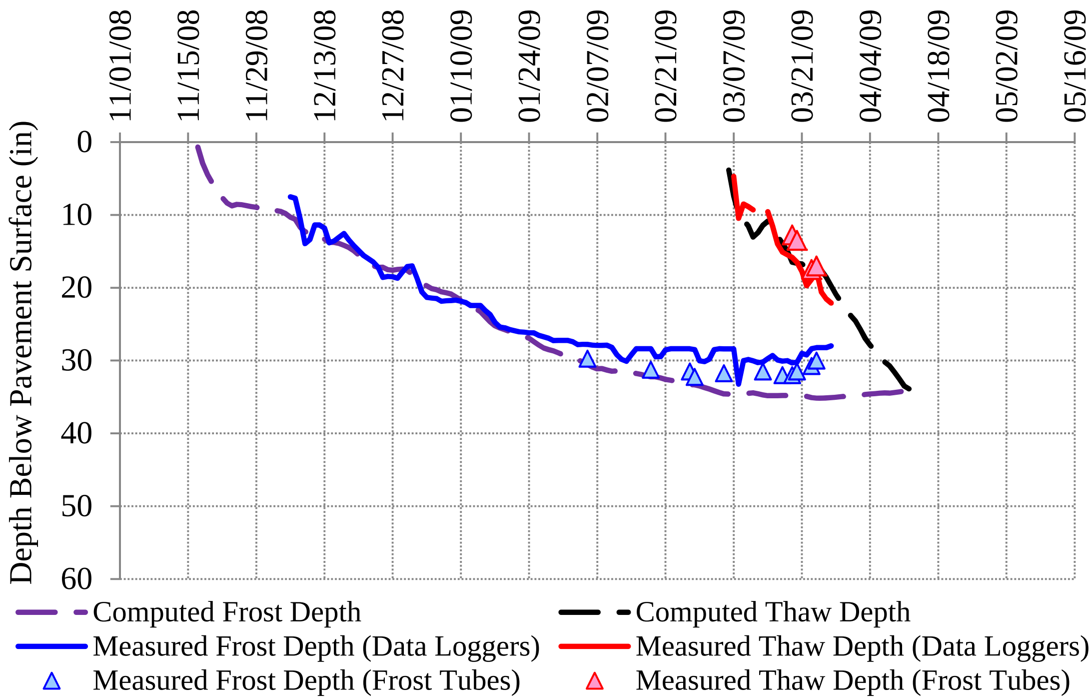


Figure B17 - WF 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

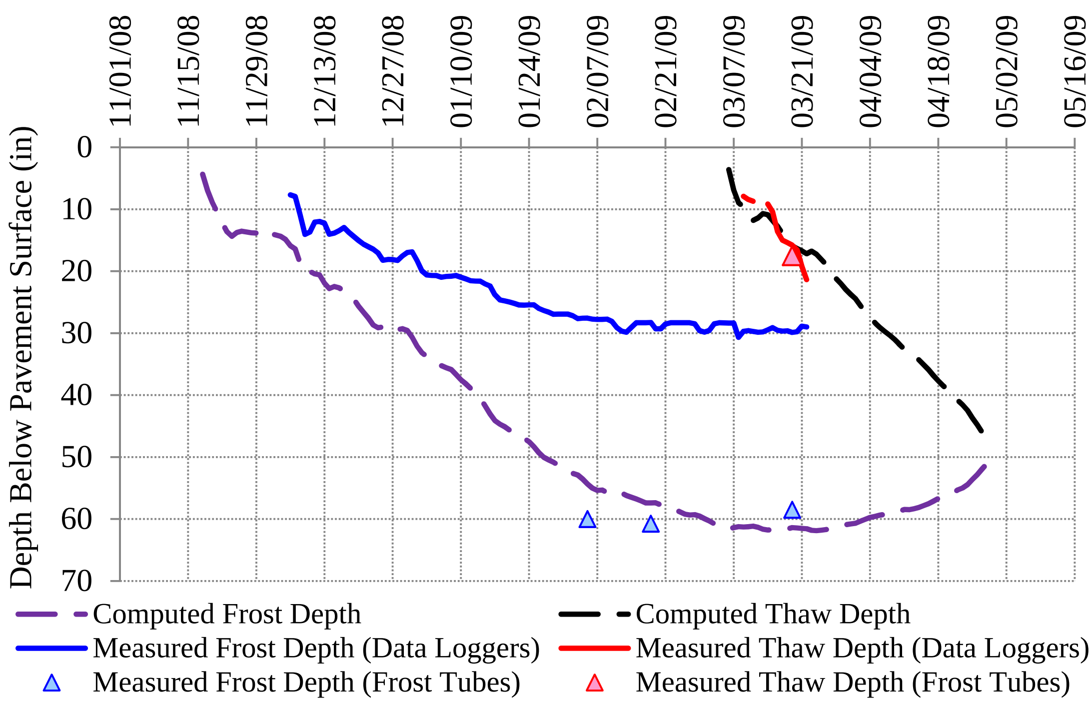


Figure B18 - WS 2008-2009 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

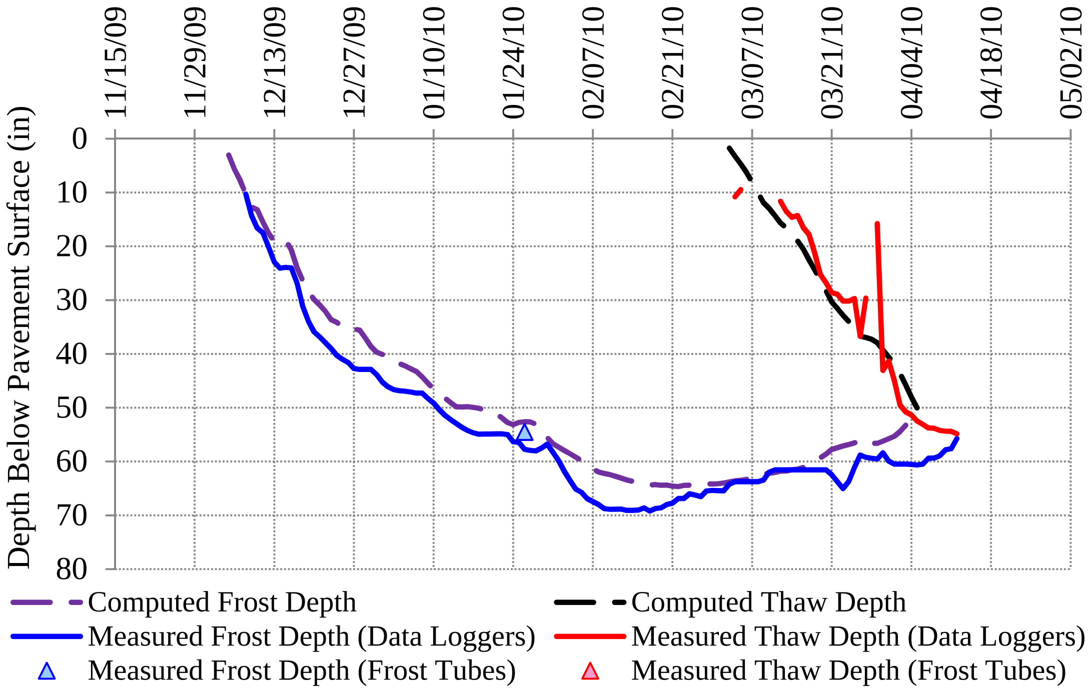


Figure B19 - K-1 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

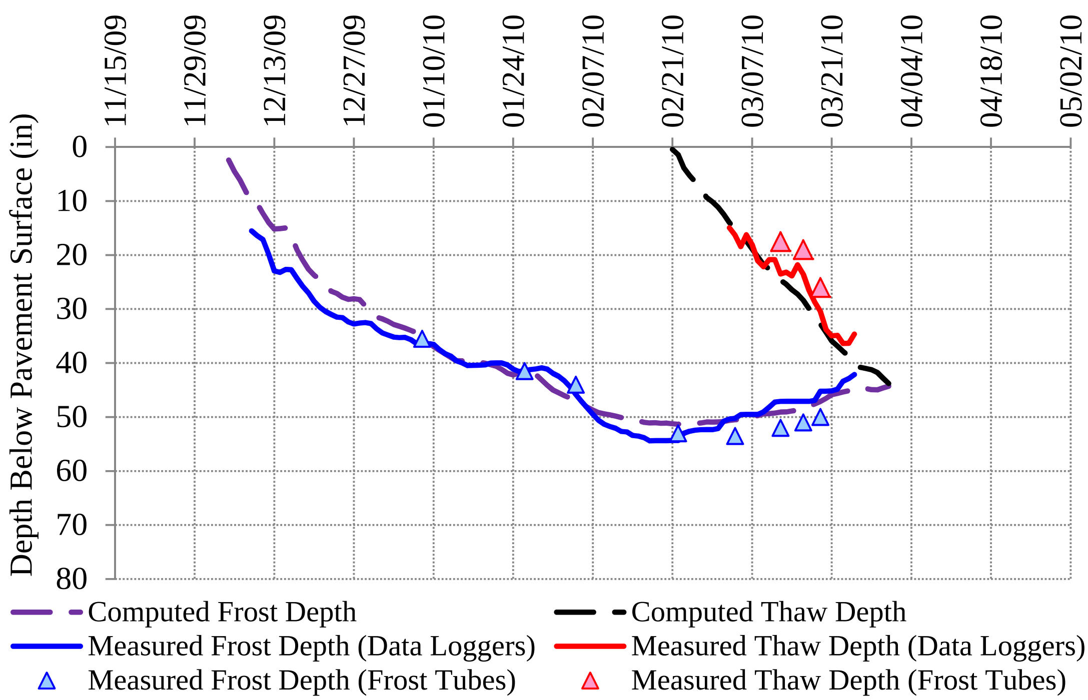


Figure B20 - K-2 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

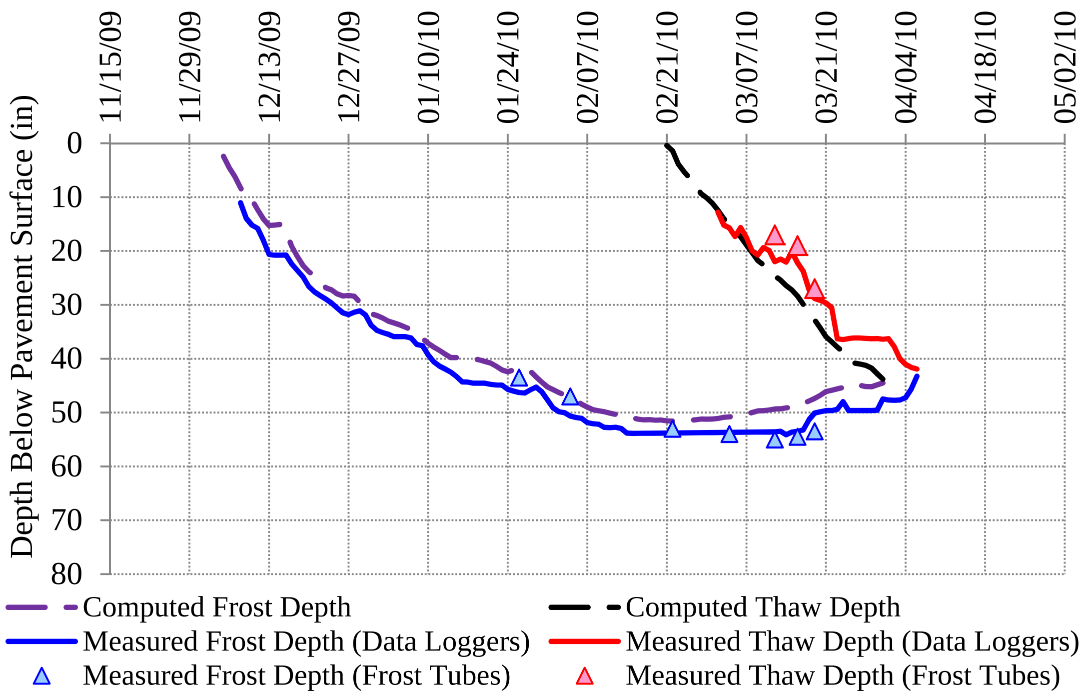


Figure B21 - K-3 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

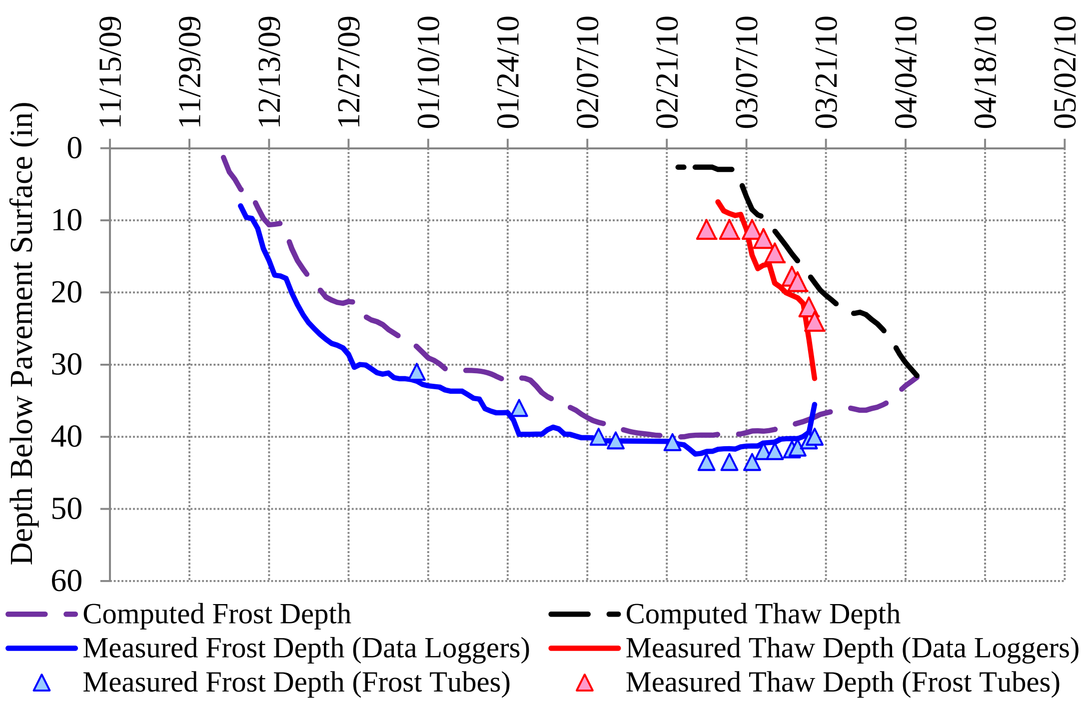


Figure B22 - LT 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

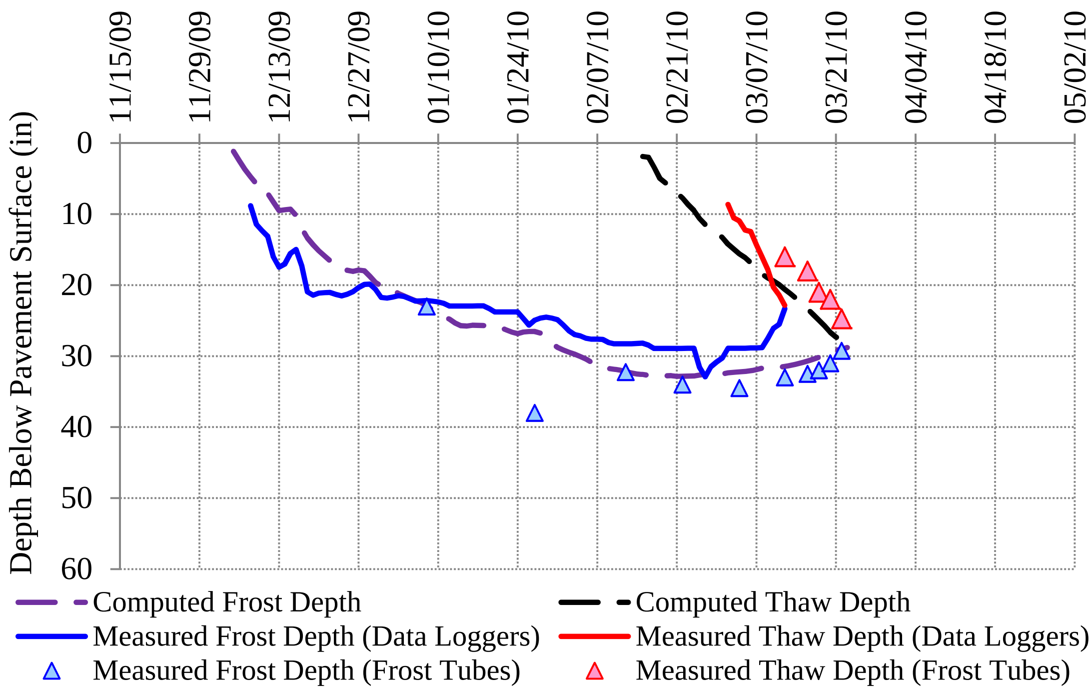


Figure B23 - NGR 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

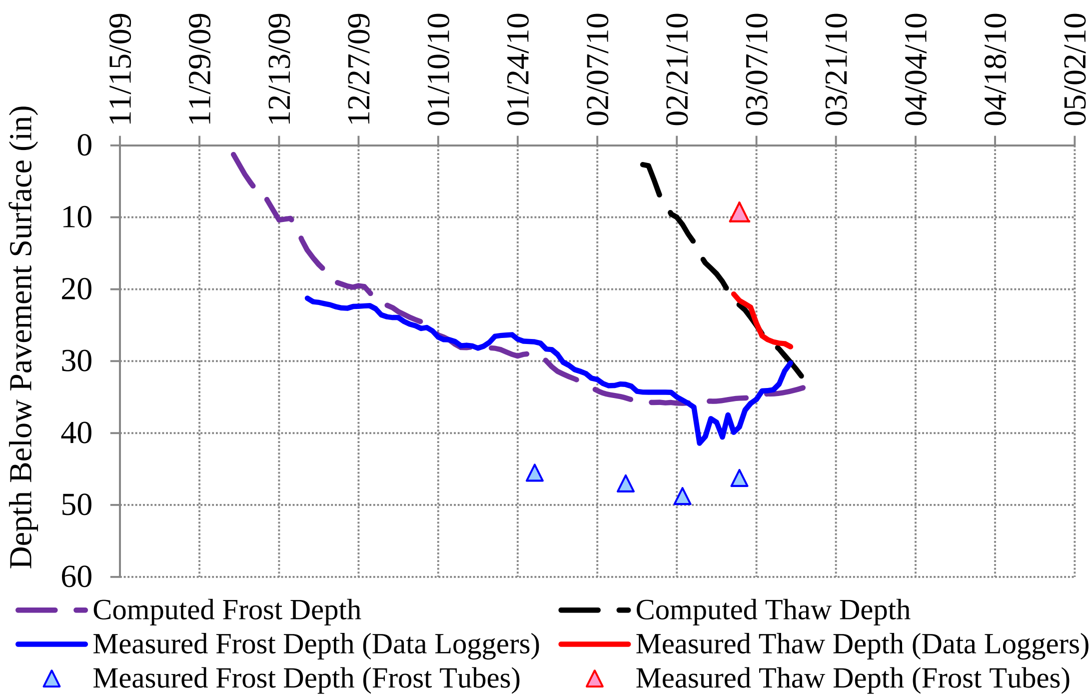


Figure B24 - RUM 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

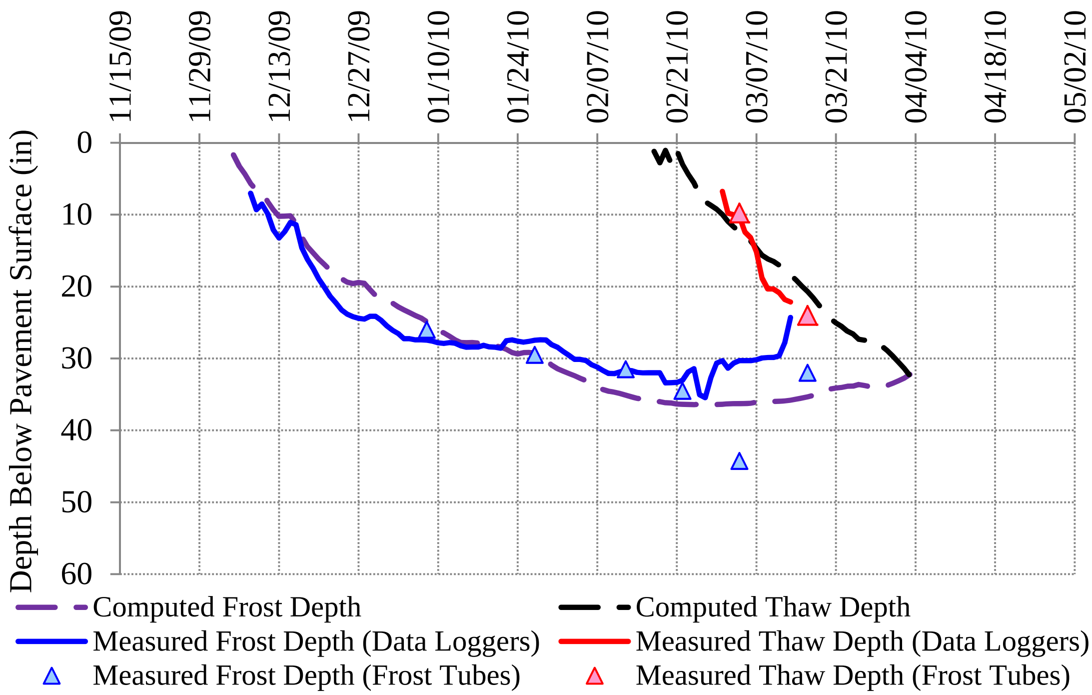


Figure B25 - SLR 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

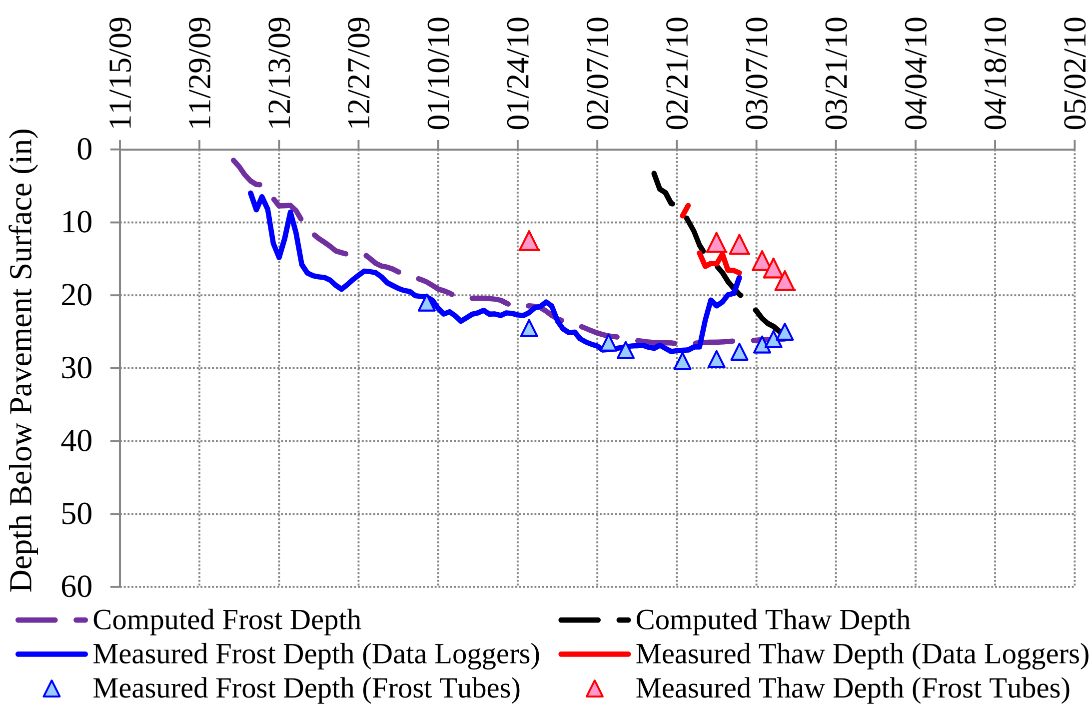


Figure B26 - WF 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

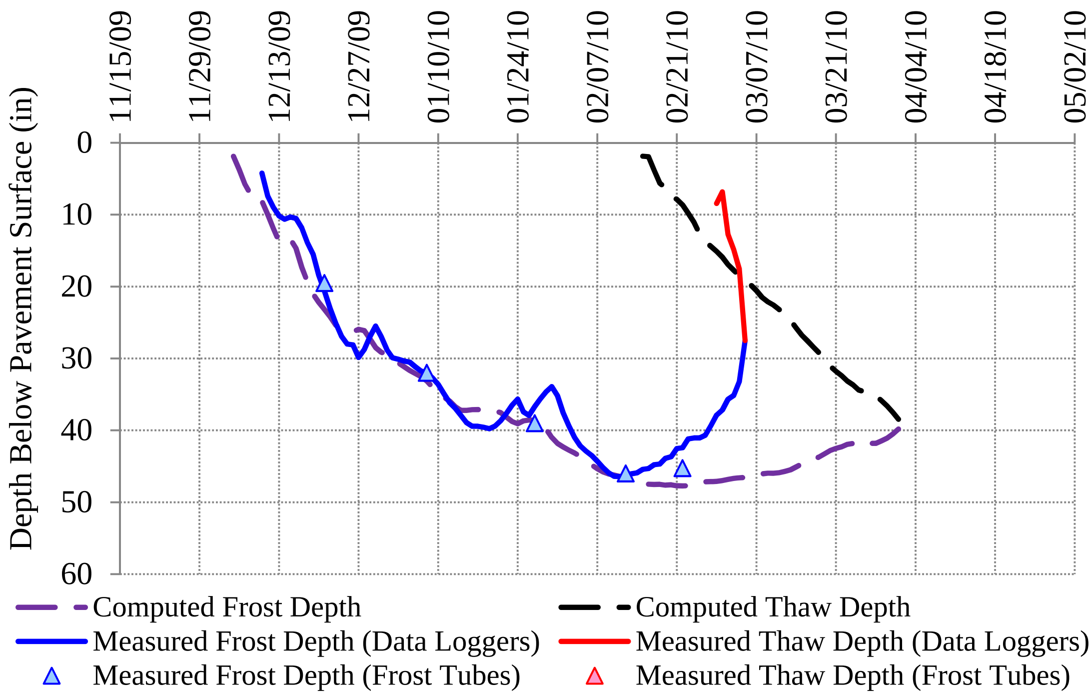


Figure B27 - WS 2009-2010 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

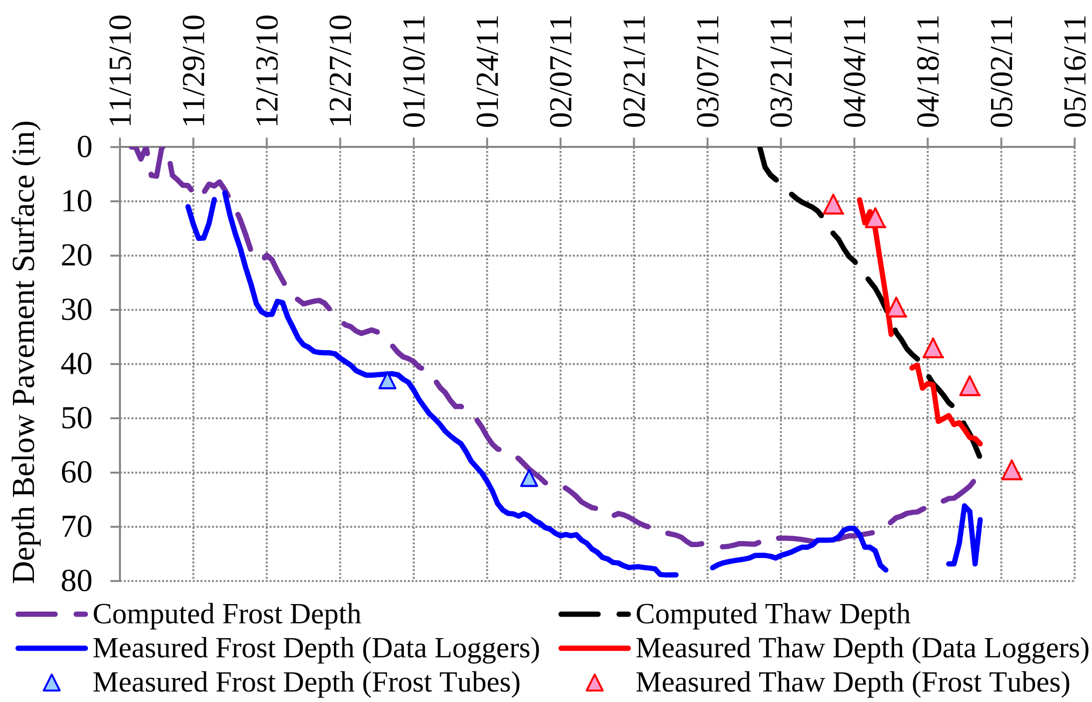


Figure B28 - K-1 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

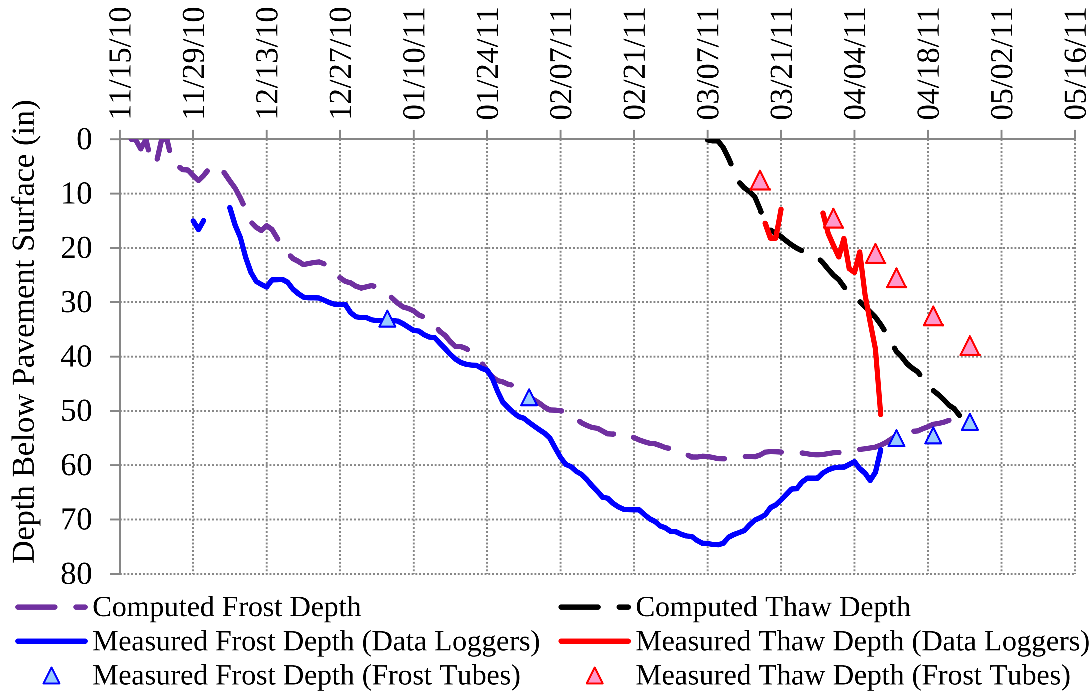


Figure B29 - K-2 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

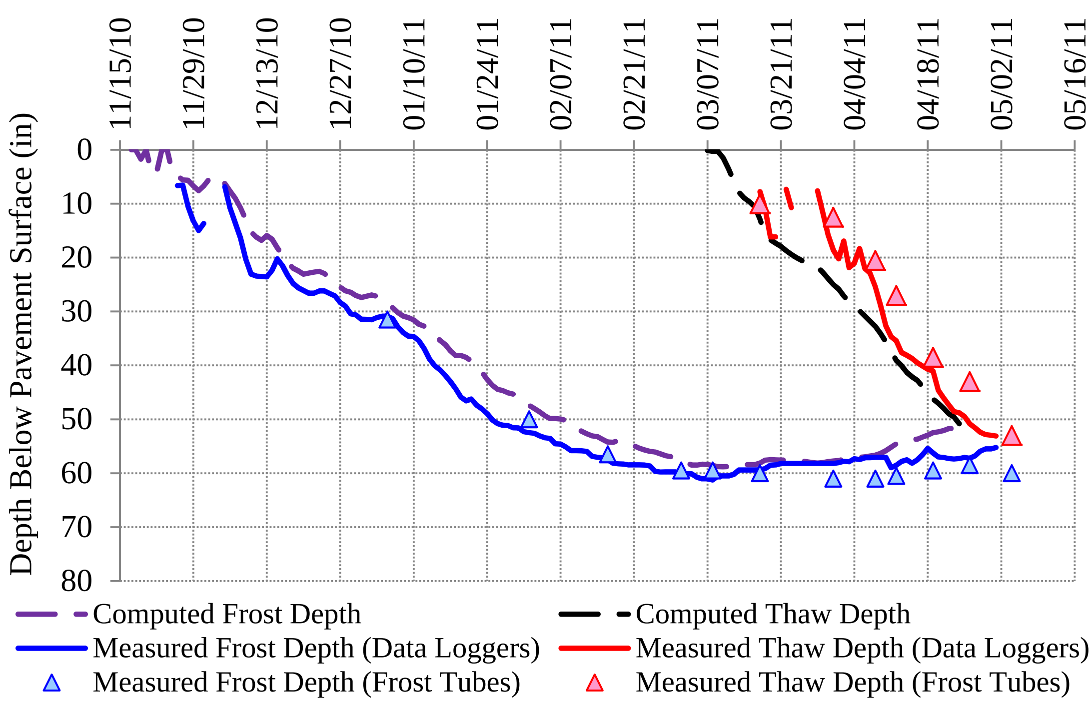


Figure B30 - K-3 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

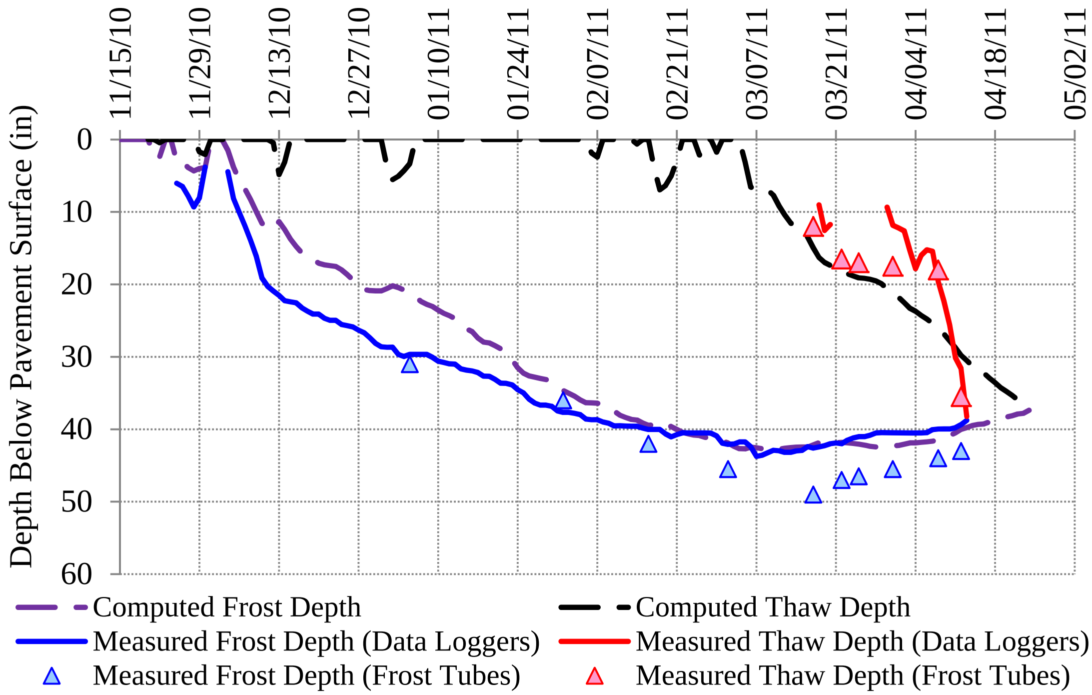


Figure B31 - LT 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

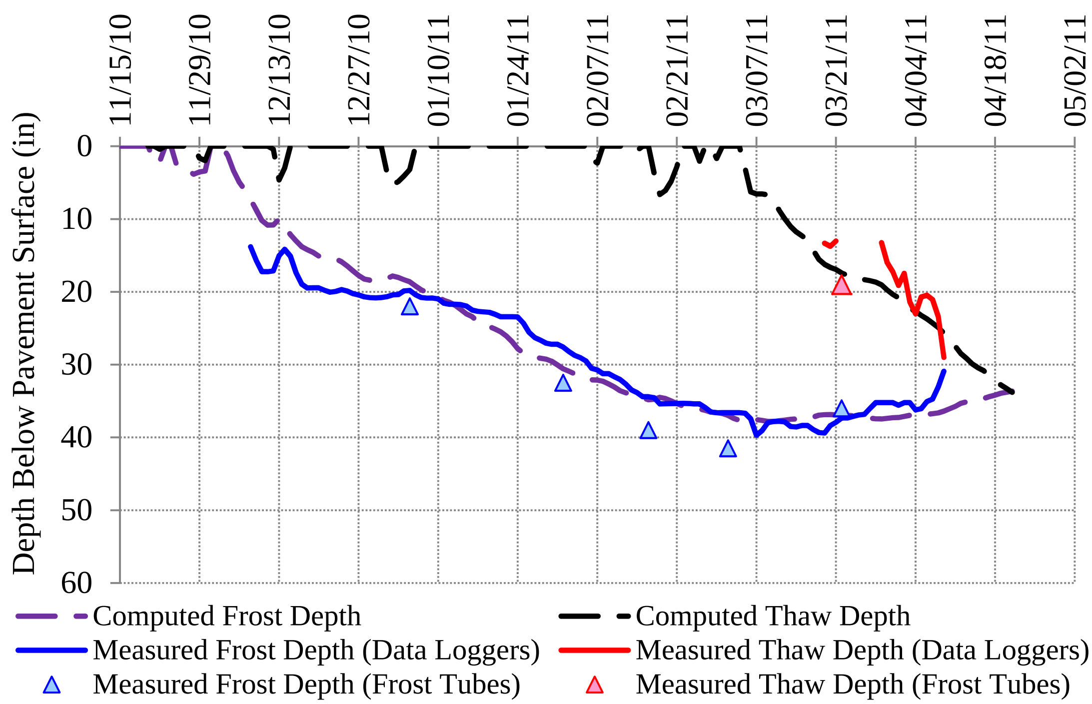


Figure B32 - NGR 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

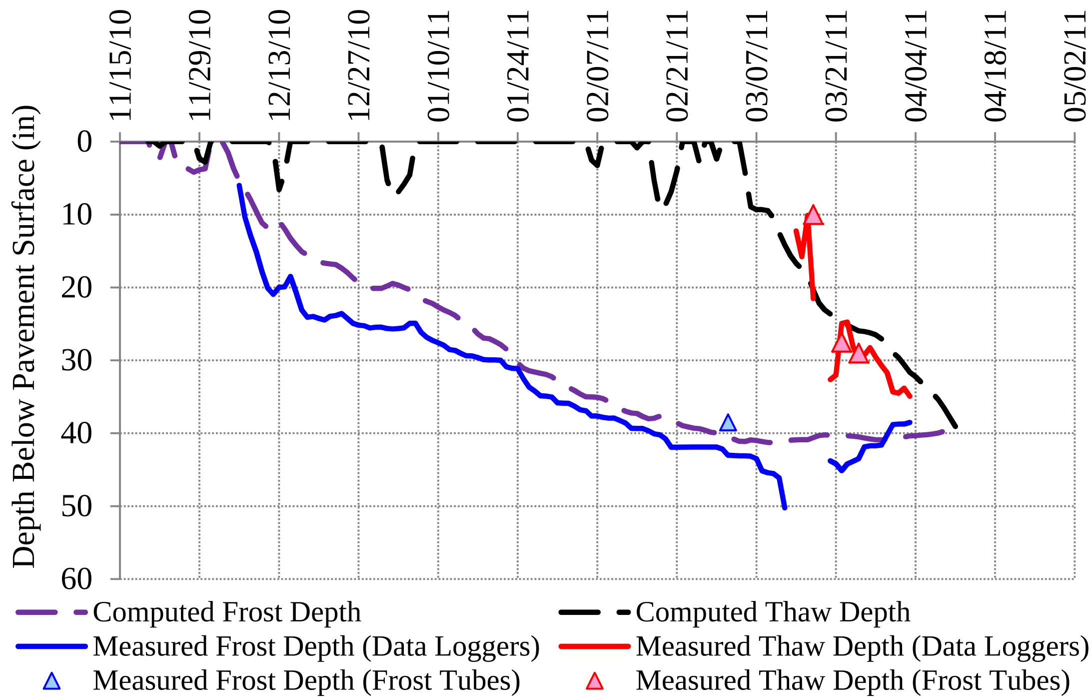


Figure B33 - RUM 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

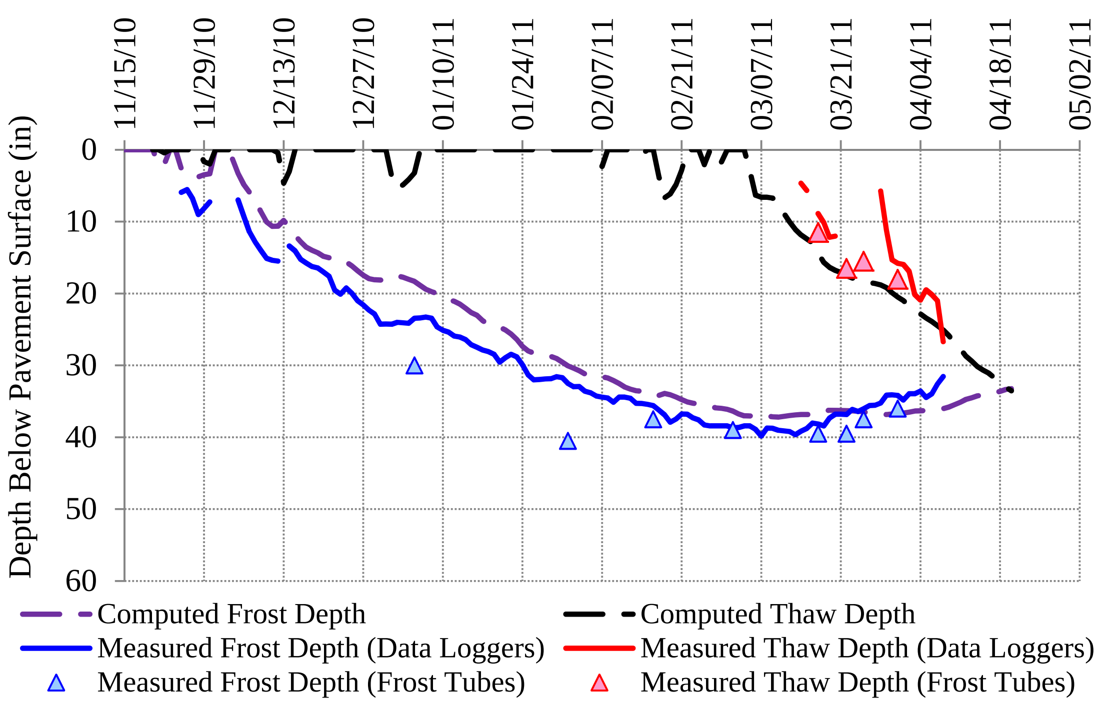


Figure B34 - SLR 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

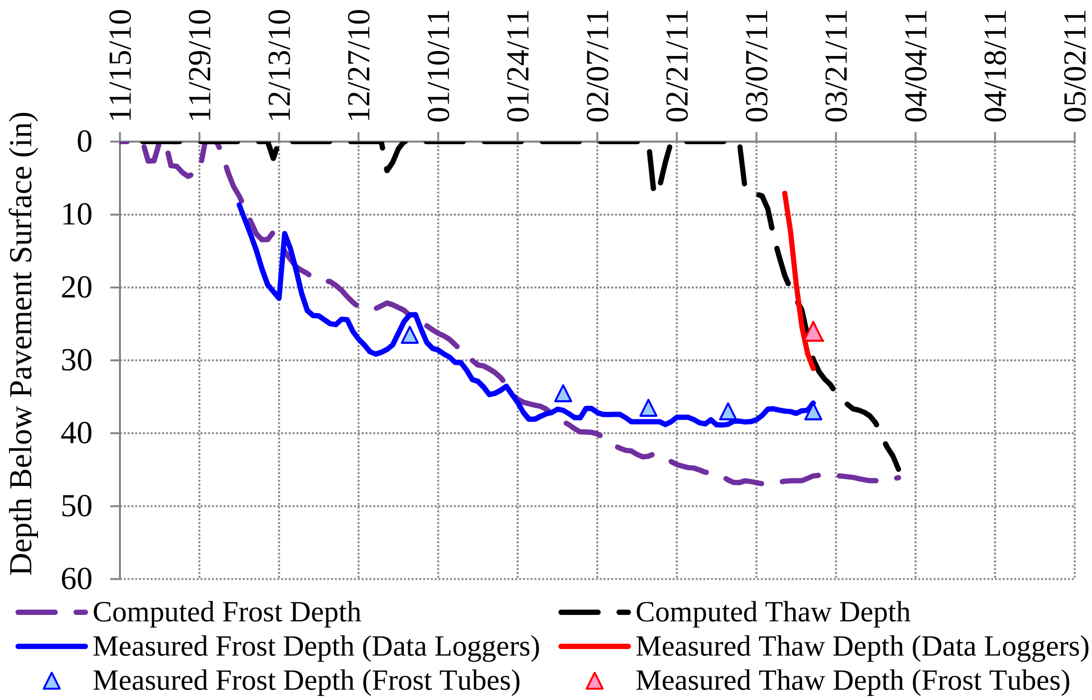


Figure B35 - WF 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

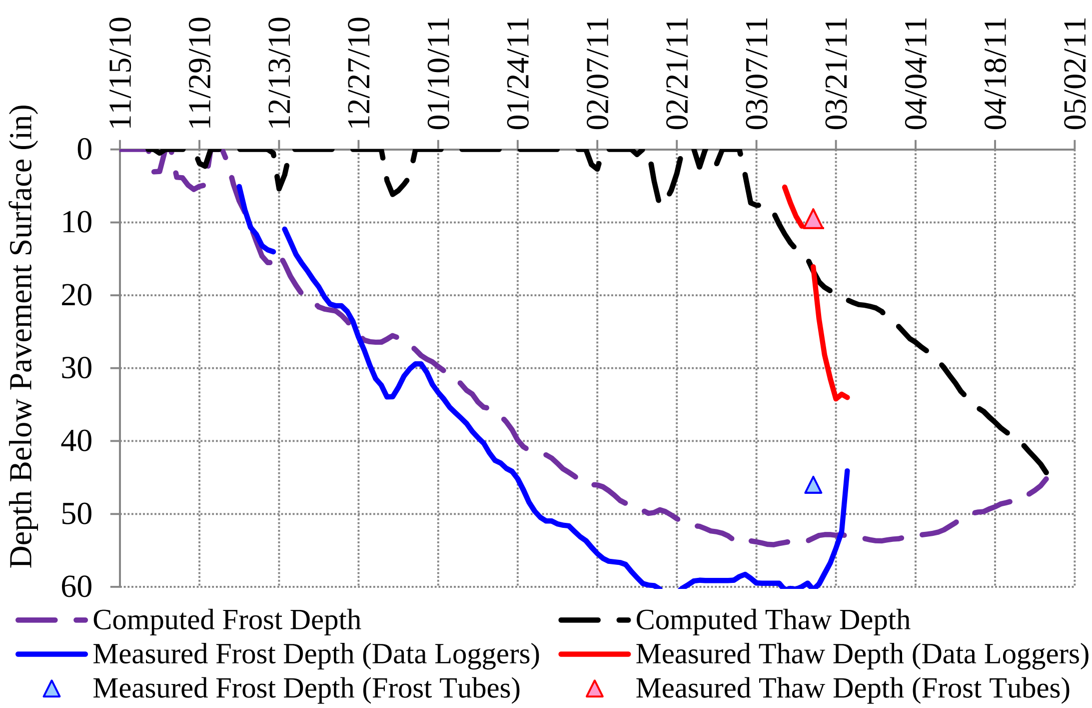


Figure B36 - WS 2010-2011 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

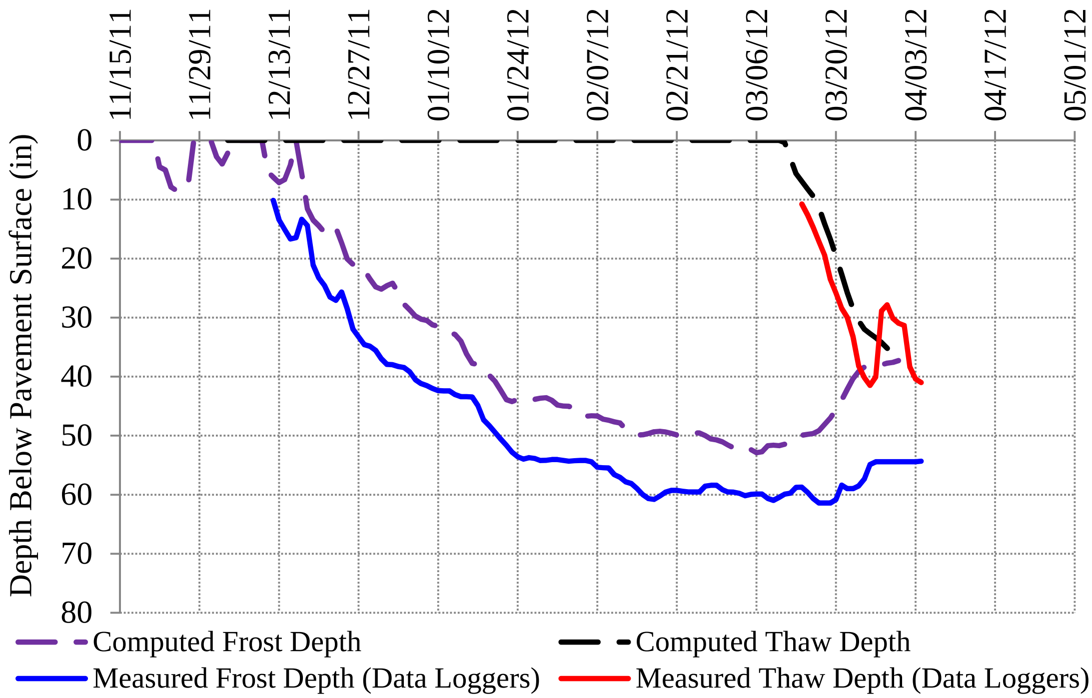


Figure B37 - K-1 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

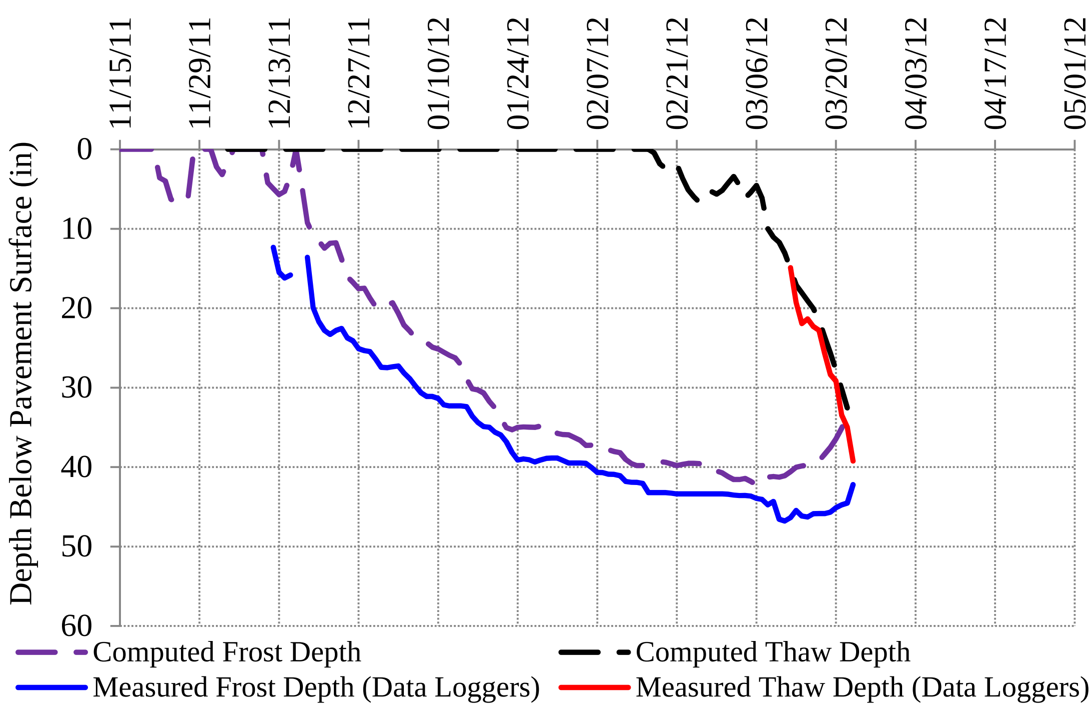


Figure B38 - K-2 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

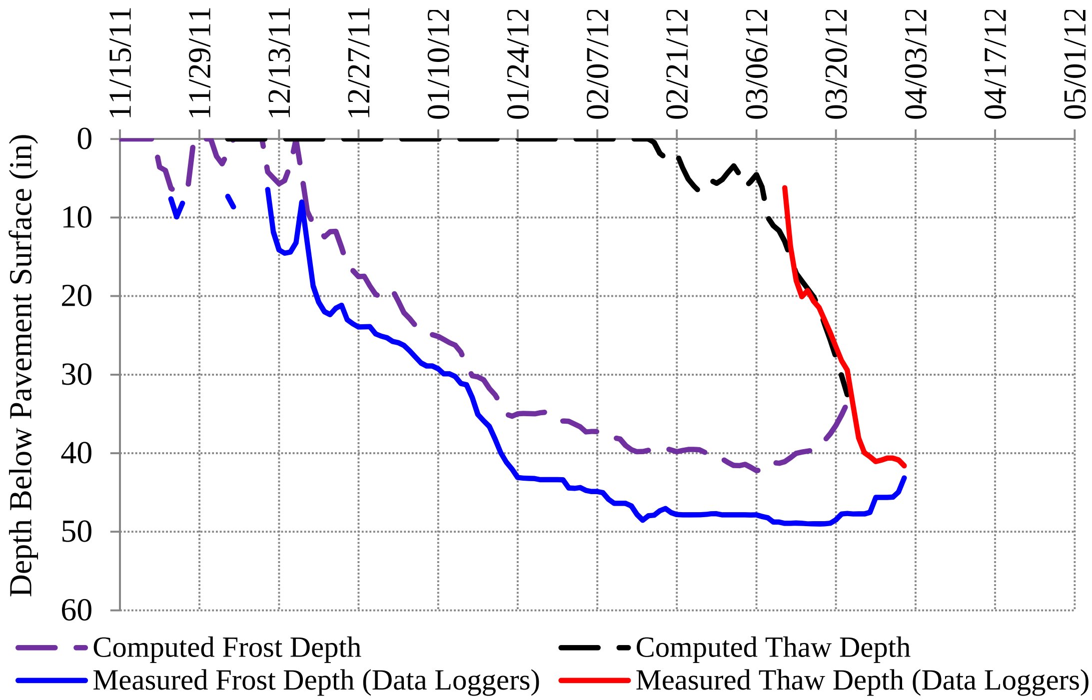


Figure B39 - K-3 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

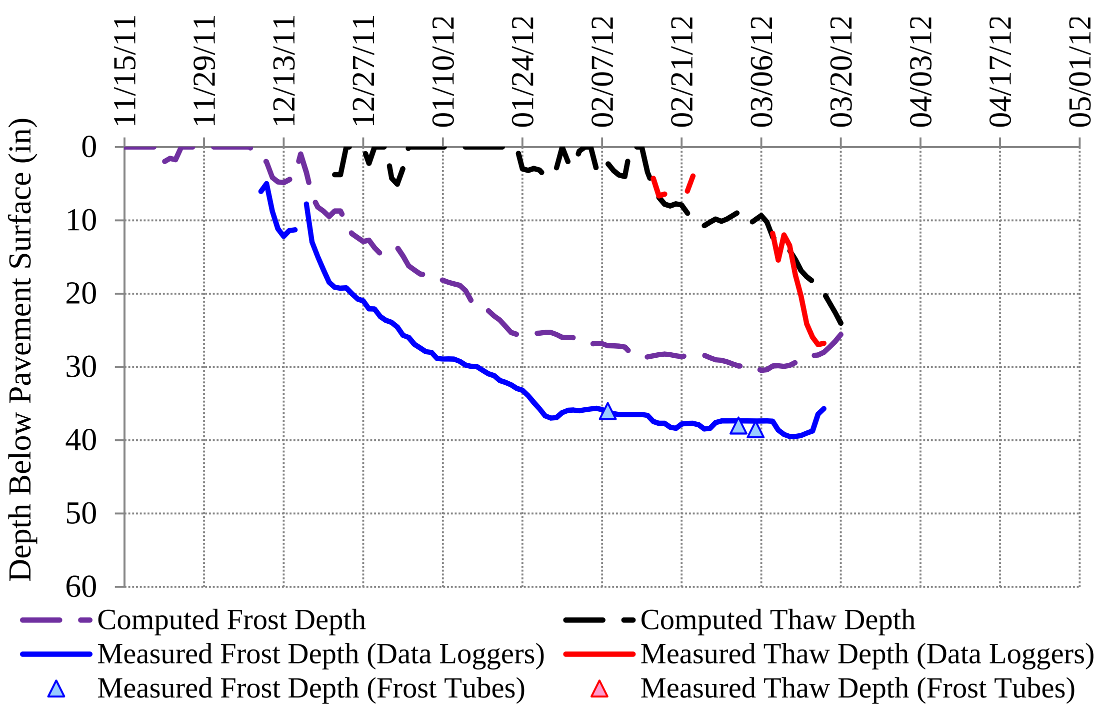


Figure B40 - LT 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

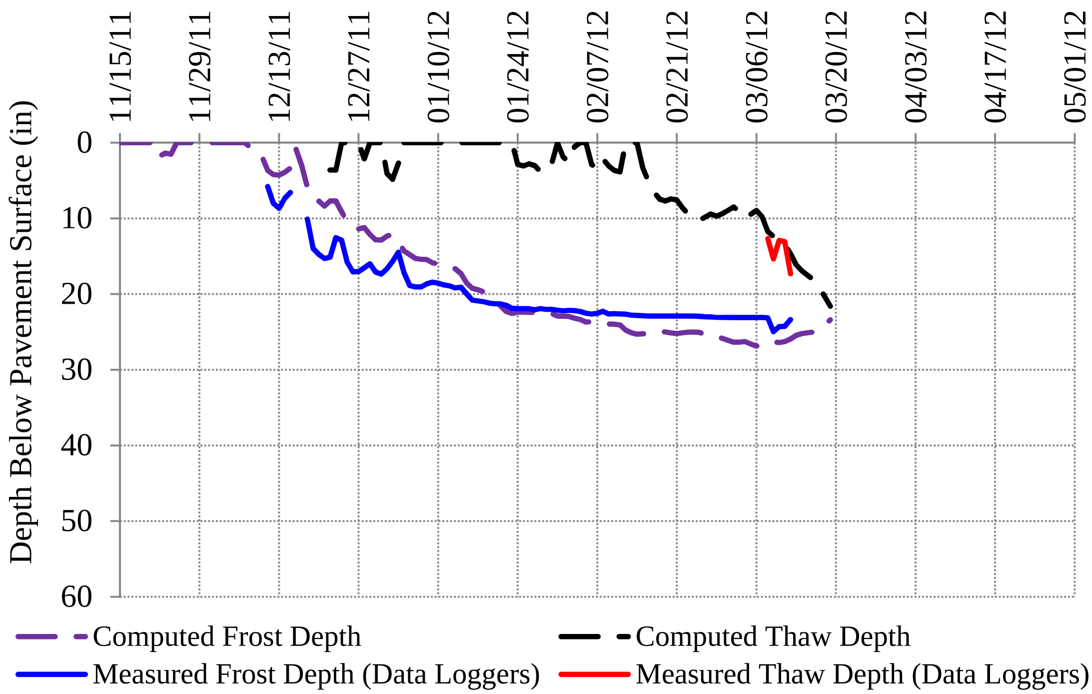


Figure B41 - NGR 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

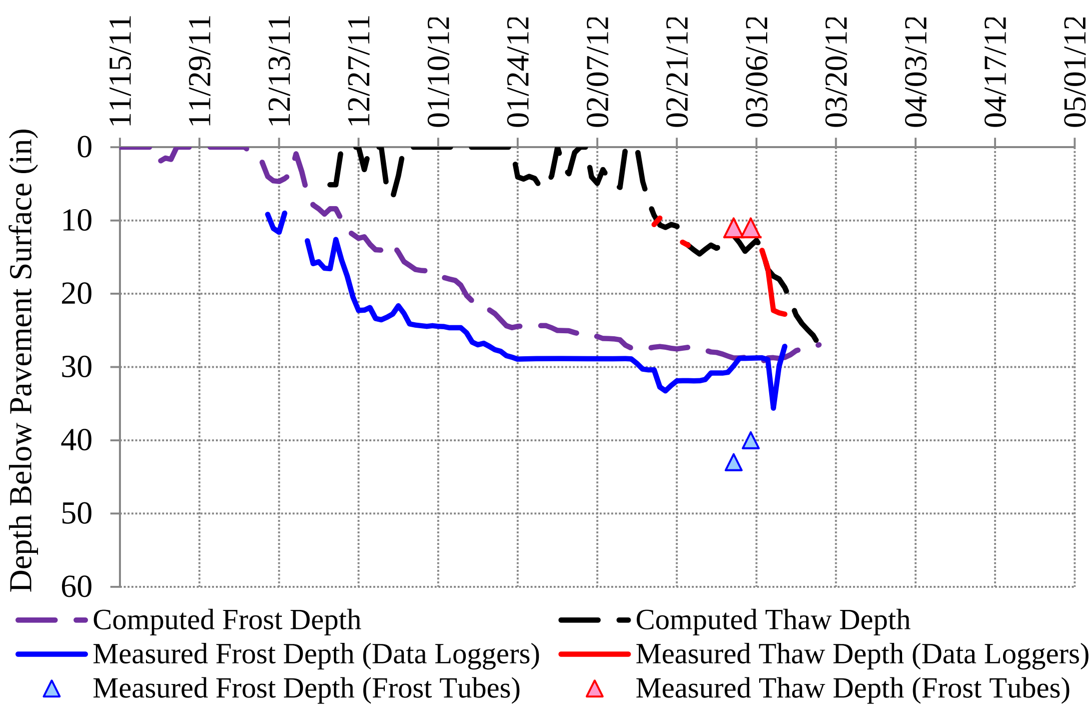


Figure B42 - RUM 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

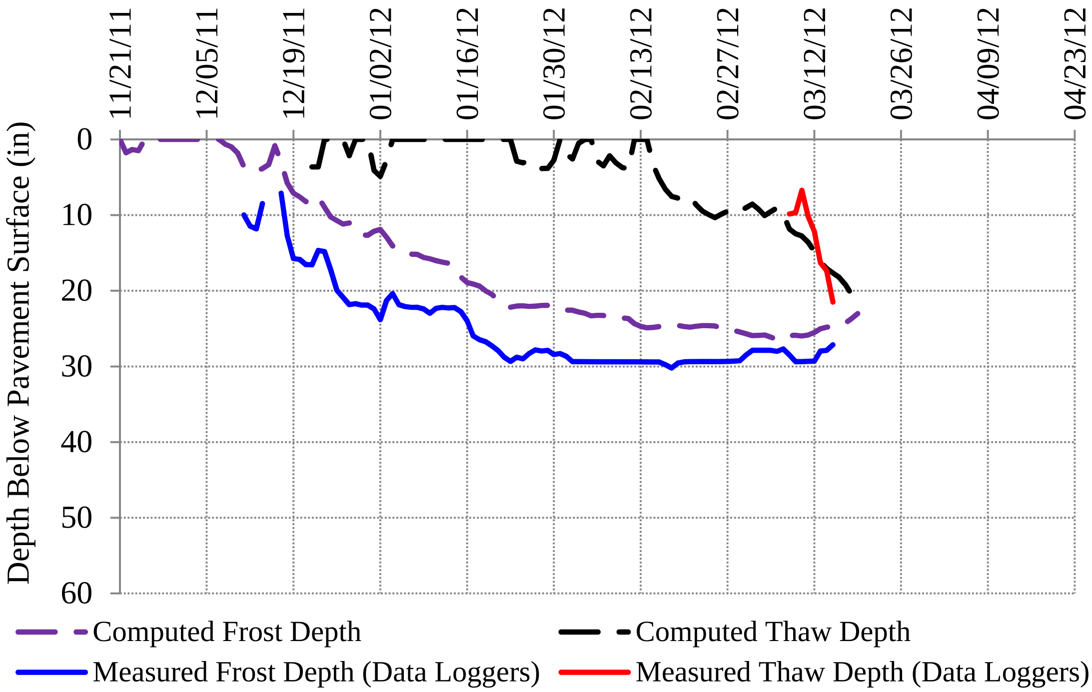


Figure B43 - SLR 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

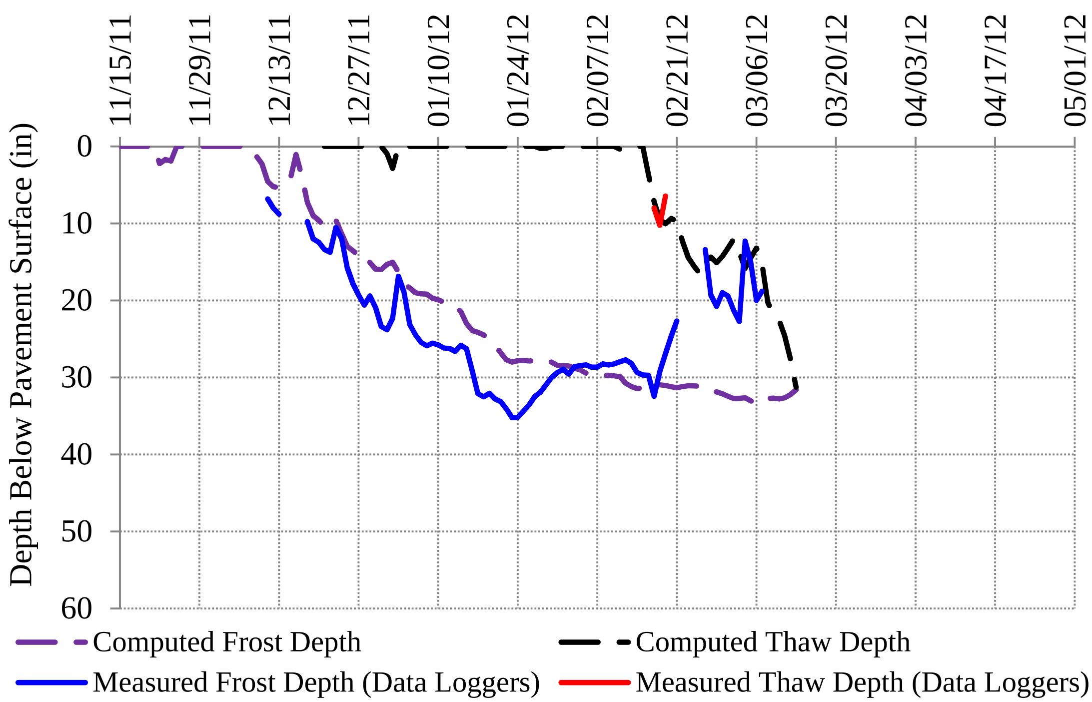


Figure B44 - WF 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

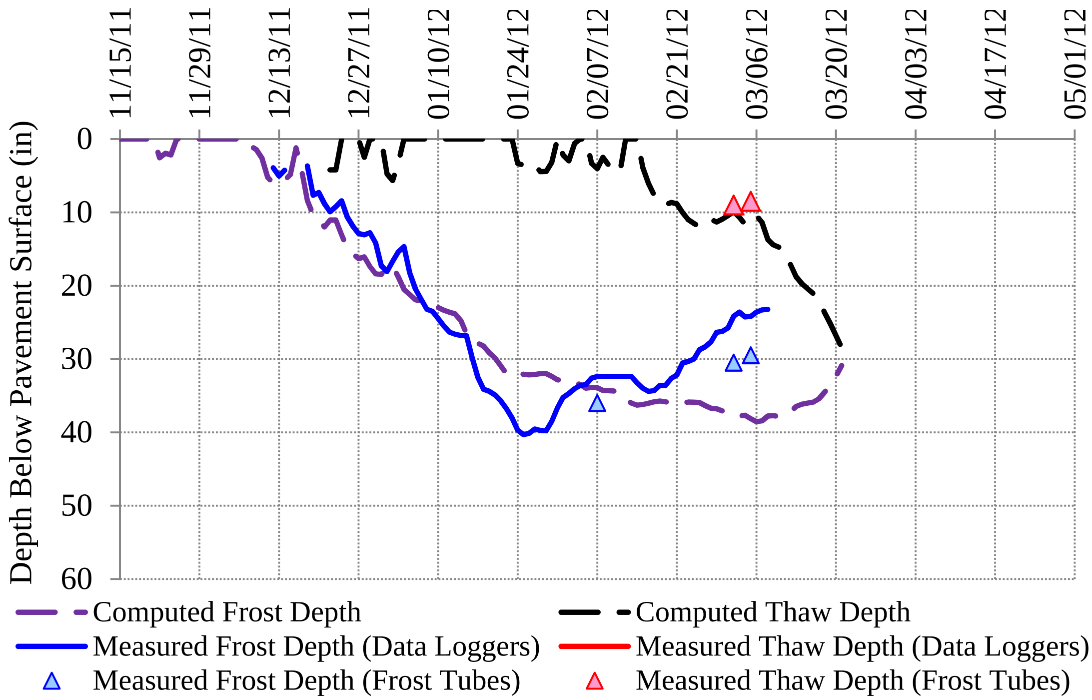


Figure B45 - WS 2011-2012 Modified Freeze-Thaw Index Model Computed vs. Measured Frost-Thaw Depths

Appendix C - Modified Model 158 Calculated vs. Measured Frost-Thaw Depths

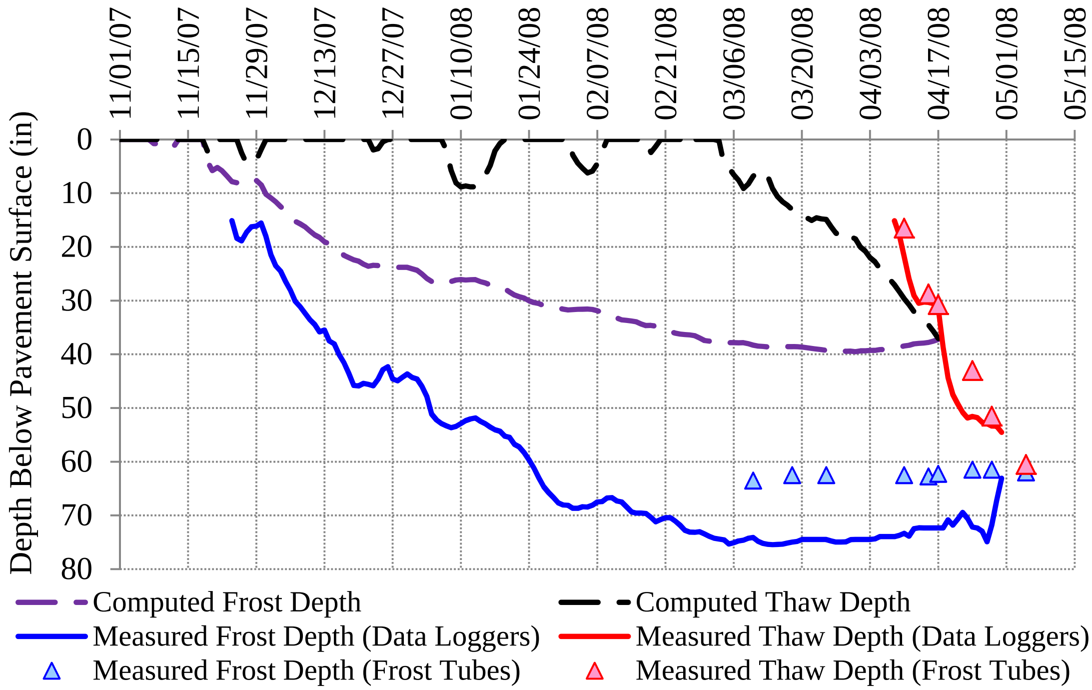


Figure C1 - K-1 2007-2008 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

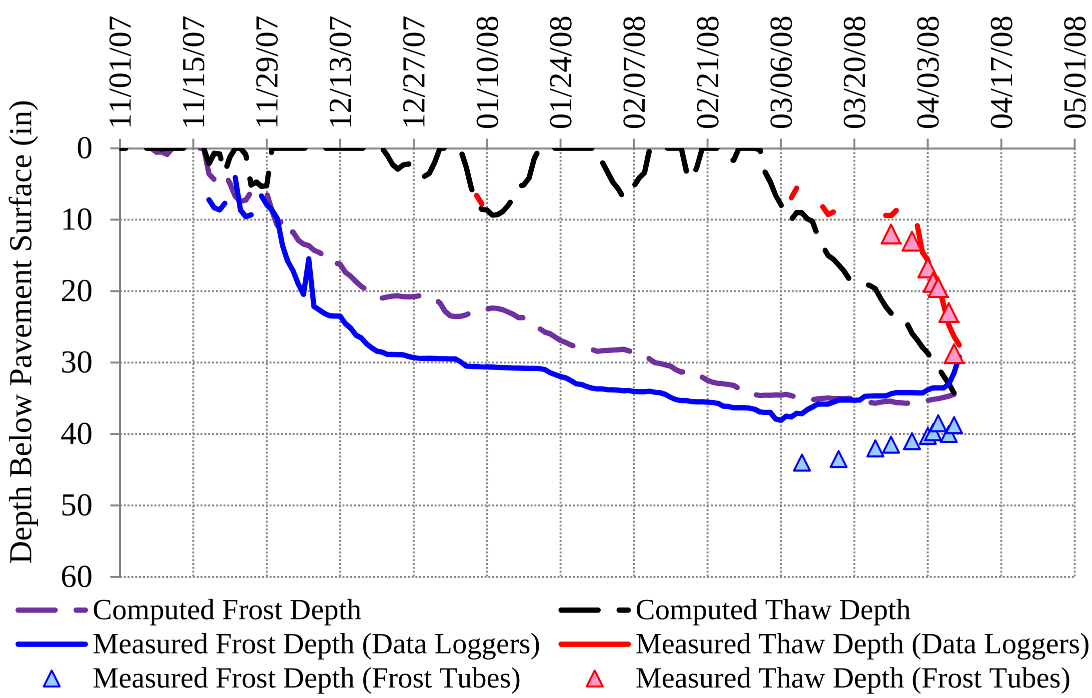


Figure C2 - LT 2007-2008 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

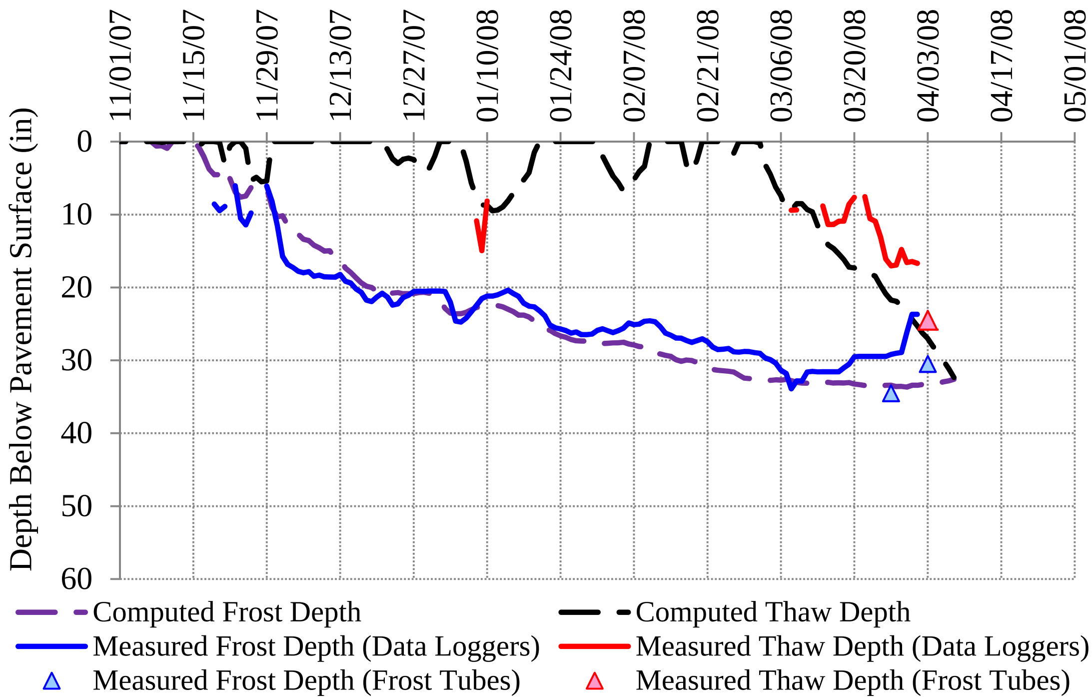


Figure C3 - NGR 2007-2008 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

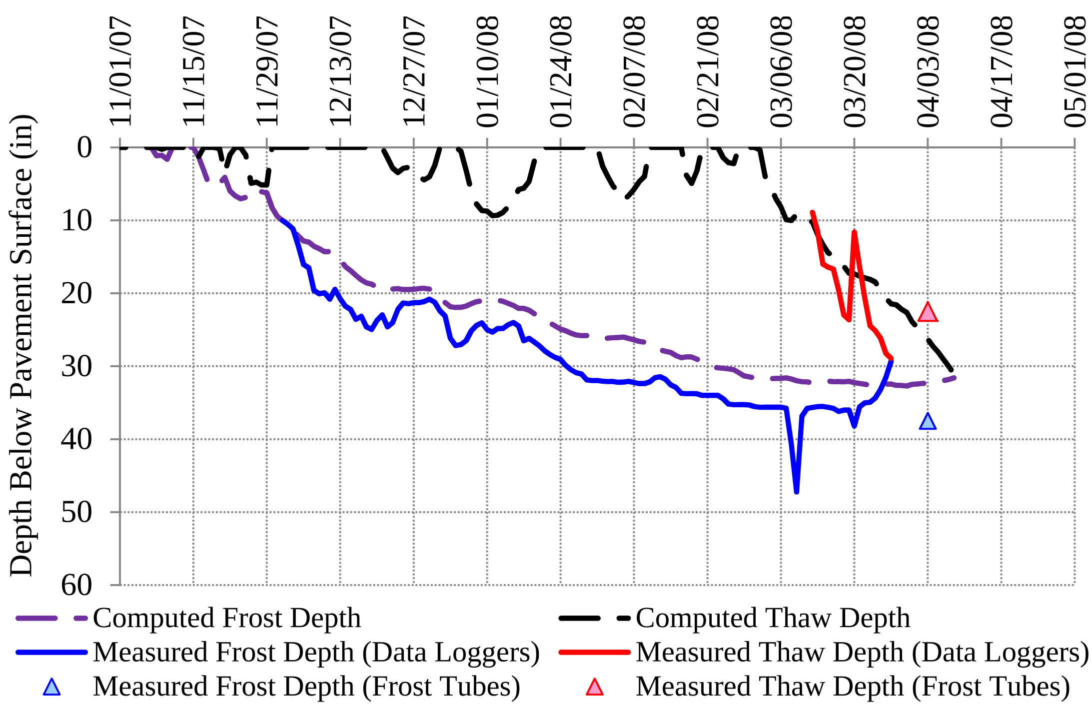


Figure C4 - RUM 2007-2008 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

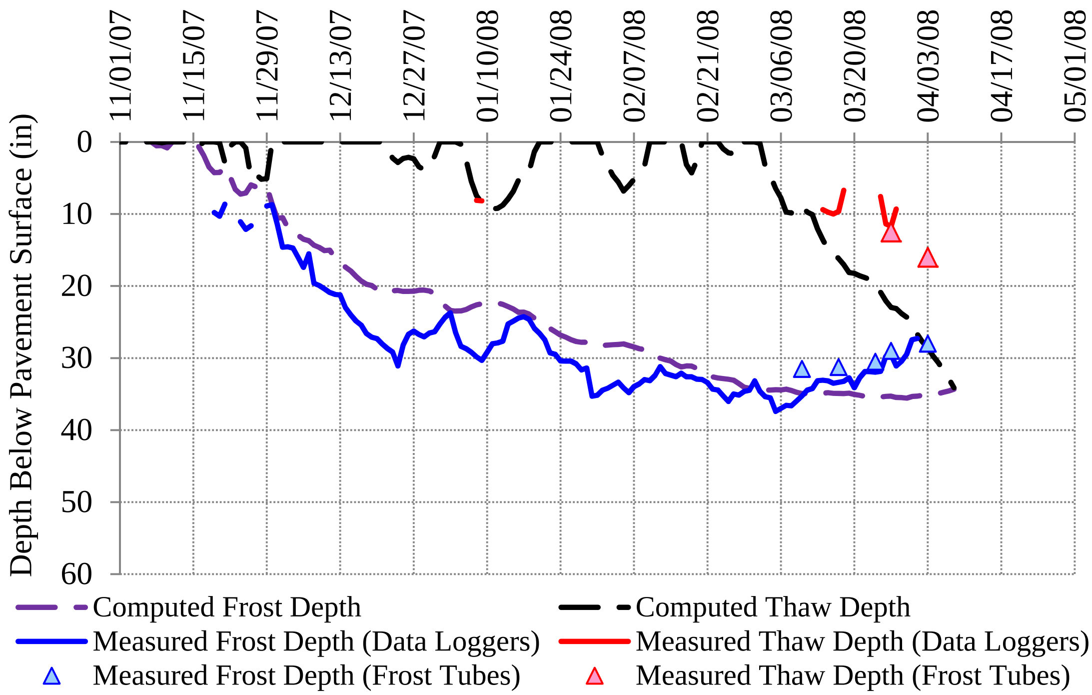


Figure C5 - SLR 2007-2008 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

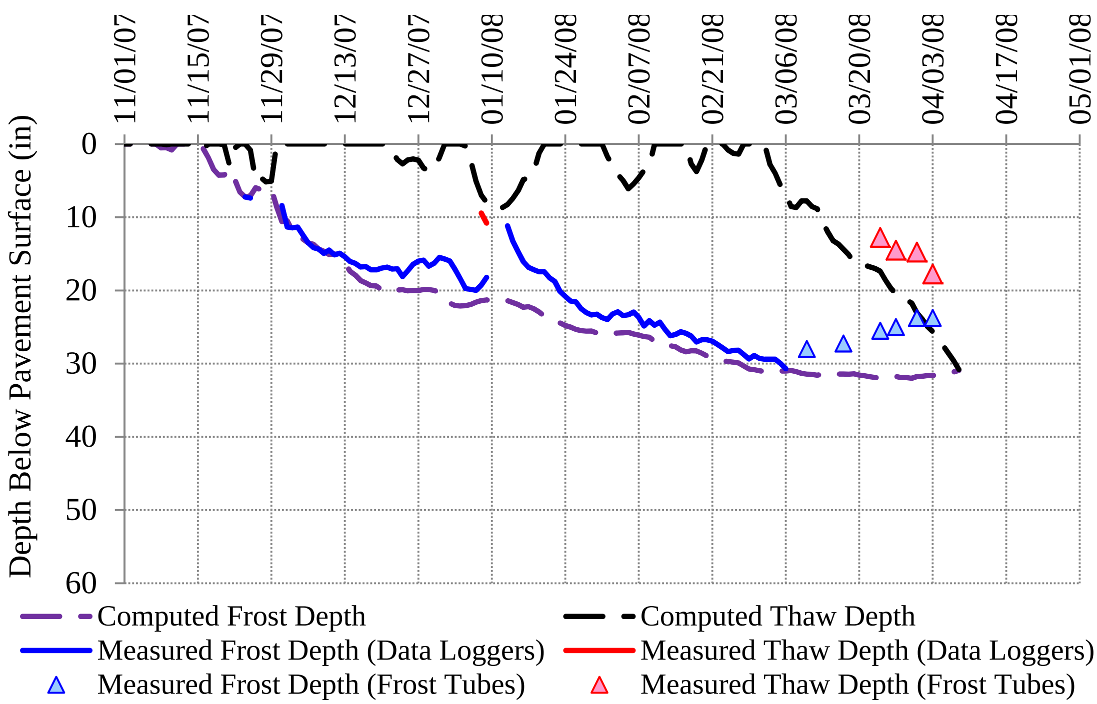


Figure C6 - WF 2007-2008 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

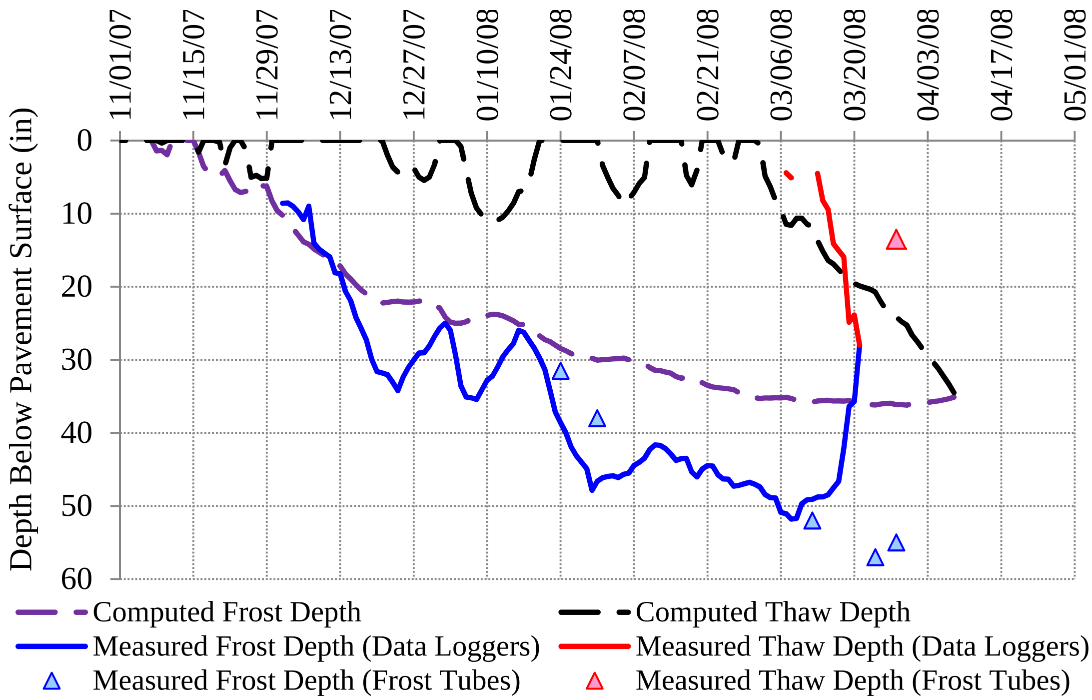


Figure C7 - WS 2007-2008 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

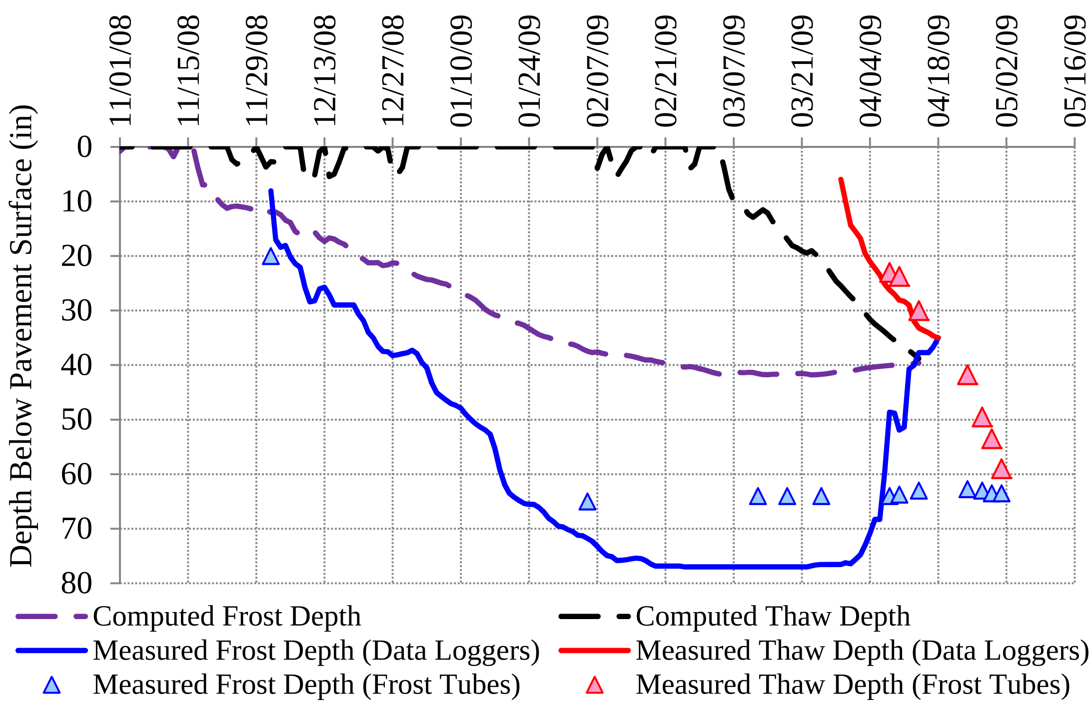


Figure C8 - K-1 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

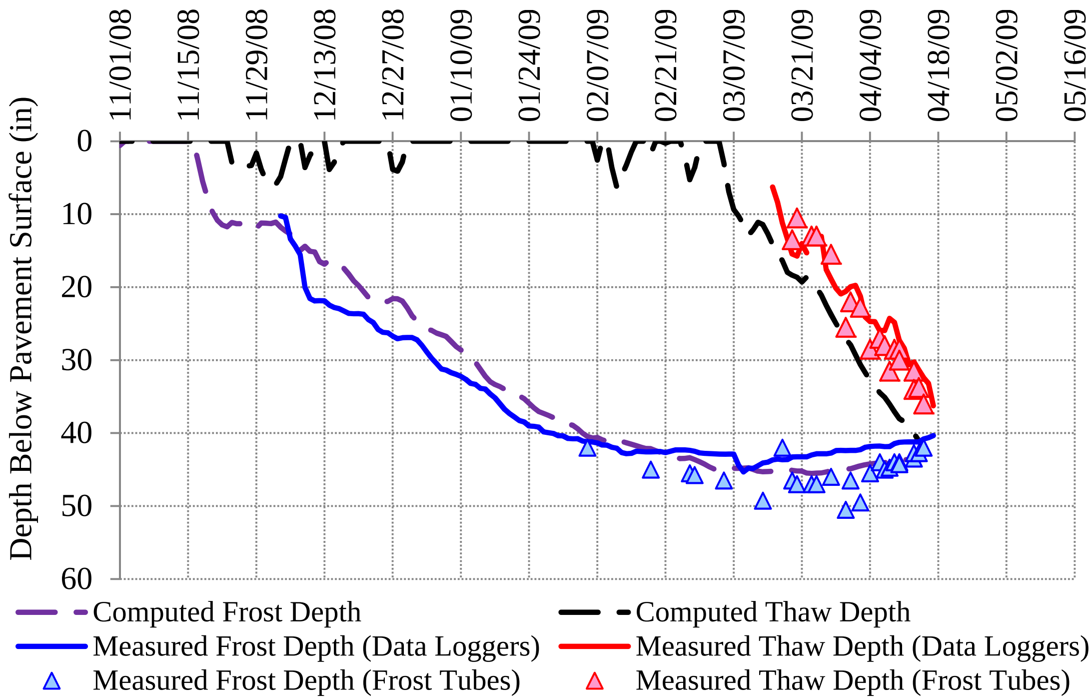


Figure C9 - LT 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

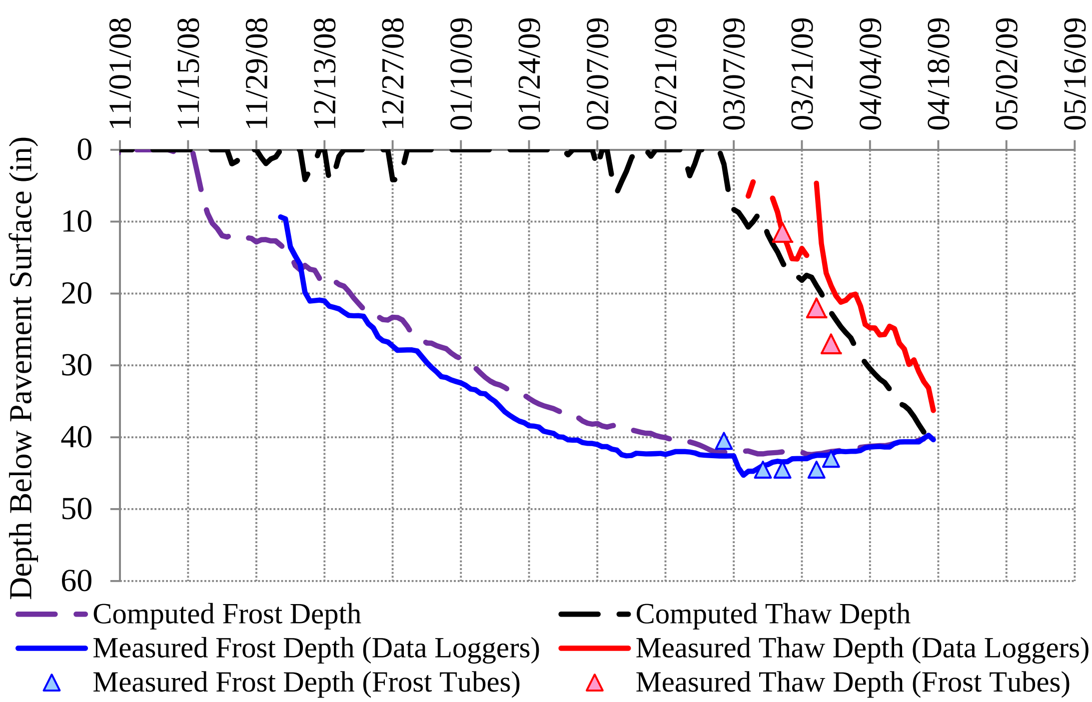


Figure C10 - NGR 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

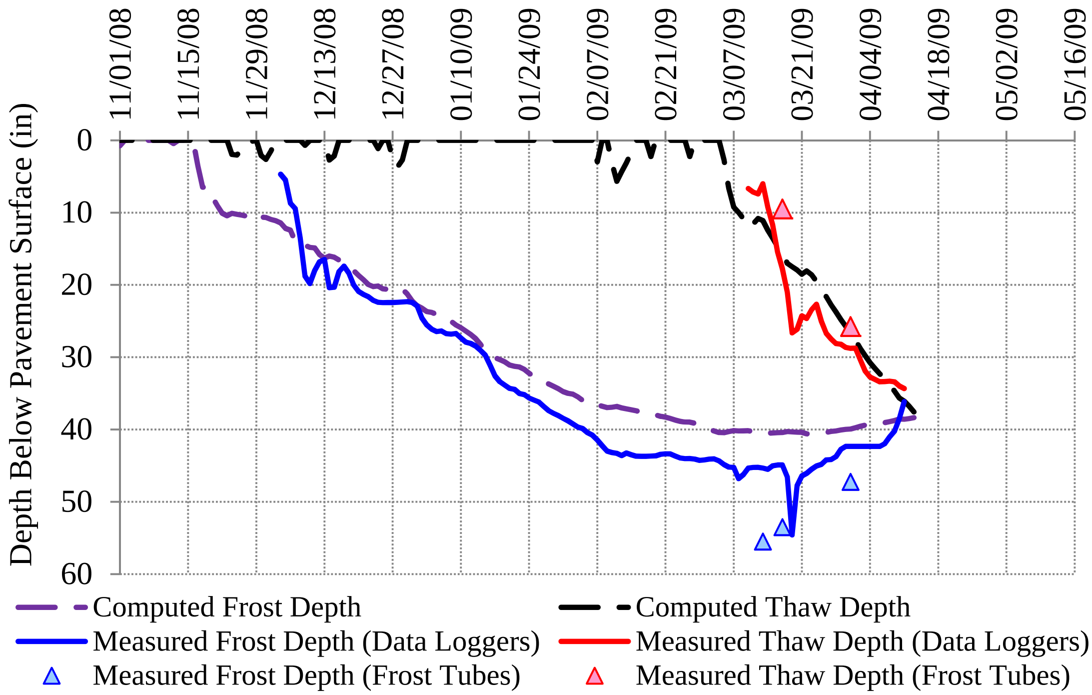


Figure C11 - RUM 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

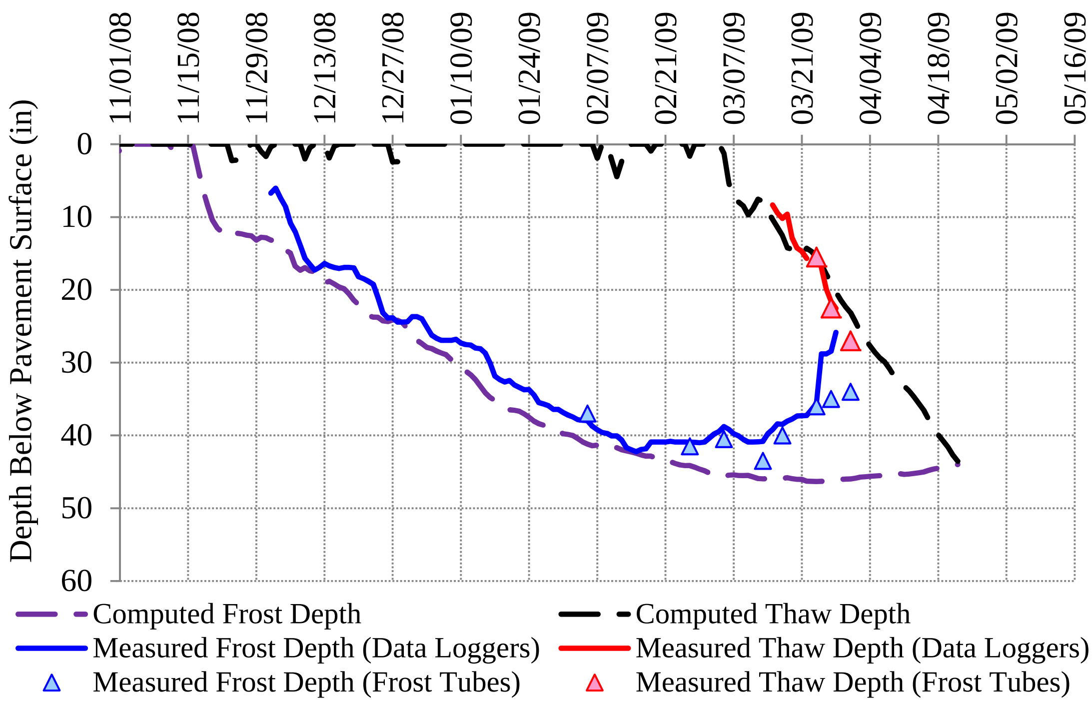


Figure C12 - SLR 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

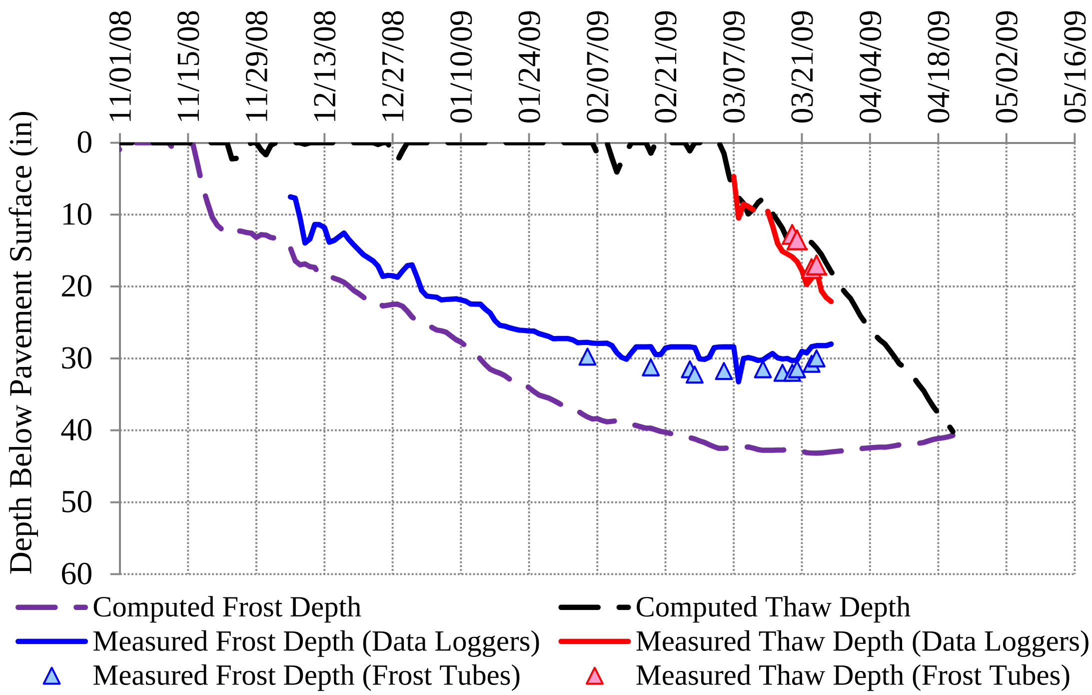


Figure C13 - WF 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

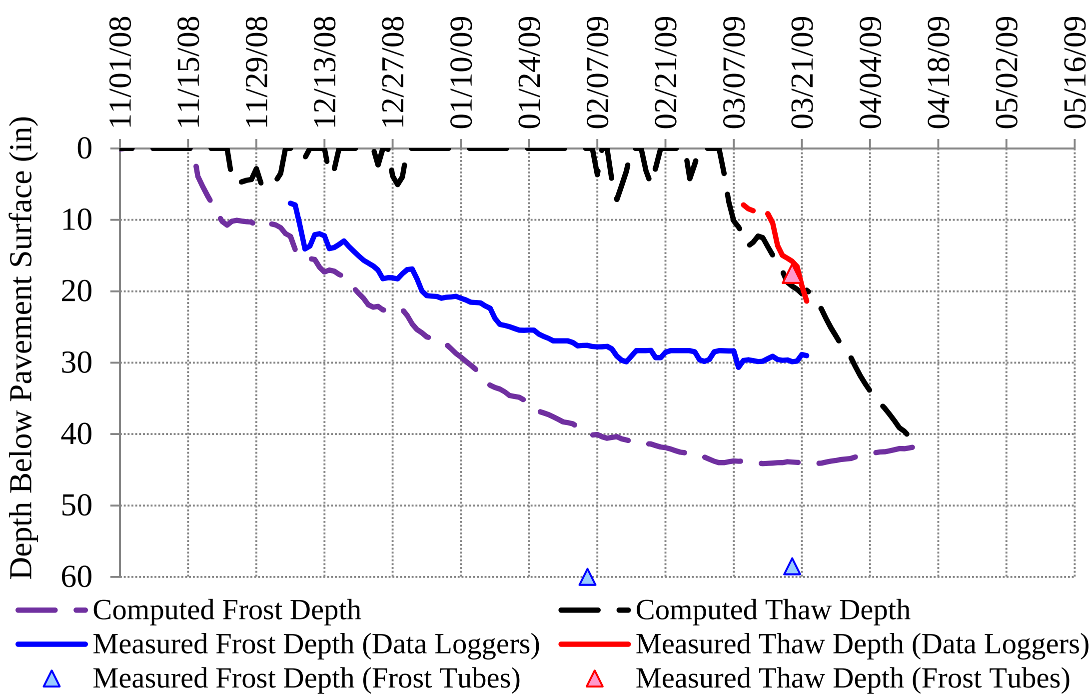


Figure C14 - WS 2008-2009 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

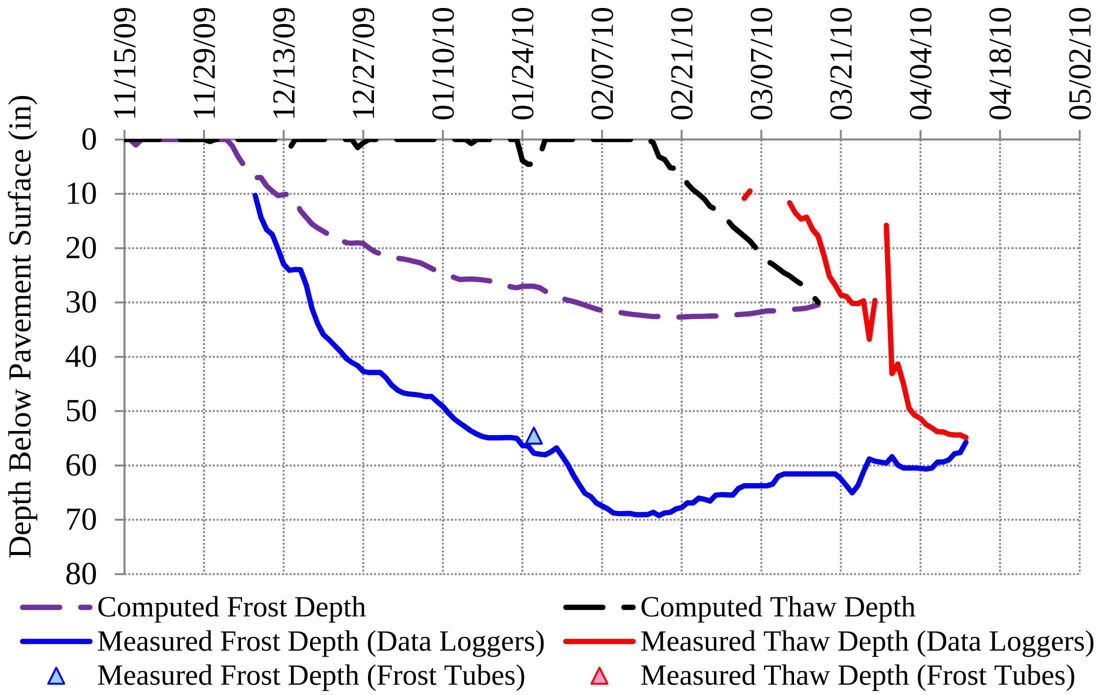


Figure C15 - K-1 2009-2010 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

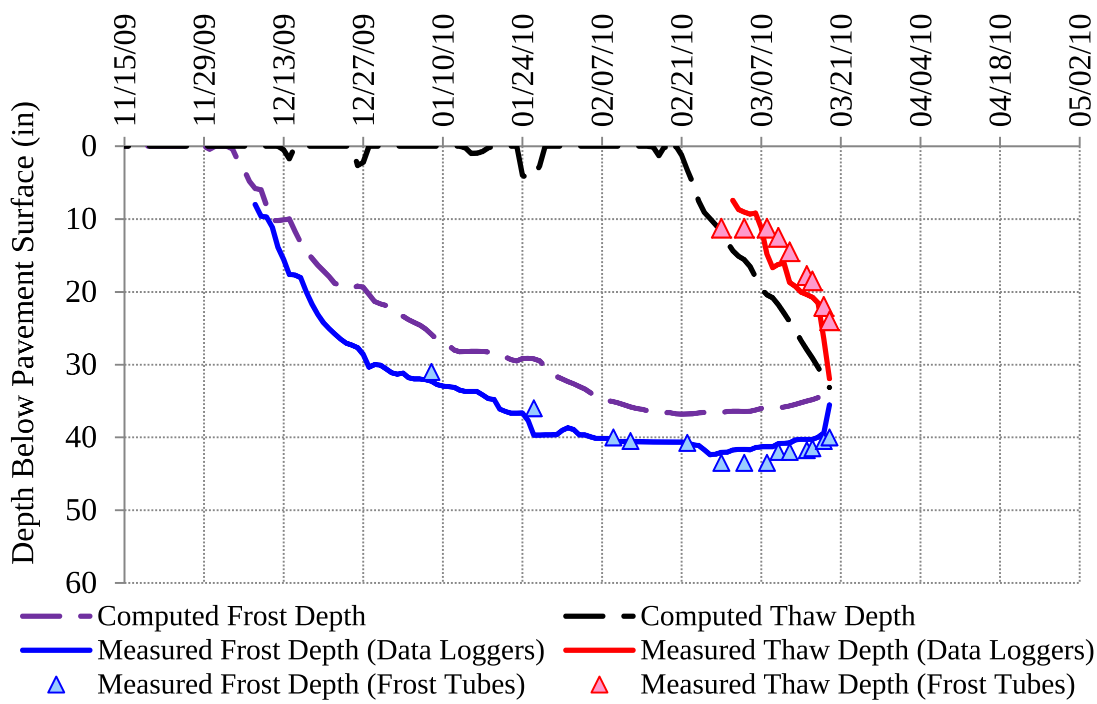


Figure C16 - LT 2009-2010 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

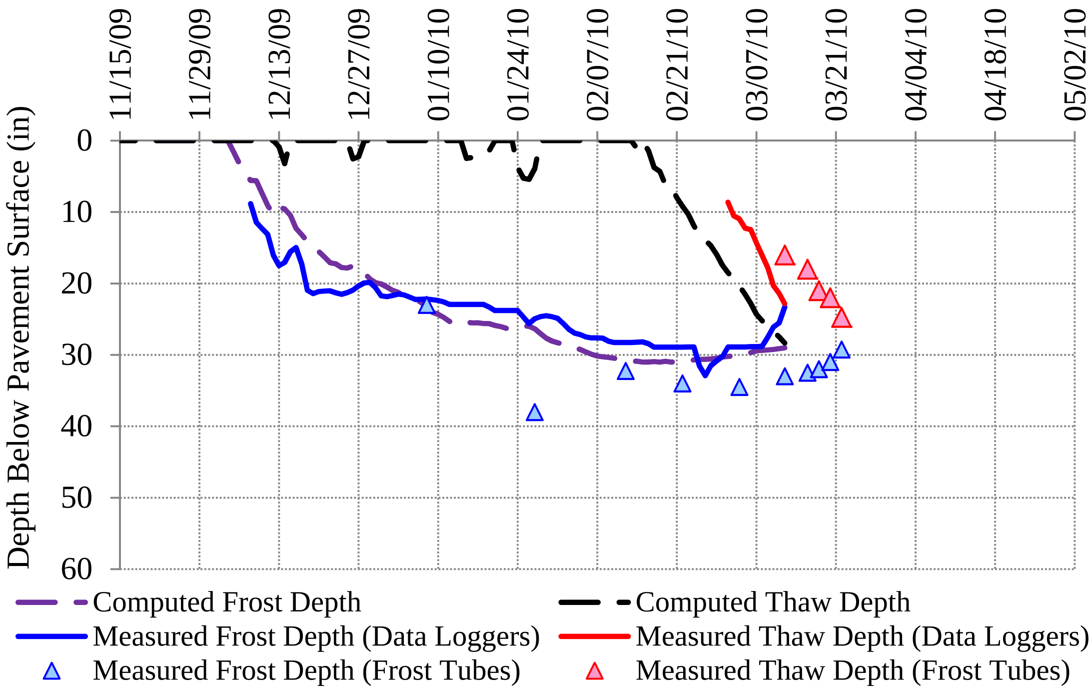
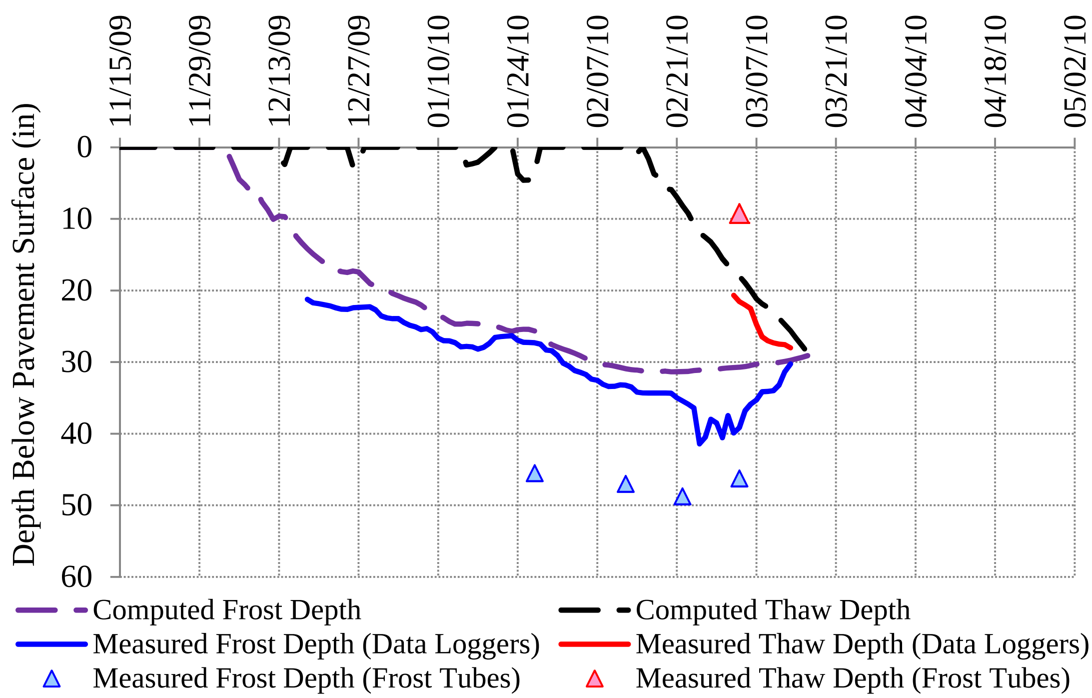


Figure C17 - NGR 2009-2010 Modified Model 158 Computed vs. Measured Frost-Thaw Depths



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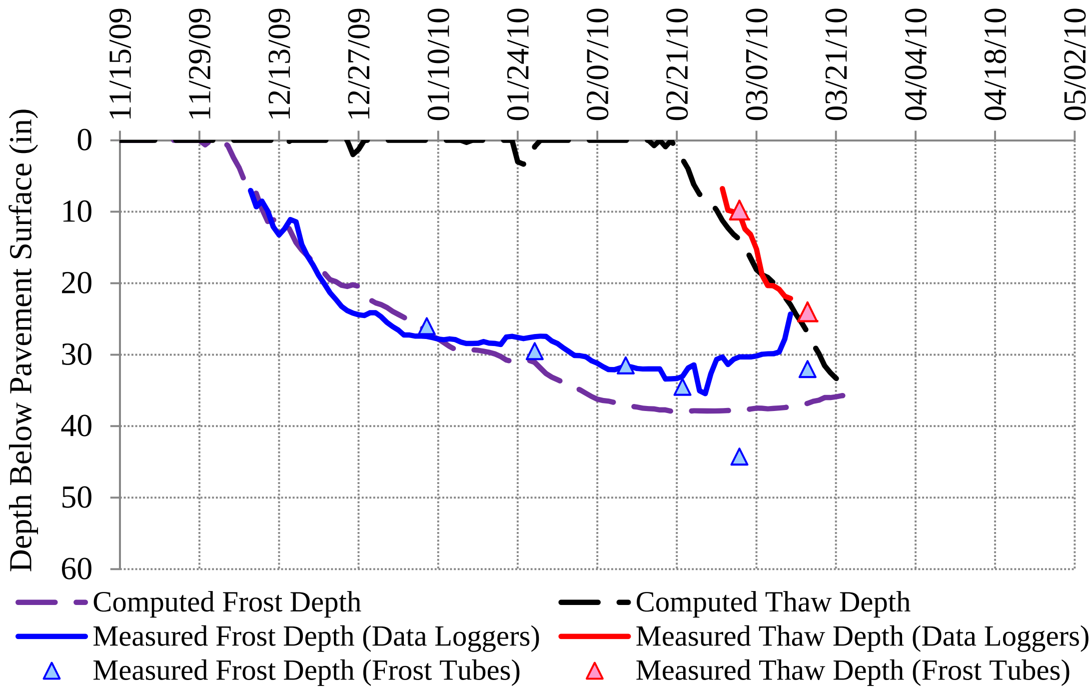


Figure C19 - SLR 2009-2010 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

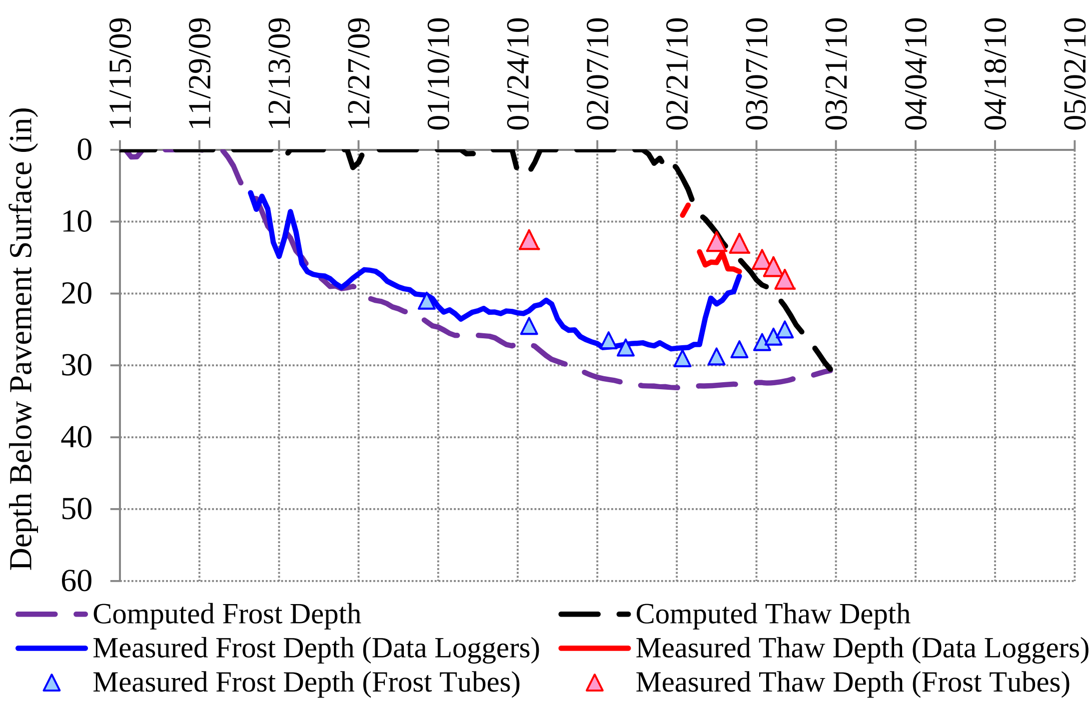


Figure C20 - WF 2009-2010 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

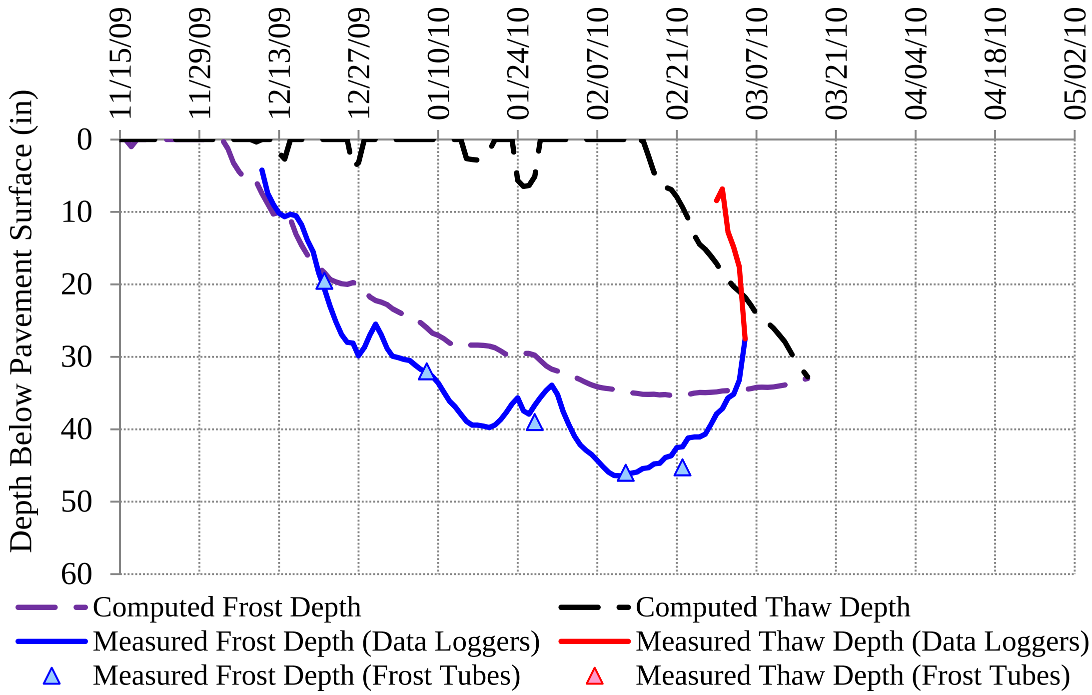


Figure C21 - WS 2009-2010 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

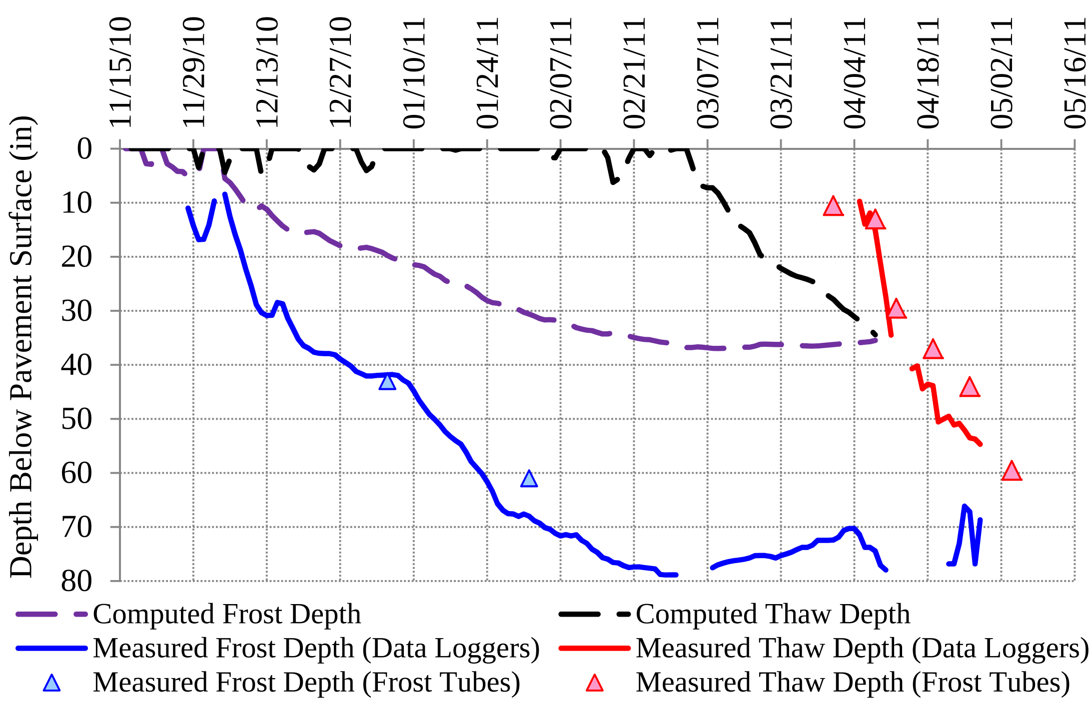
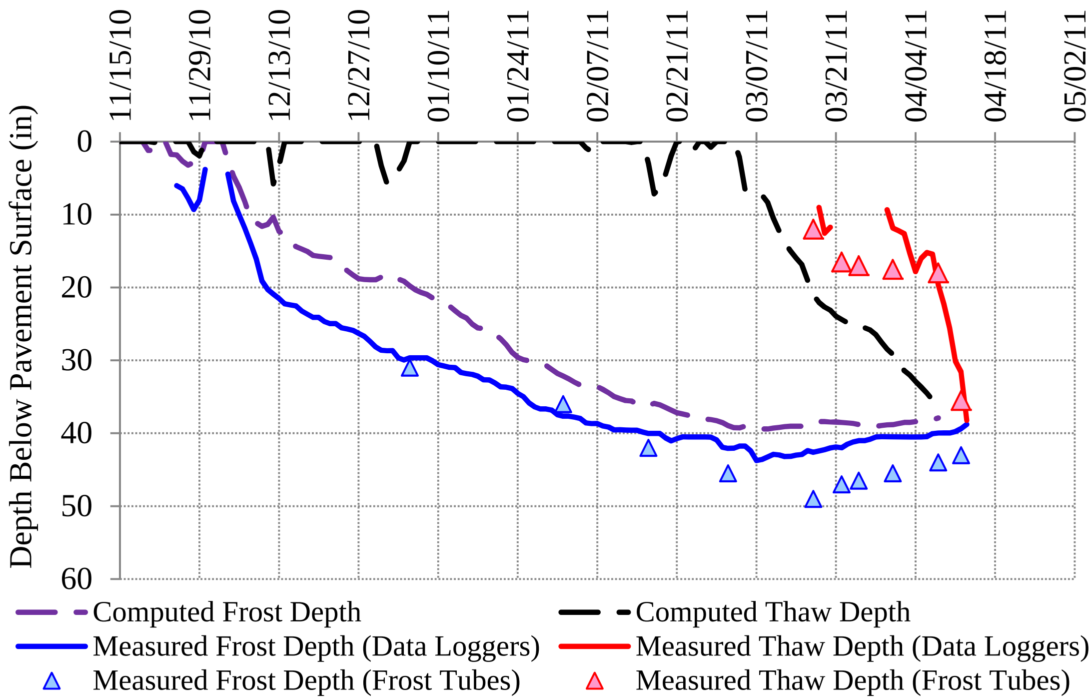


Figure C22 - K-1 2010-2011 Modified Model 158 Computed vs. Measured Frost-Thaw Depths



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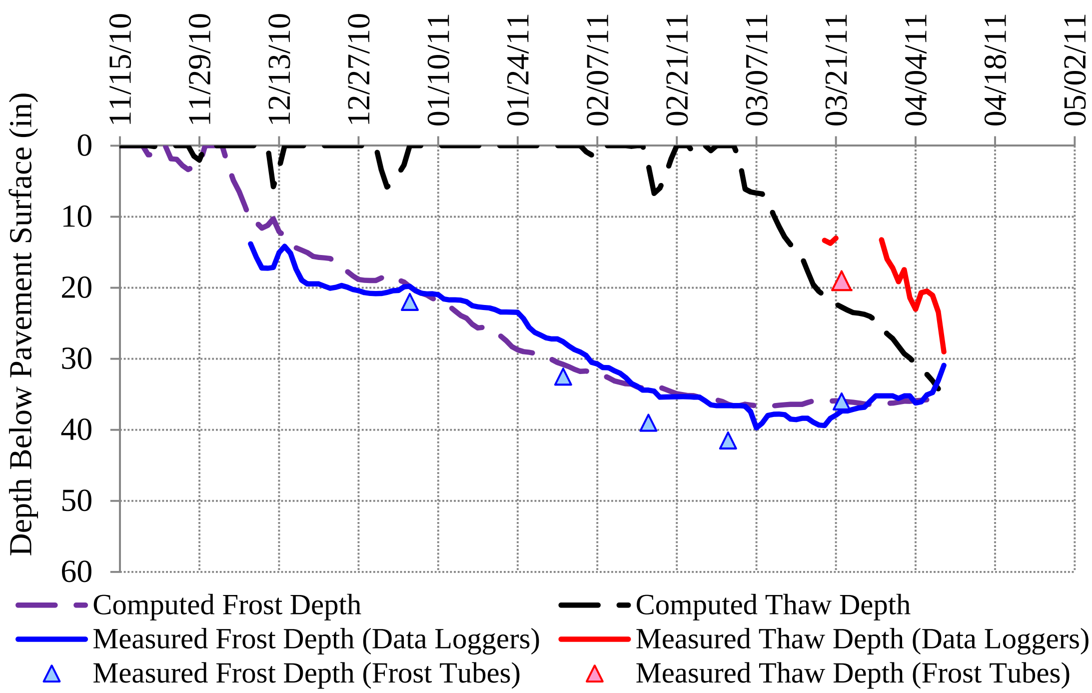


Figure C24 - NGR 2010-2011 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

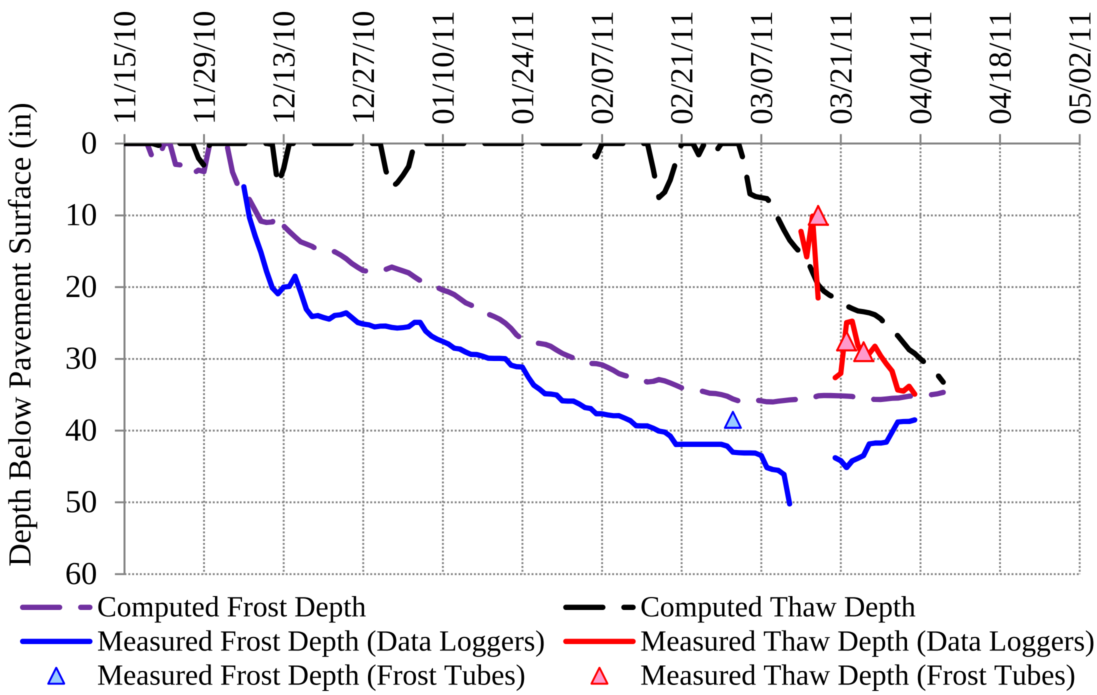


Figure C25 - RUM 2010-2011 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

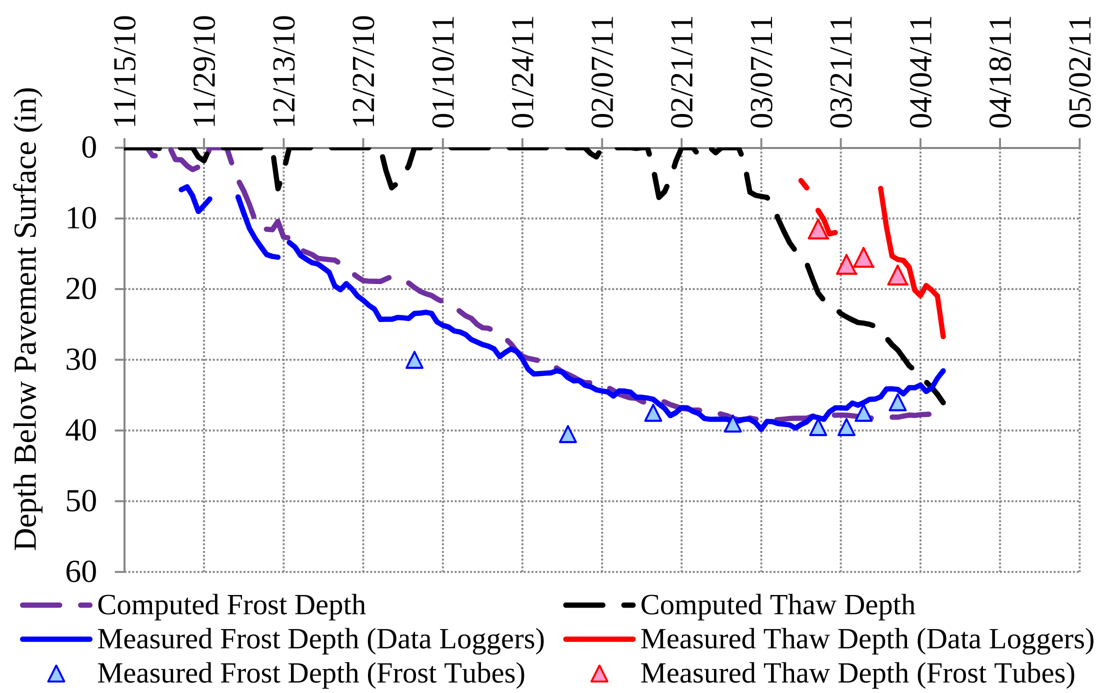


Figure C26 - SLR 2010-2011 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

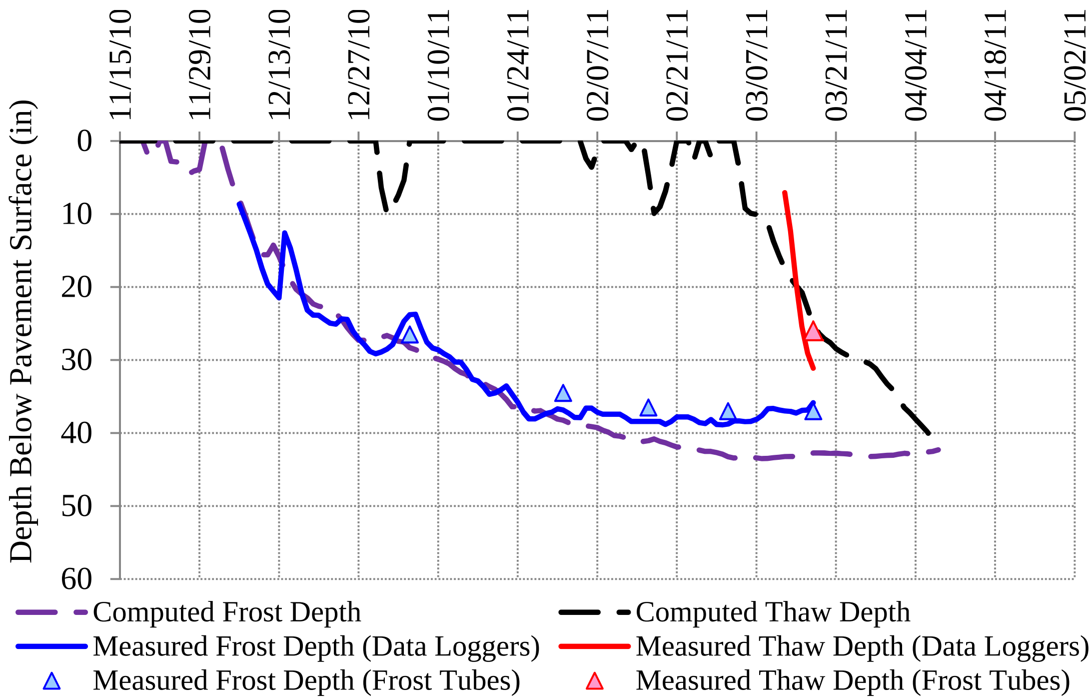


Figure C27 - WF 2010-2011 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

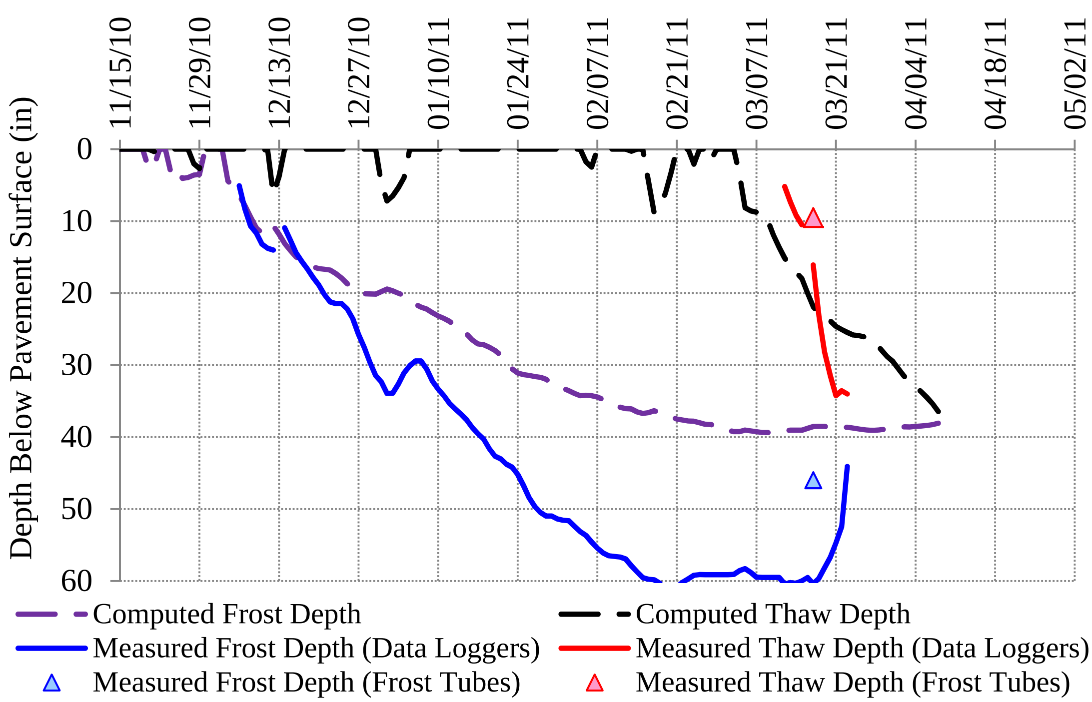


Figure C28 - WS 2010-2011 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

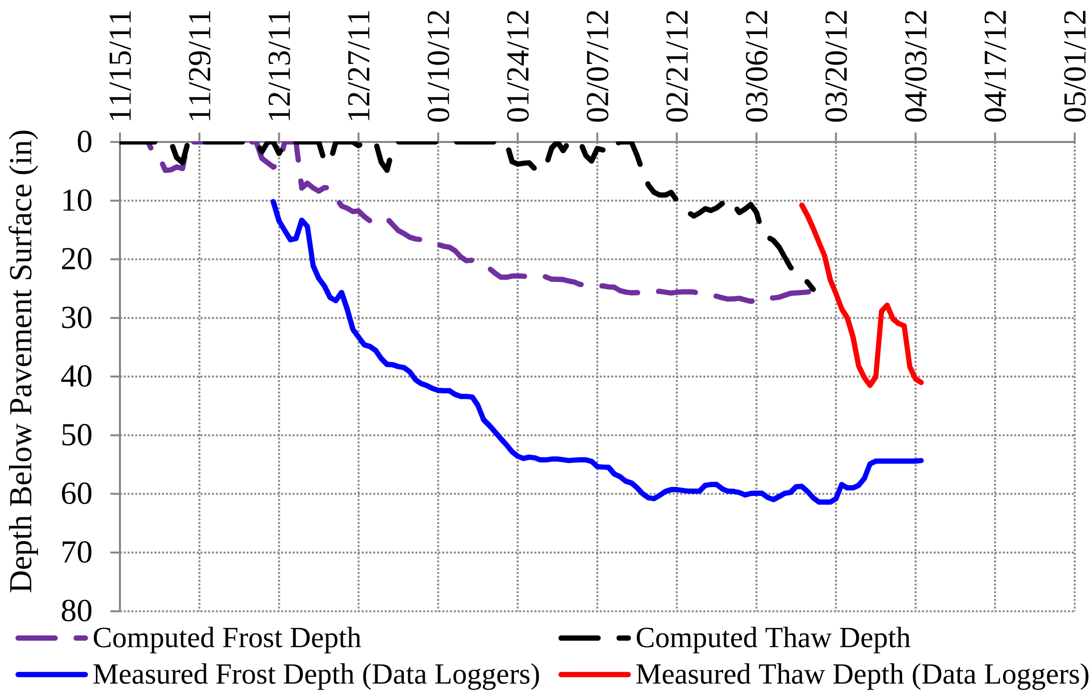


Figure C29 - K-1 2011-2012 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

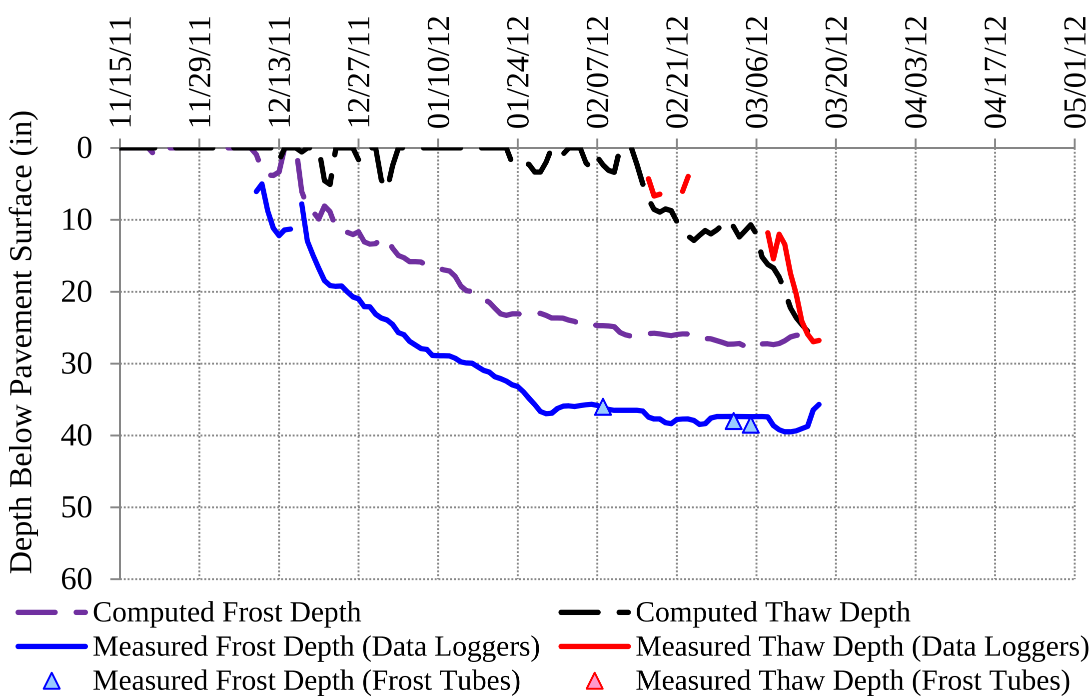


Figure C30 - LT 2011-2012 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

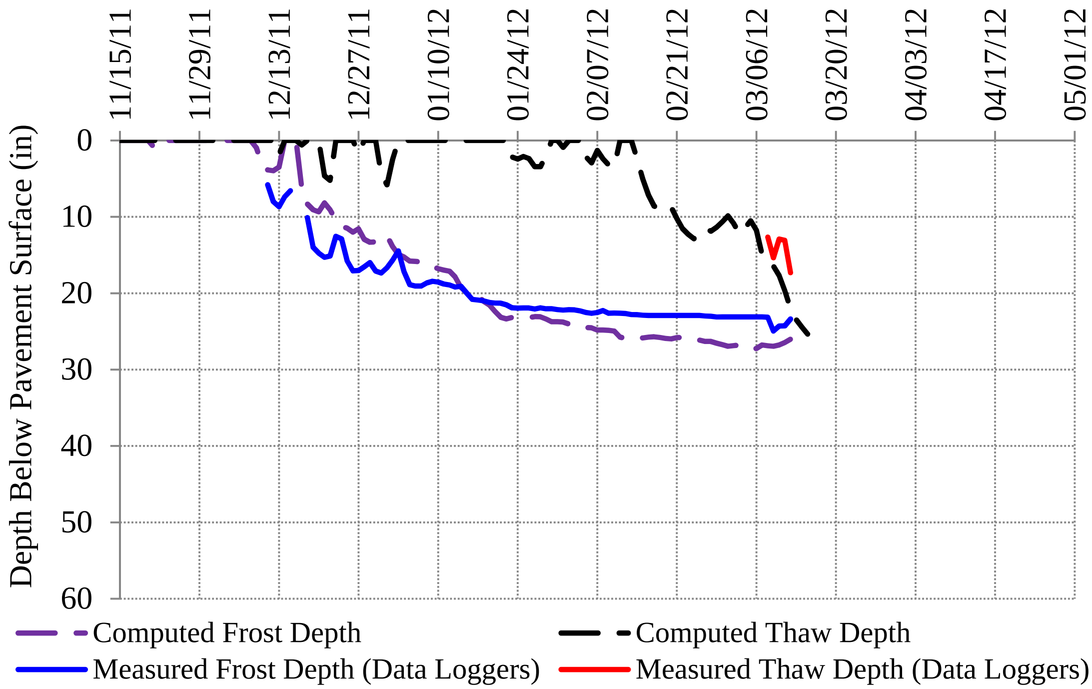


Figure C31 - NGR 2011-2012 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

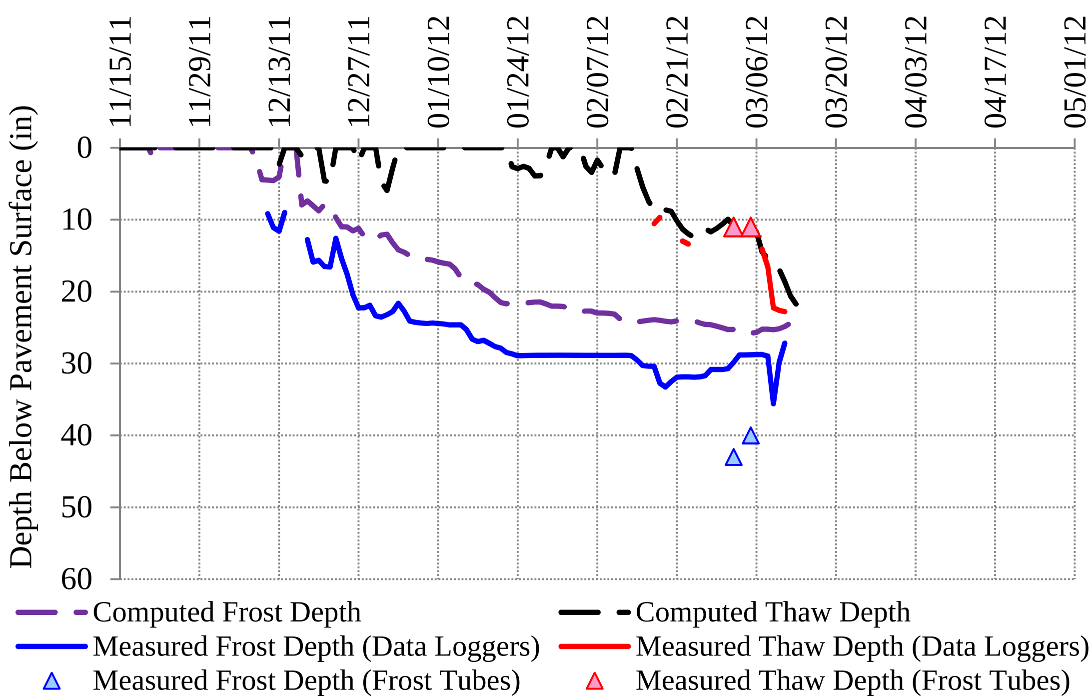


Figure C32 - RUM 2011-2012 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

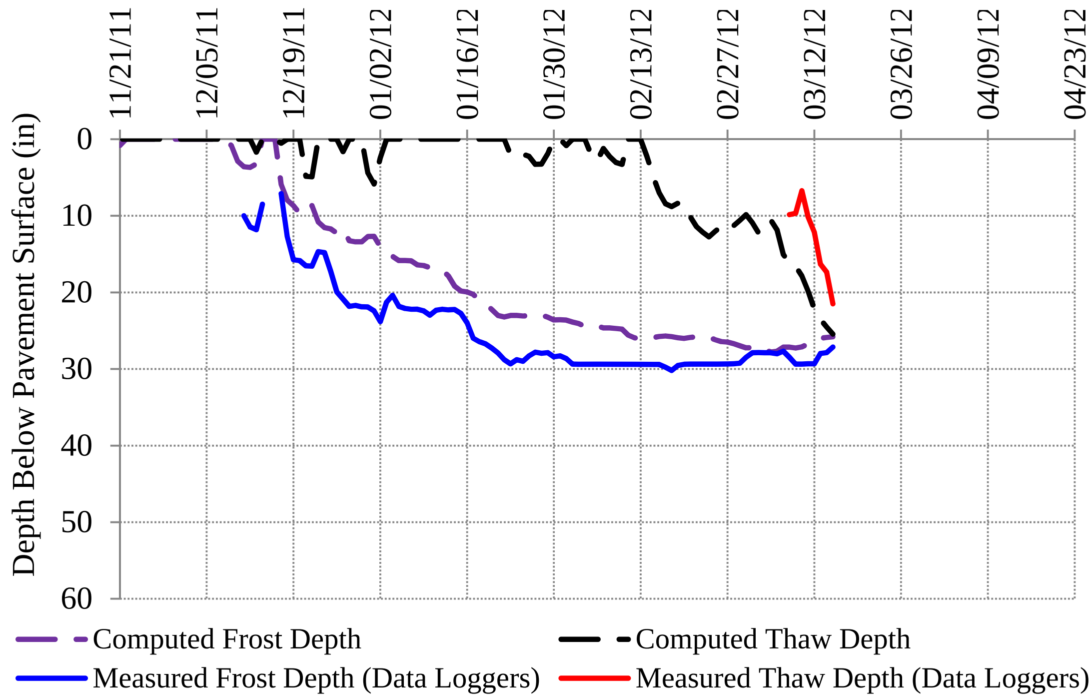


Figure C33 - SLR 2011-2012 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

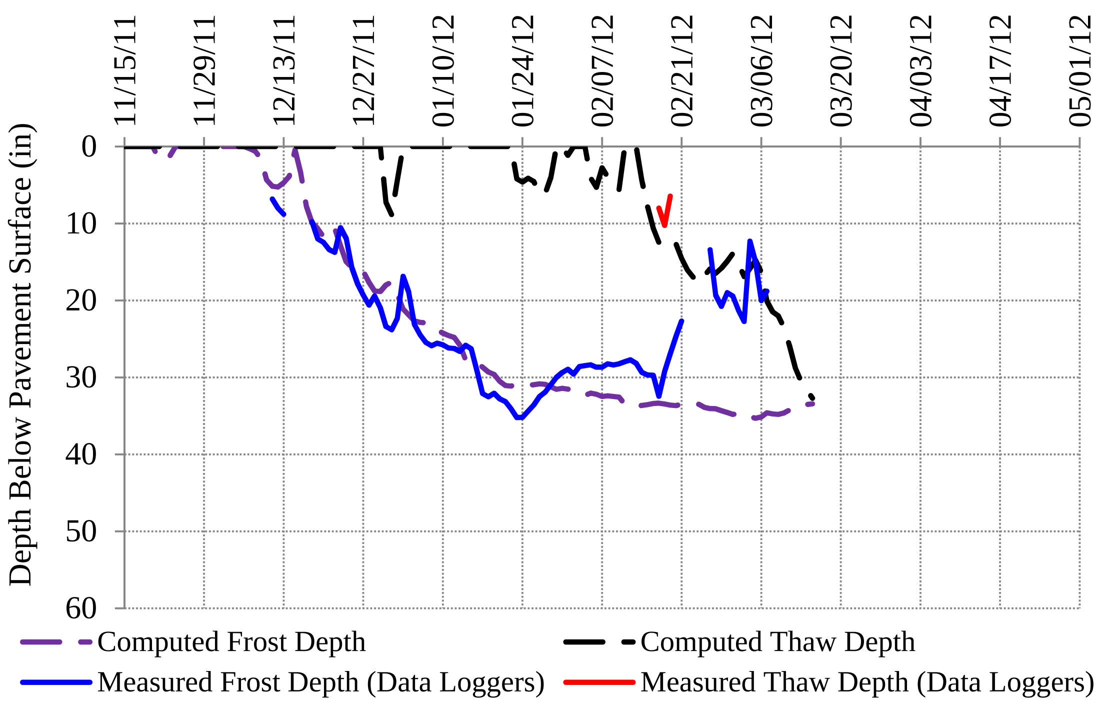


Figure C34 - WF 2011-2012 Modified Model 158 Computed vs.
Measured Frost-Thaw Depths

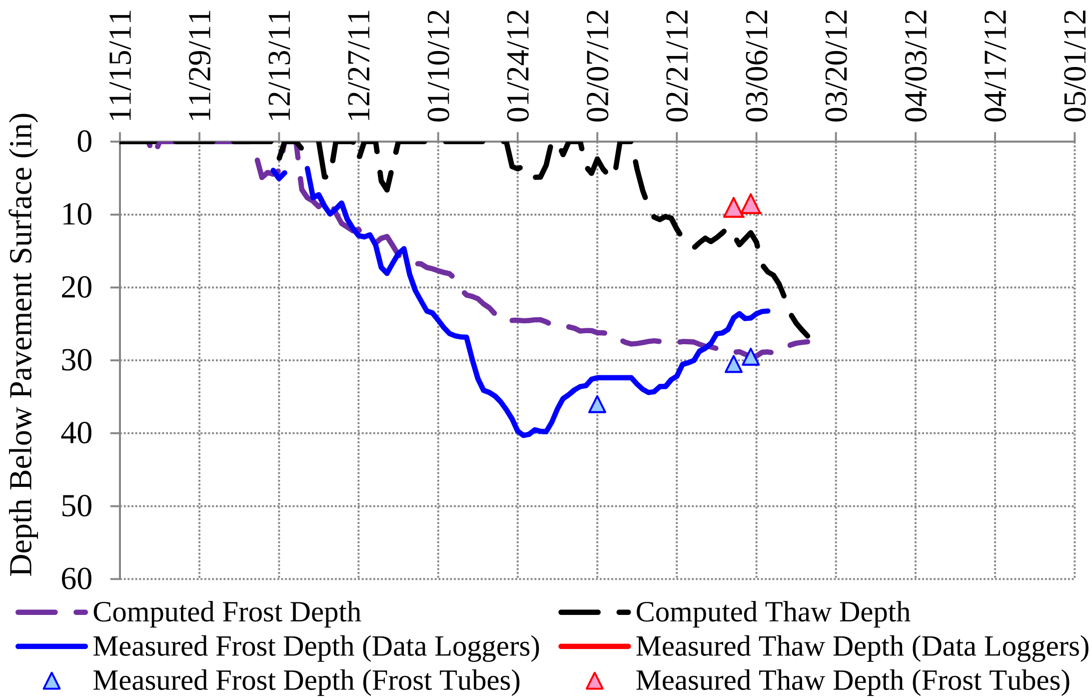


Figure C35 - WS 2011-2012 Modified Model 158 Computed vs. Measured Frost-Thaw Depths

Appendix D - EICM Calculated vs. Measured Frost-Thaw Depths

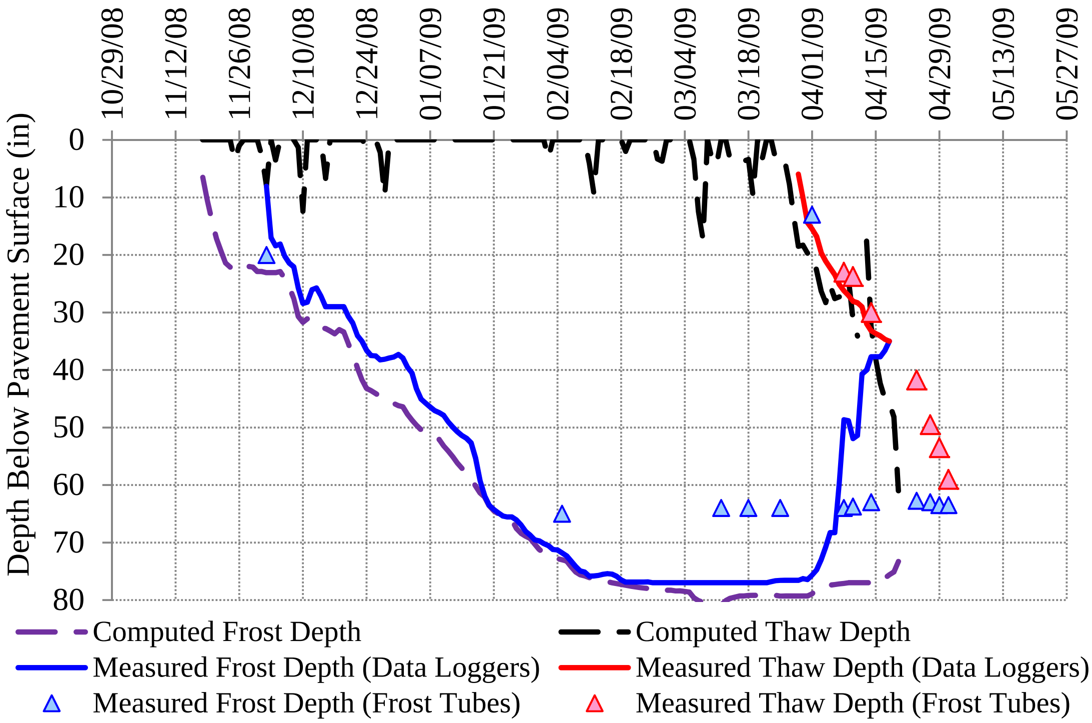


Figure D1 - K-1 2008-2009 EICM Computed vs. Measured Frost-Thaw Depths

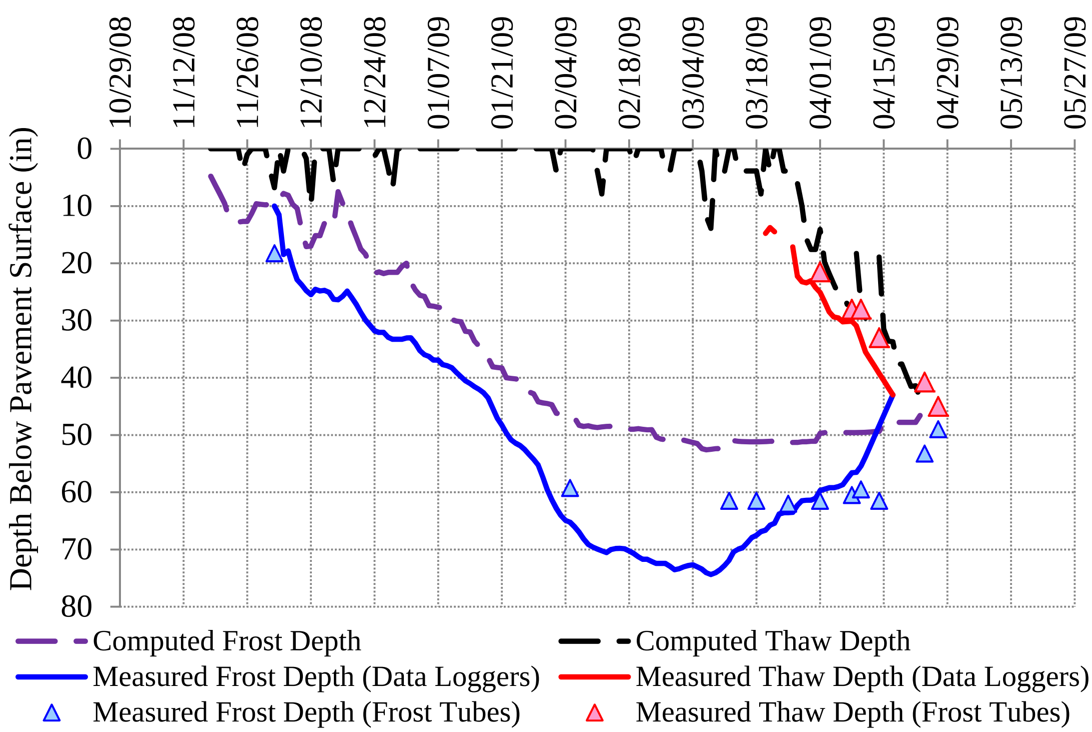


Figure D2 - K-2 2008-2009 EICM Computed vs. Measured Frost-Thaw Depths

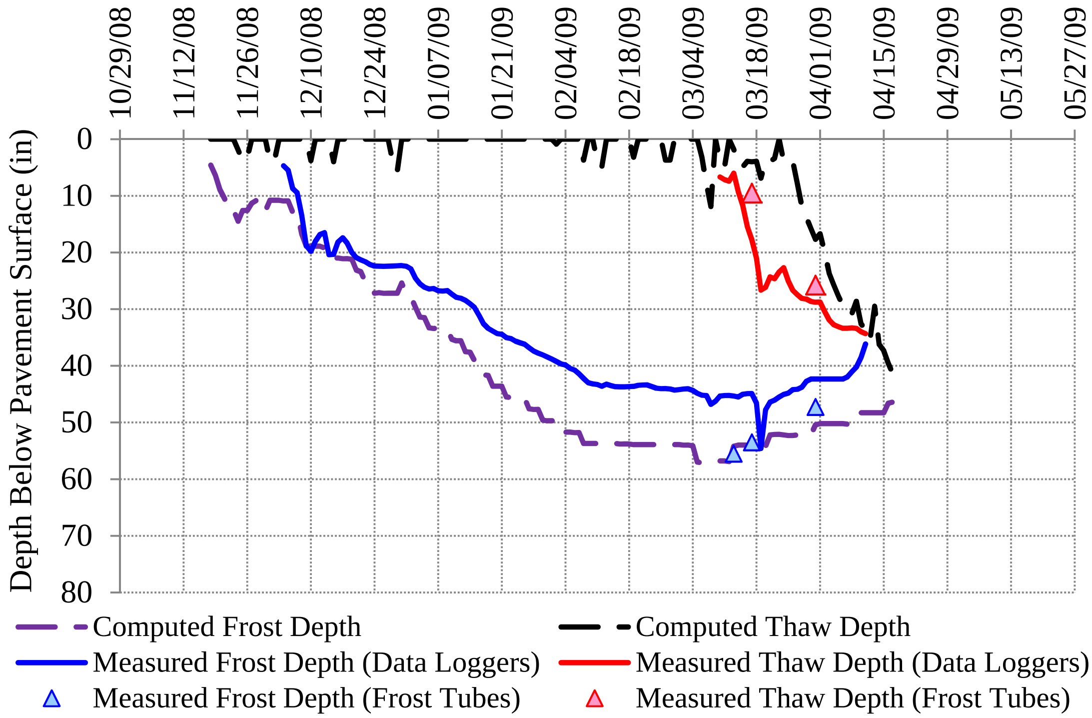


Figure D3 - RUM 2008-2009 EICM Computed vs. Measured Frost-Thaw Depths

Appendix E - SLR Application and Removal Methods

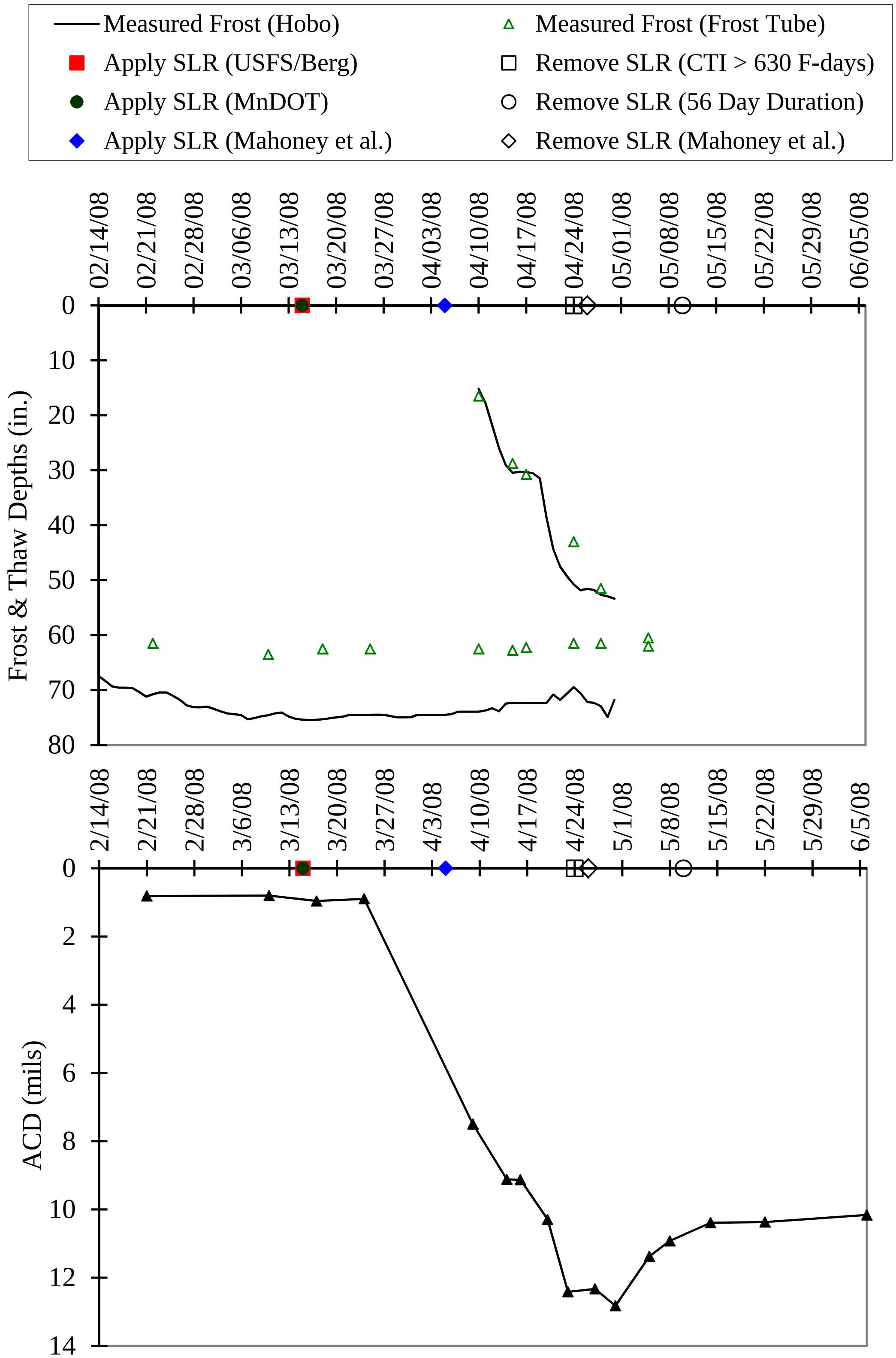
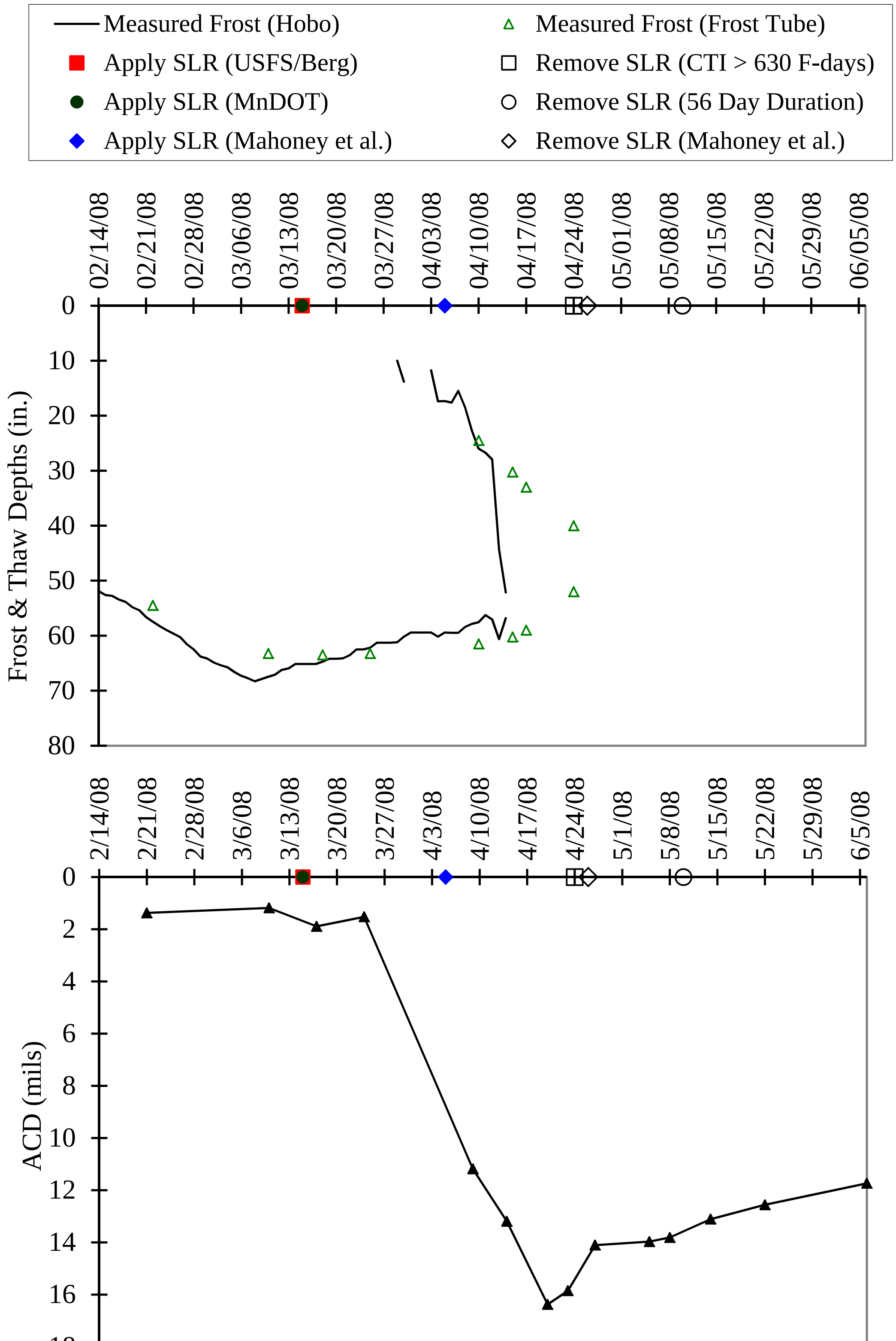


Figure E17 - K-1 Spring 2008 SLR Trigger Dates vs.
Measured Frost-Thaw Depths and ACD Data



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Measured Frost-Thaw Depths and ACD Data

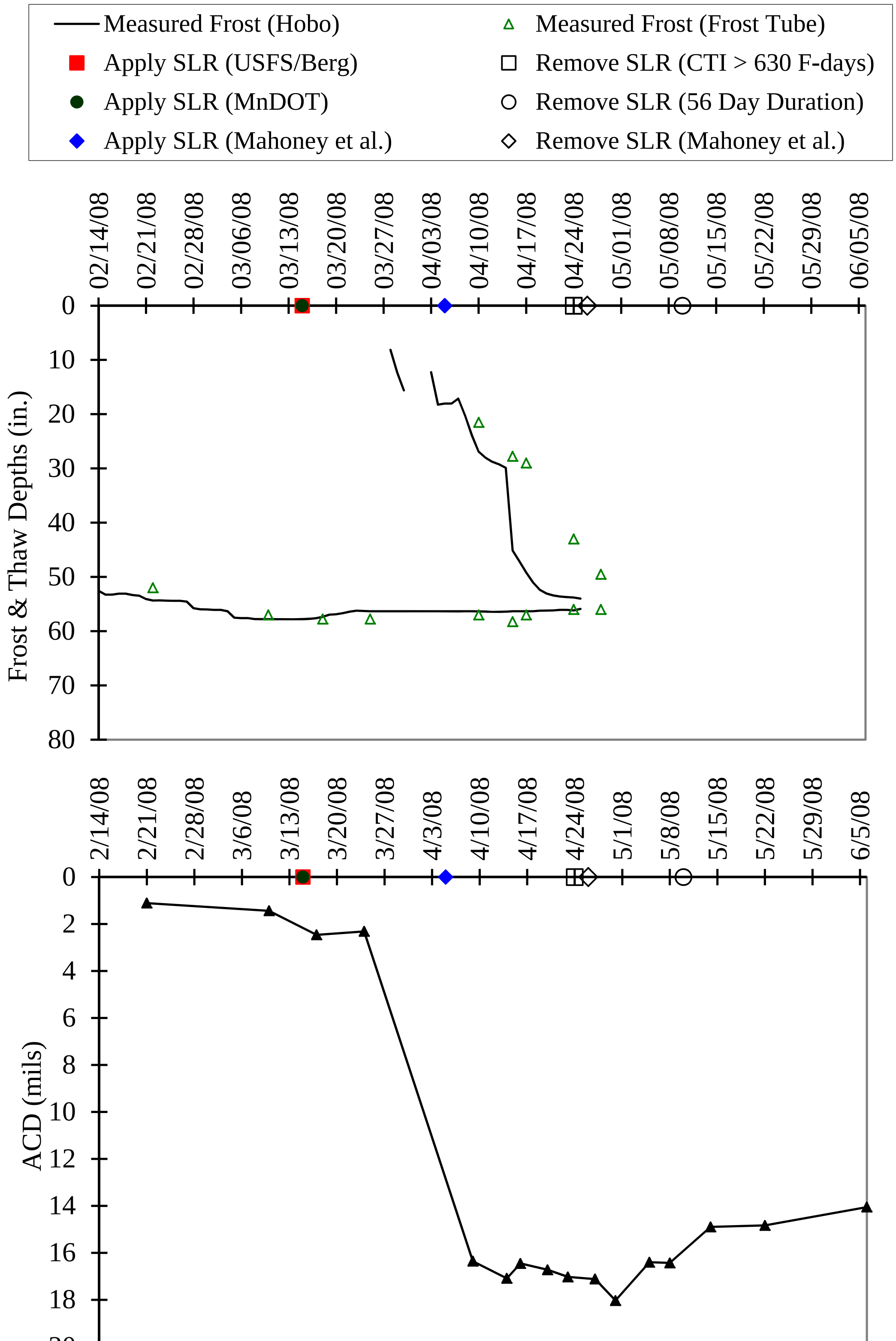


Figure E3 - K-3 Spring 2008 SLR Trigger Dates vs.
Measured Frost-Thaw Depths and ACD Data

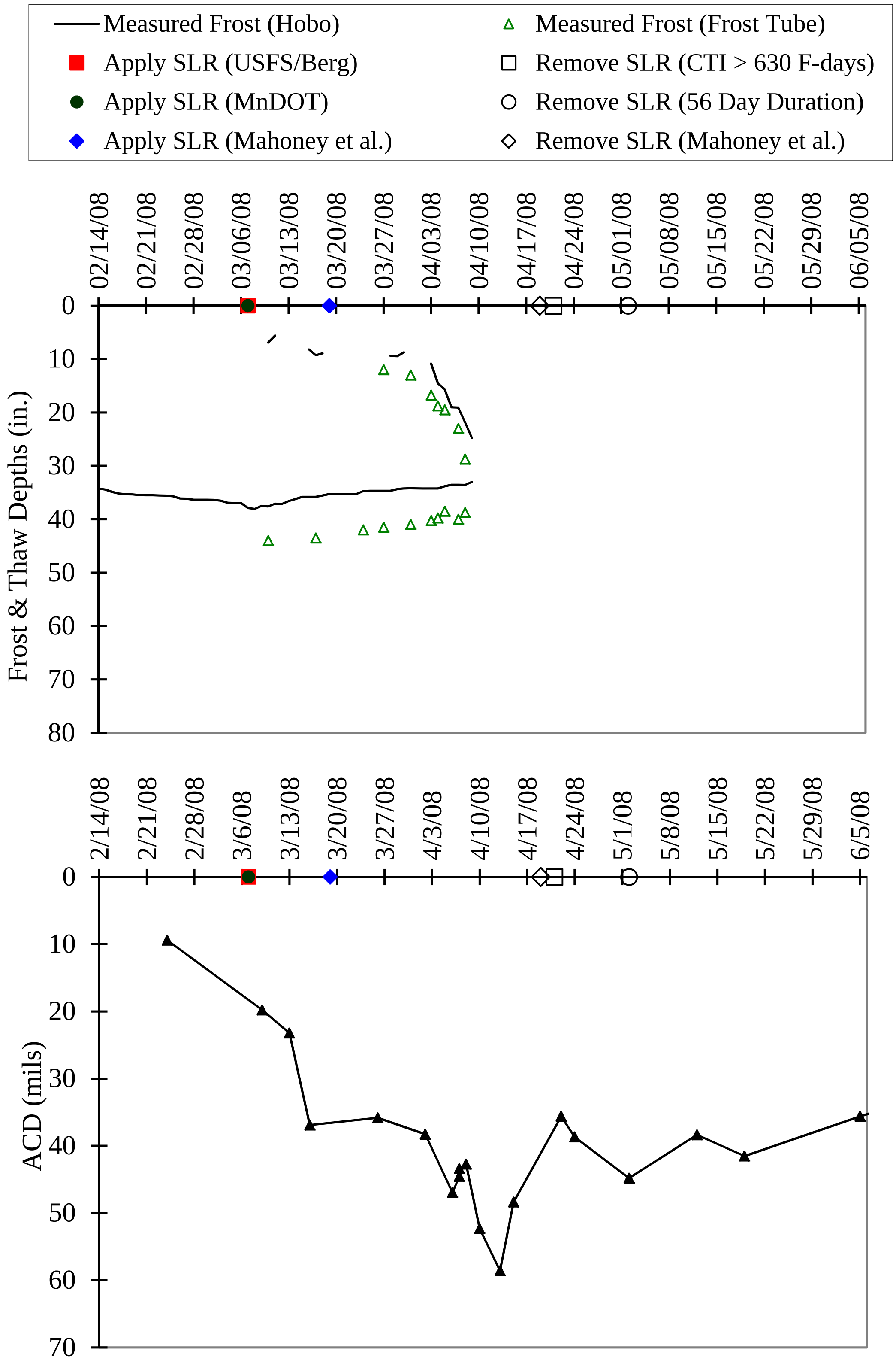


Figure E4 - LT Spring 2008 SLR Trigger Dates vs.
Measured Frost-Thaw Depths and ACD Data

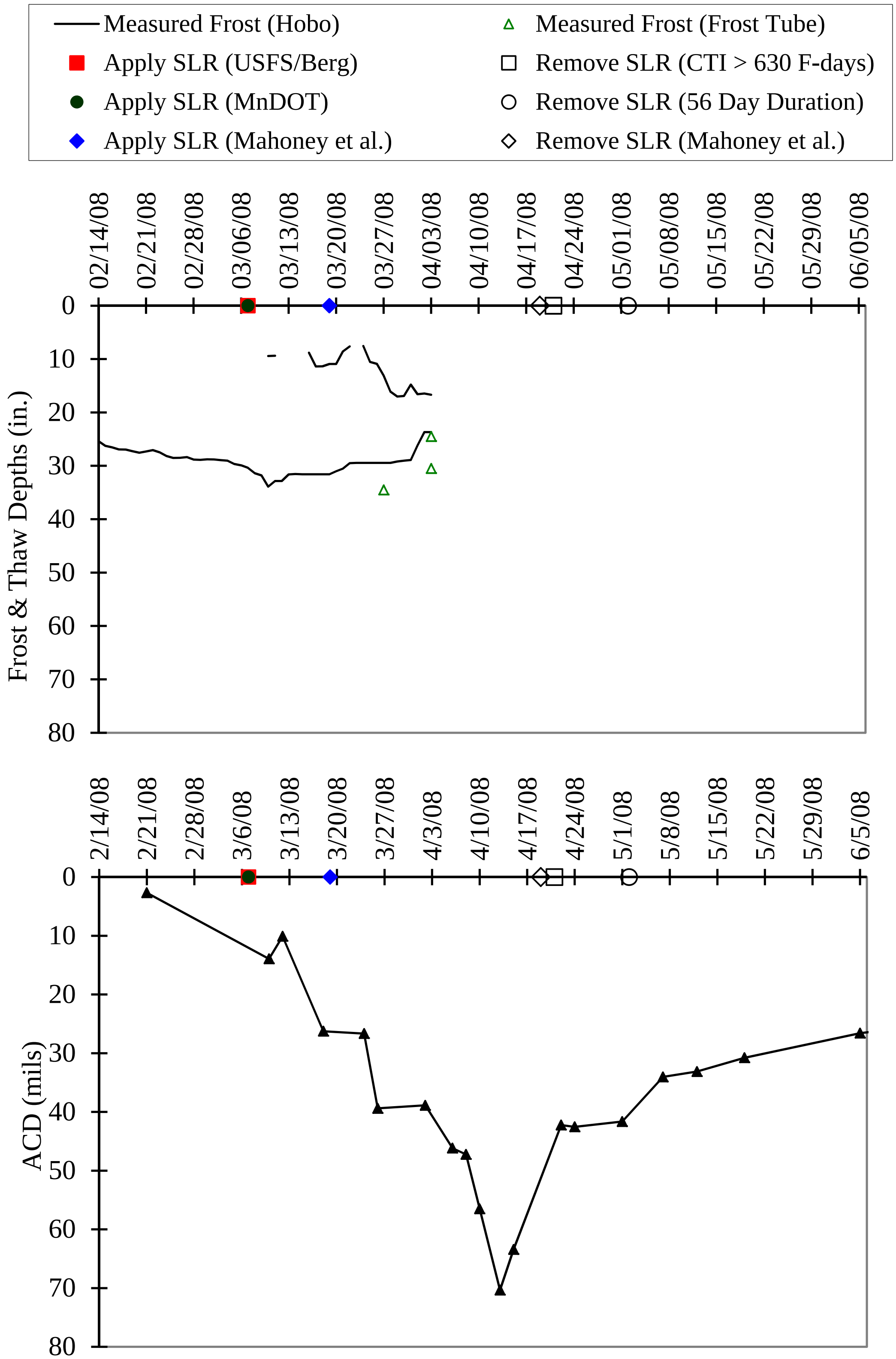
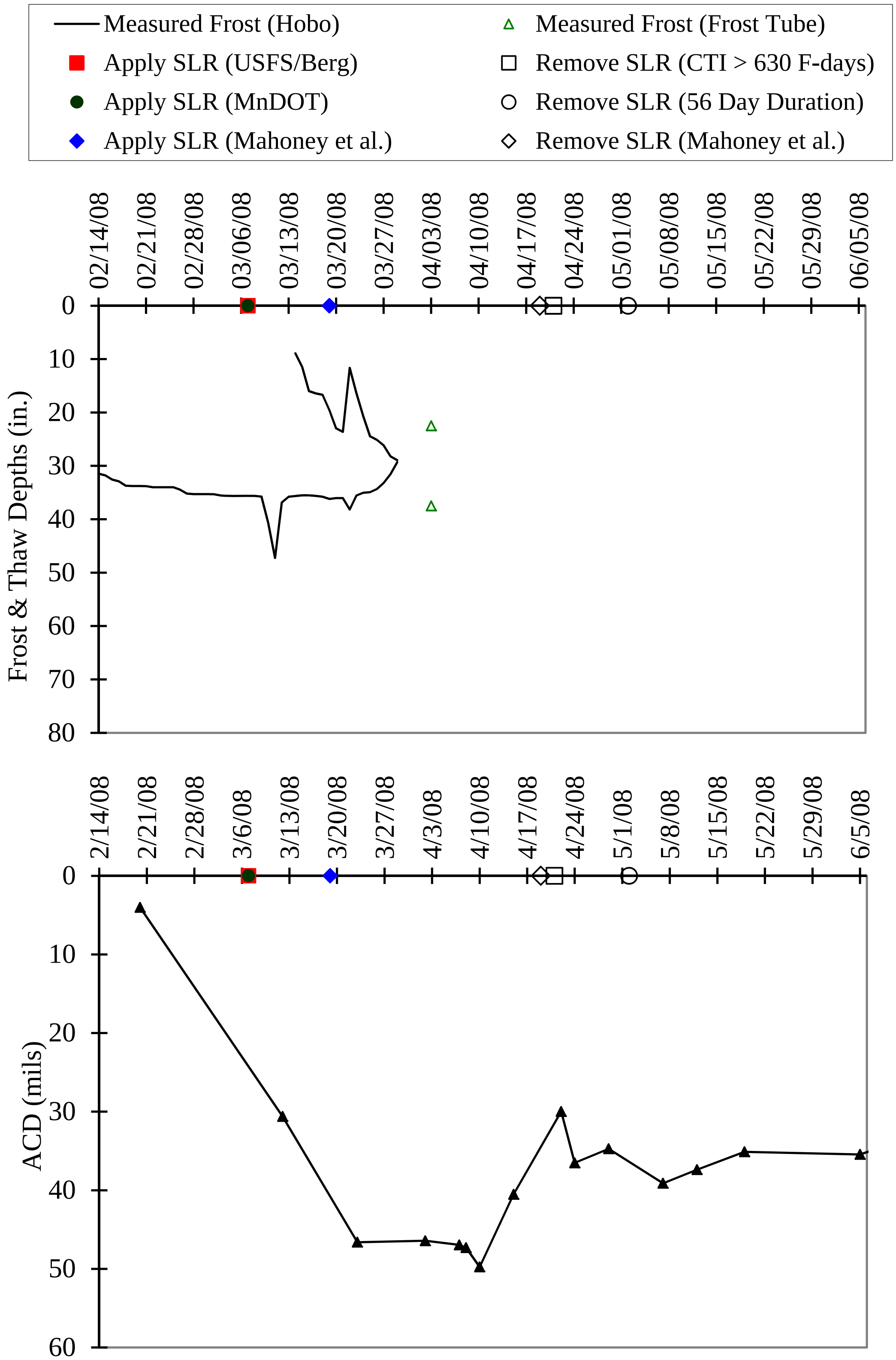


Figure E5 - NGR Spring 2008 SLR Trigger Dates vs.
Measured Frost-Thaw Depths and ACD Data



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Measured Frost-Thaw Depths and ACD Data

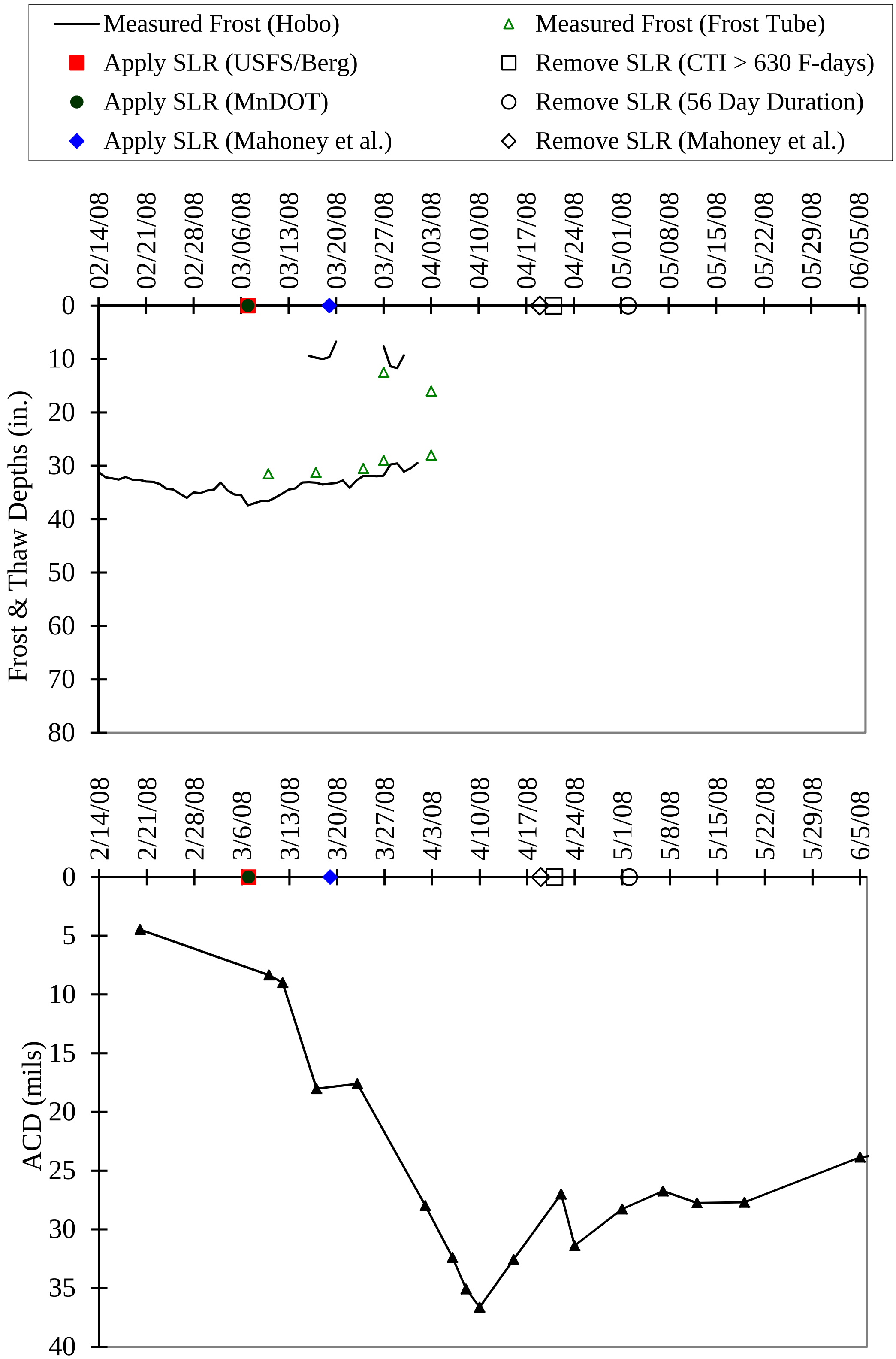

Figure E7 - SLR Spring 2008 SLR Trigger Dates vs.
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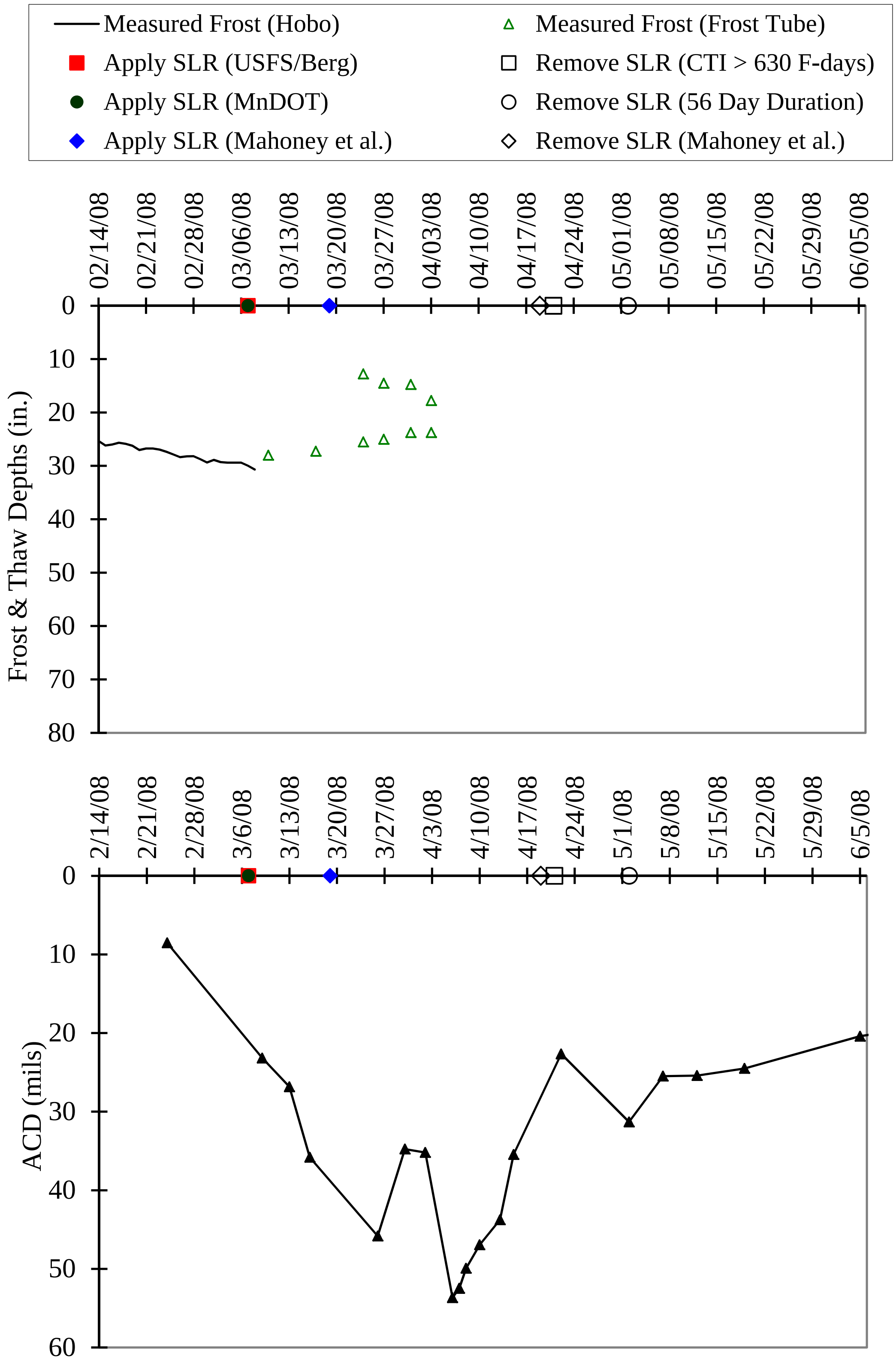

Figure E8 - WF Spring 2008 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

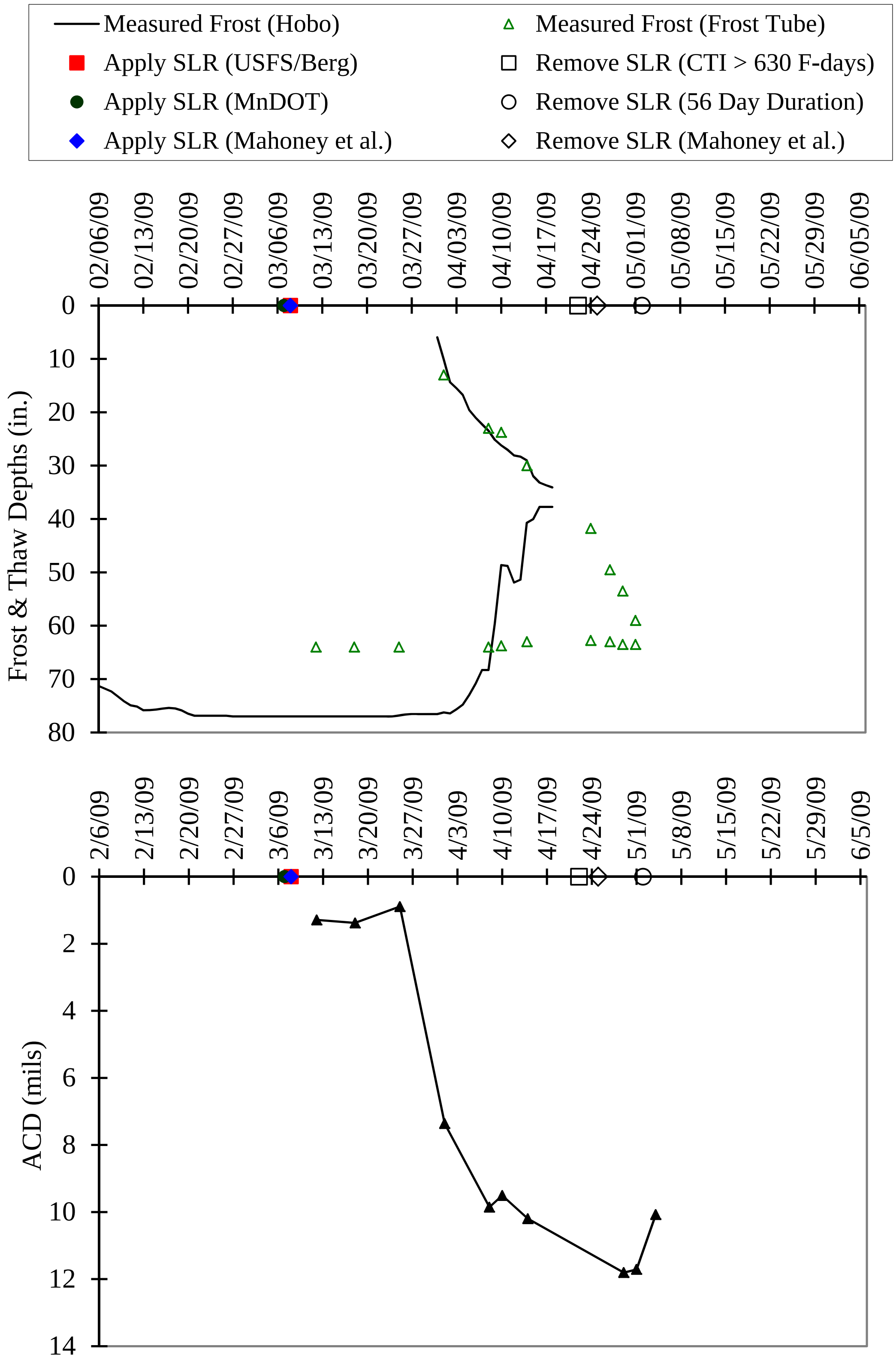

Figure E9 - K-1 Spring 2009 SLR Trigger Dates vs.
Measured Frost-Thaw Depths and ACD Data

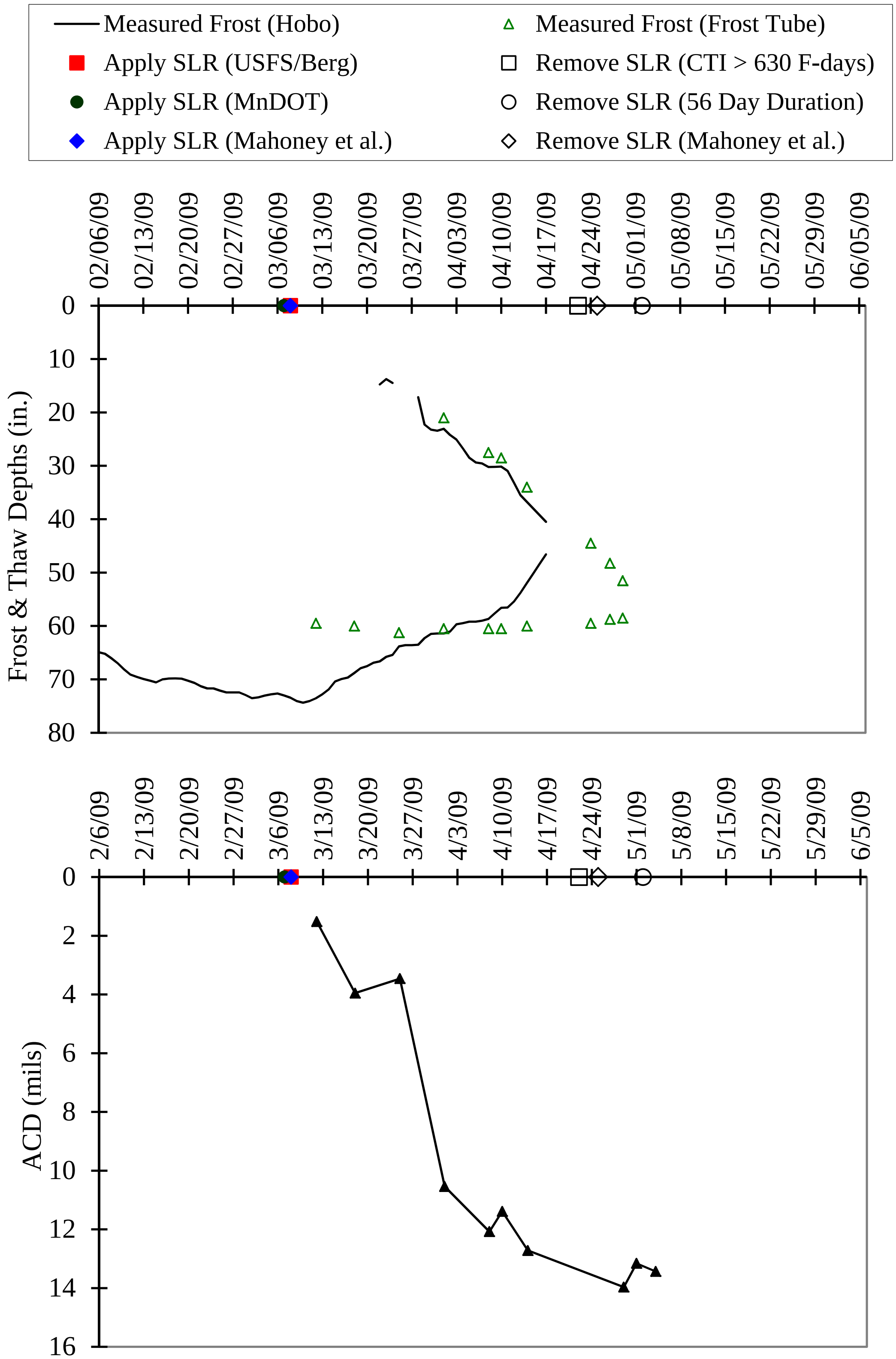

Figure E10 - K-2 Spring 2009 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

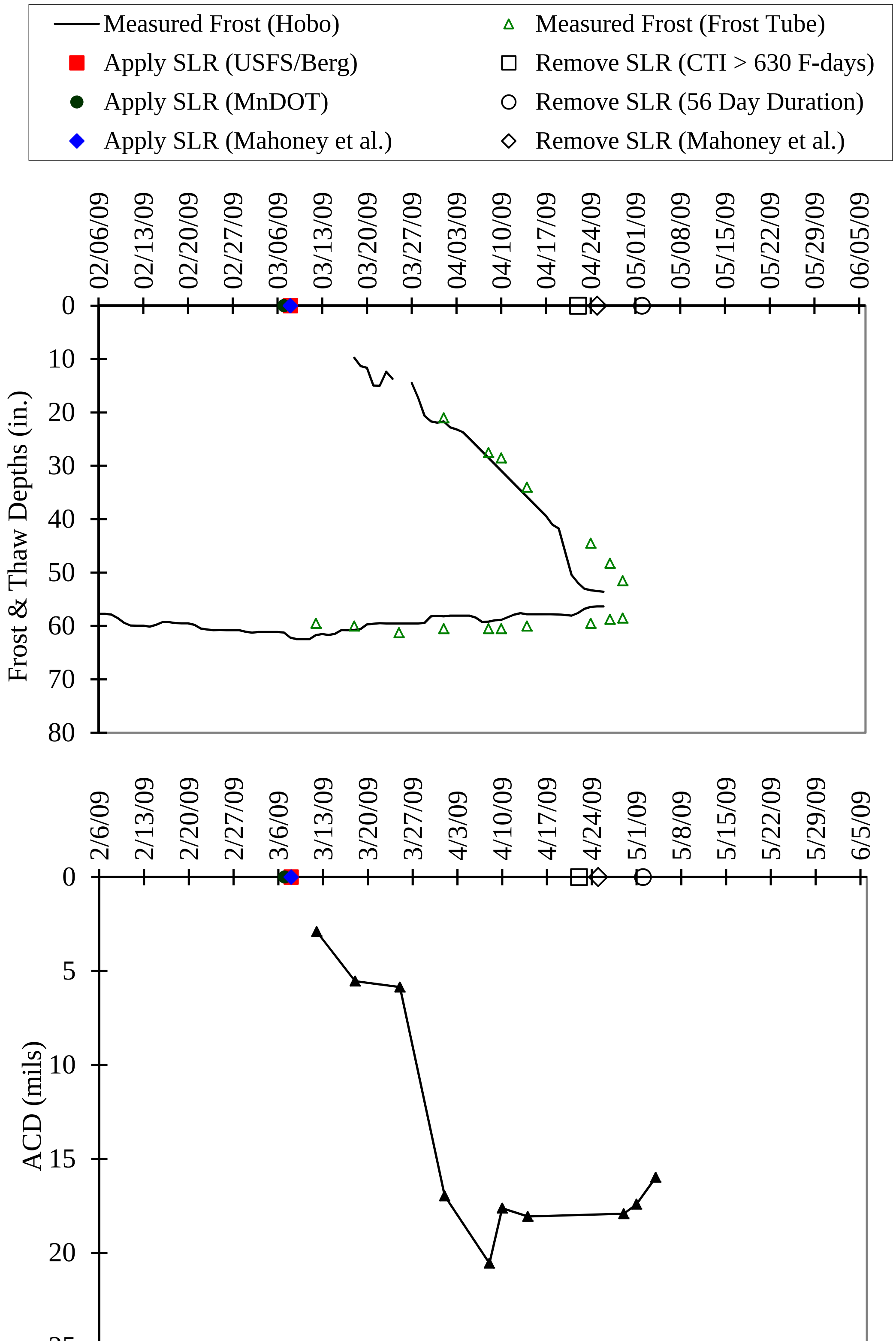

Figure E11 - K-3 Spring 2009 SLR Trigger Dates vs.
Measured Frost-Thaw Depths and ACD Data

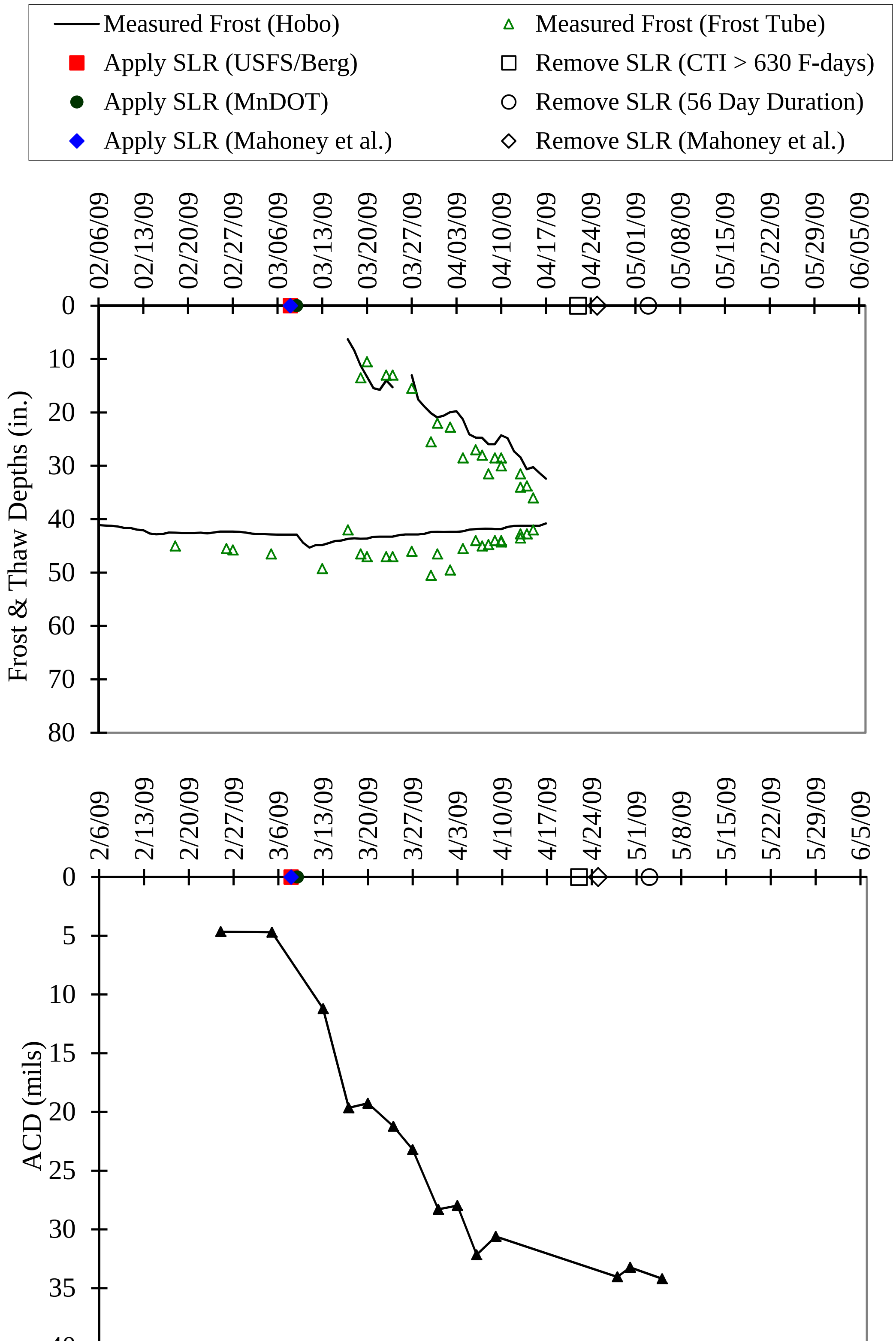

Figure E12 - LT Spring 2009 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

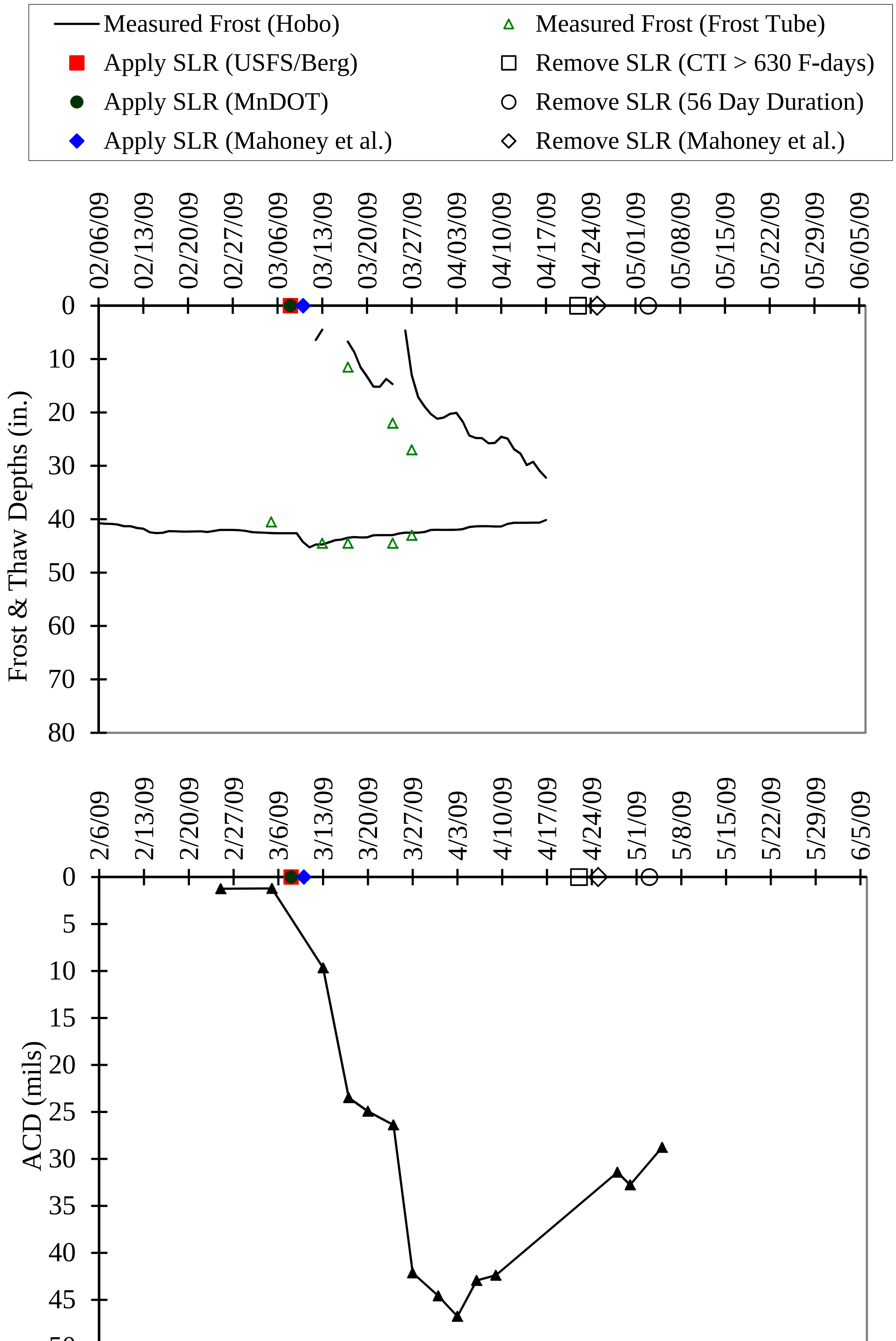

Figure E13 - NGR Spring 2009 SLR Trigger Dates vs.
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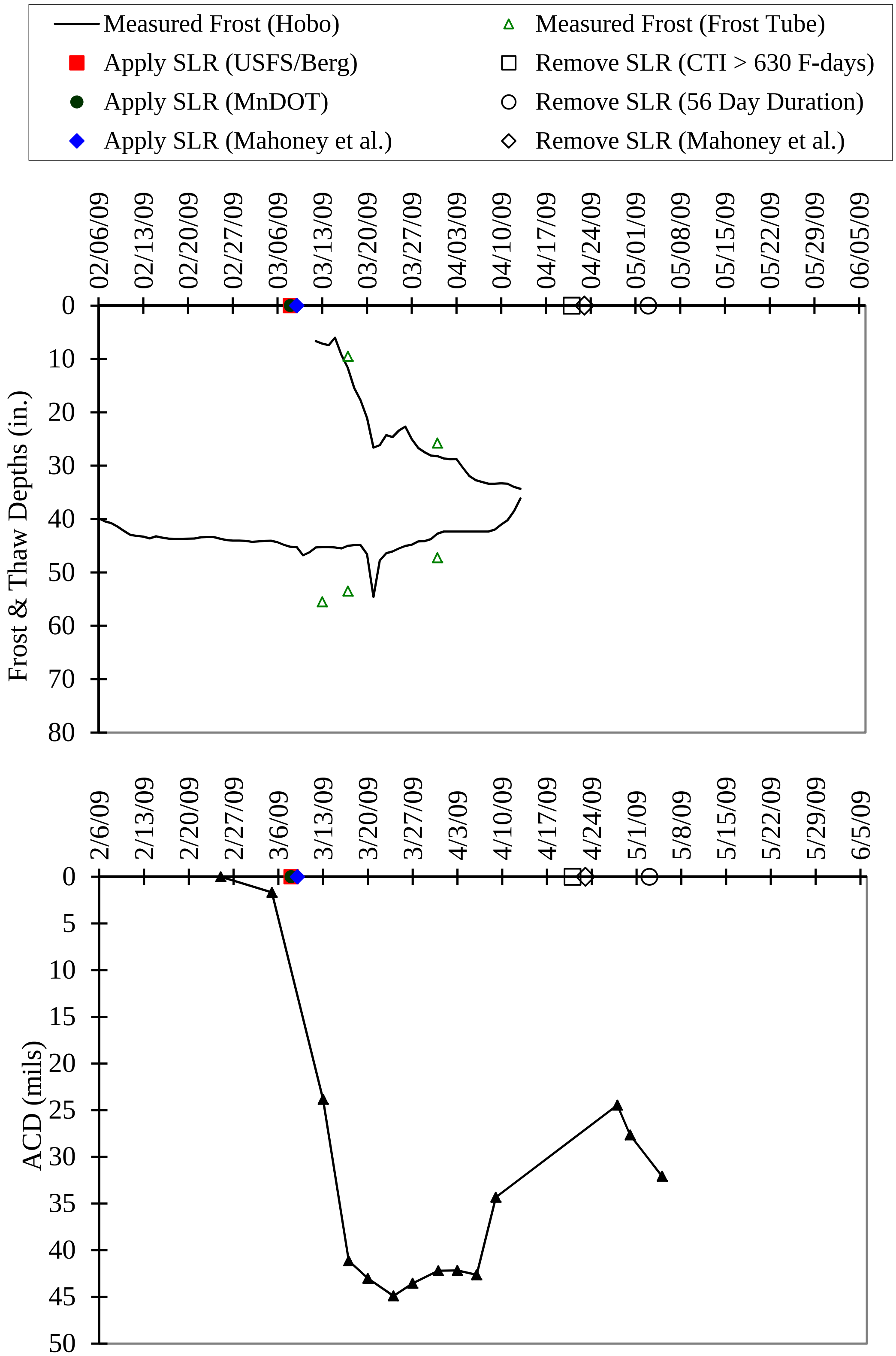

Figure E14 - RUM Spring 2009 SLR Trigger Dates vs. Measured Frost-Thaw Depths and ACD Data

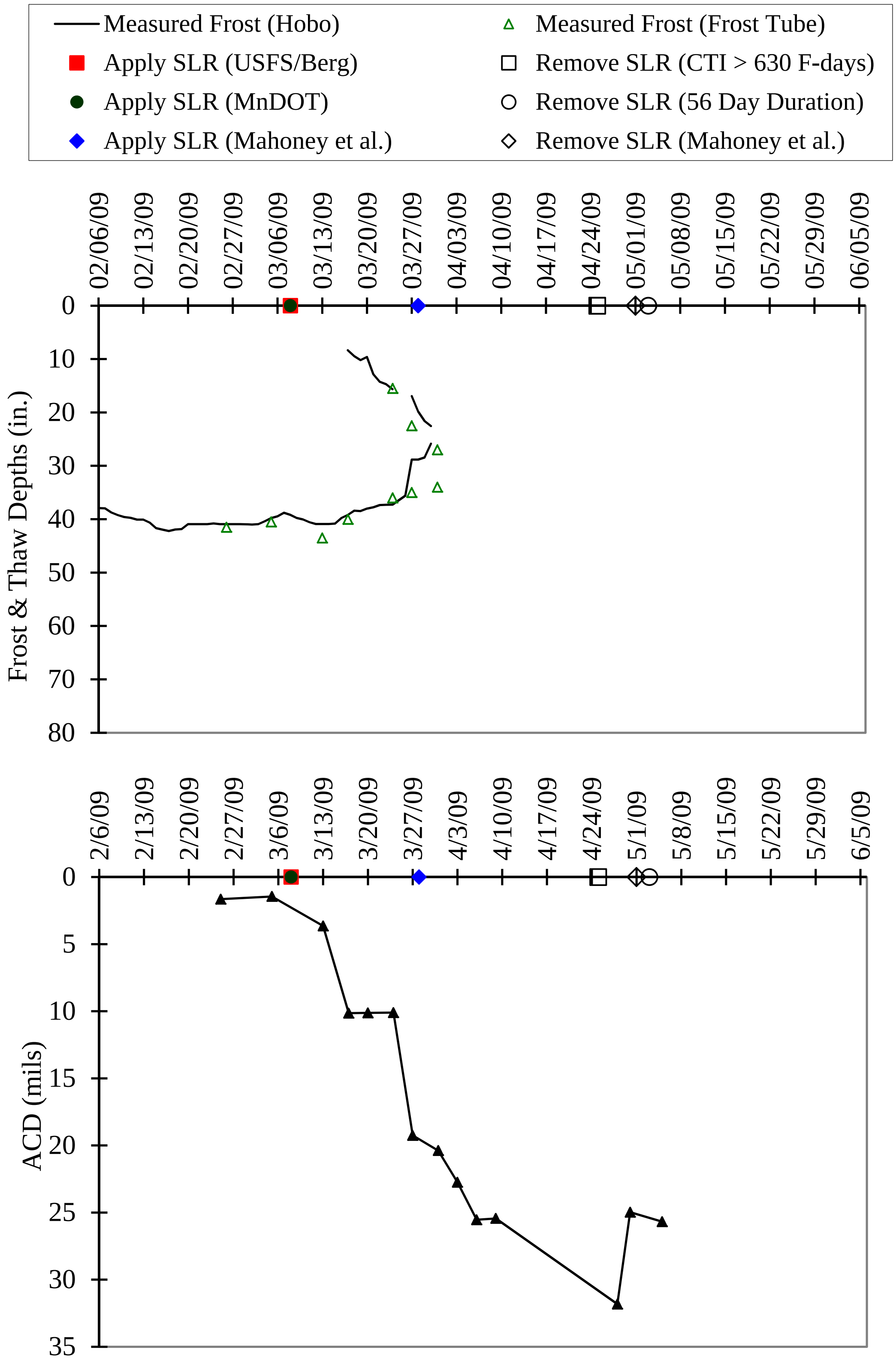

Figure E15 - SLR Spring 2009 SLR Trigger Dates vs.
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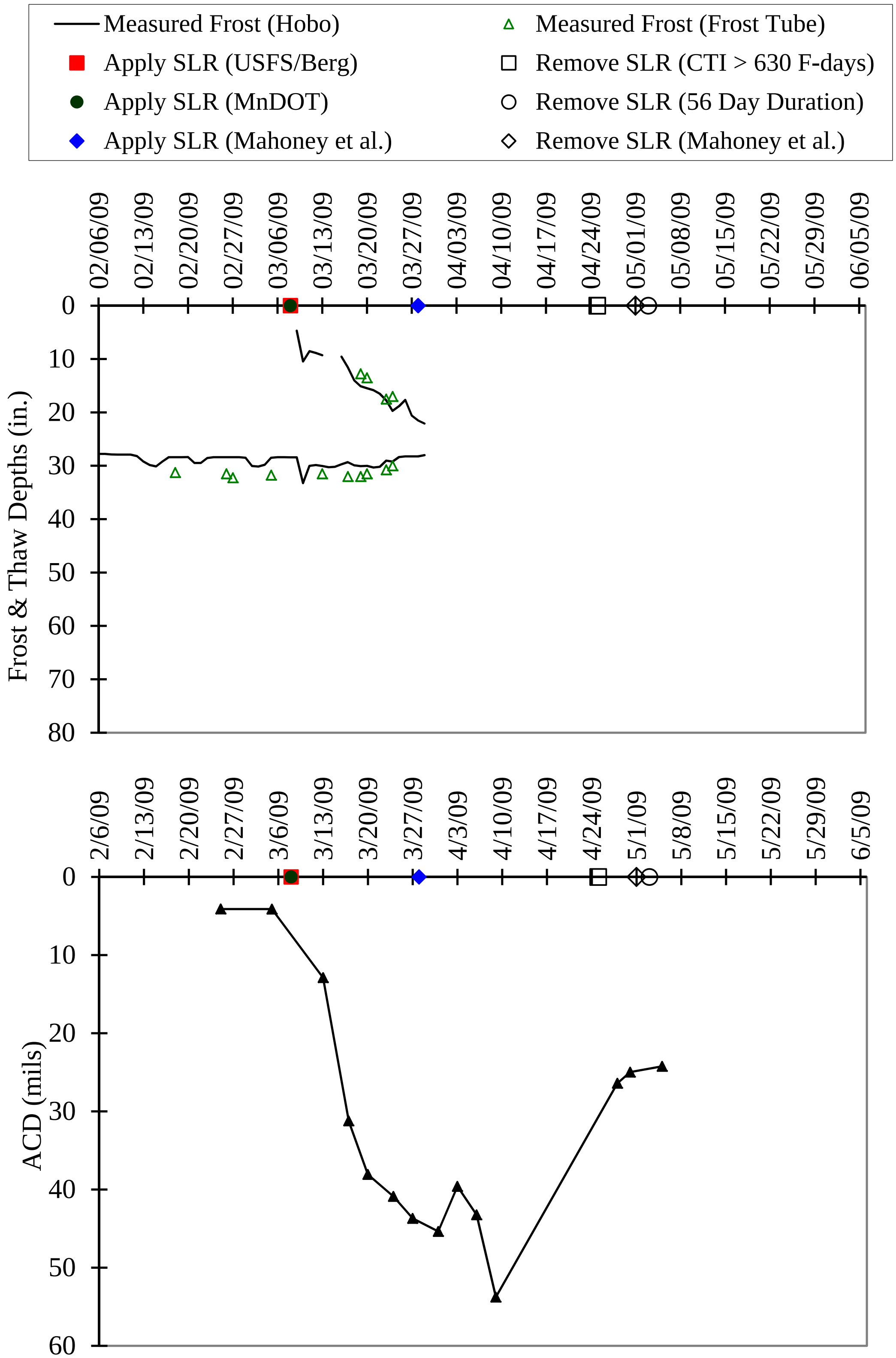

Figure E16 - WF Spring 2009 SLR Trigger Dates vs.
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Appendix-IX:

Deployment report, establishment of deployment sites

- ***Deployment maps, Site Plans and Equipment Details***
- ***Deployment Photographs***
- ***Deployment Soil Test Results***

Use of Remote Sensing for

Seasonal Load Restriction (SLR) Application & Removal

COOPERATIVE AGREEMENT No. RITA RS-11-H-UMDA

Between

University of Massachusetts Dartmouth

and

U.S. DEPARTMENT OF TRANSPORTATION

RESEARCH AND INNOVATIVE TECHNOLOGY AMINISTRATION (RITA)

Report on Task #5:

Establishment of Field Test Sites

Prepared by

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DRAFT 3: January 11 2013

Disclaimer

The views, opinions, findings and conclusions reflected in this report are the responsibility of the authors only and do not represent the official policy or position of the USDOT/RITA, or any State, Federal, or other entity.

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1. Introduction and Background

There are several million miles of low-volume roads in the United States, and approximately half of them are located in seasonal frost areas. Many of these roads in seasonal frost areas are highly susceptible to damage from trafficking during spring thaw. Therefore, seasonal load restriction (SLR) policies that limit the axle loads of heavy trucks during the spring thaw period have been implemented in many parts of the United States and other countries in an effort to minimize costly roadway damage. These load restrictions, however, pose an economic hardship to the timber industry and other truckers 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. Clearly, spring weight restrictions pose sustainability as well as financial concerns over many regions of our nation. The challenge is to protect the infrastructure and minimize roadway maintenance costs, but to also allow commerce to flow as much as possible during spring thaw and strength recovery period, which typically lasts 6-8 weeks.

Historically, load restrictions have mainly been based on set dates and/or visual inspection procedures. However, many transportation agencies are moving toward establishing SLR application and duration according to science-based decisions rather than merely using hard physical dates, or the judgment of one, or a few individuals. A major limitation to use of science-based decision algorithms is obtaining, in real-time, the necessary information to make such decisions. Many of the roadways requiring SLRs are in very remote locations where it is not feasible for field personnel to physically visit the sites to determine whether the soil conditions are suitable to sustain vehicular traffic without creating unacceptable damage.

Therefore, the main objective of the research conducted under RITA Cooperative Agreement RS-11-H-UMDA is to demonstrate the application of commercial remote sensing and spatial information (CRS&SI) technology for monitoring roadway conditions in real time during the spring thaw and strength recovery period. This will provide critical quantitative data to eliminate or supplement components of current visual inspection procedures, and thus greatly assist transportation agencies in making SLR placement and removal decisions.

In addition to real time monitoring of roadway conditions, many states are interested in using predictive models to assist them in their SLR decisions. Predictive models are desirable because most agencies are required to notify the public of SLR postings at least 3 to 5 days in advance. Thus, a second objective of this research project is to incorporate a predictive model on a web-based decision support system (DSS). Various predictive models are under evaluation for use on this project. One of the more advanced models for predicting the depth of frost and thaw penetration is the Enhanced Integrated Climatic Model (EICM). Structural inputs to the EICM include the pavement layer thicknesses, material types, and depth to water table. Climatic factors input into the EICM include the wind speed, precipitation, air temperature, and incident shortwave radiation (input as percent sunshine). Therefore, instrumentation to collect data required for the EICM was also installed at two of the three field test sites for this demonstration project.

This report describes the work conducted under Task #5 of the RITA Cooperative Agreement: "Establishment of Remote CRS&TI Test Sites."

2. Selection of Test Sites and Instrumentation

To achieve the two project objectives, three demonstration sites were established in northern New England during the summer and fall months of 2012. Initially, two sites were selected (one in Warren, NH and another in Mariaville, ME) at locations where the NH and Maine DOTs desired real-time information to assist them with SLR postings. At these sites, data transmission via satellite was selected due to their remote locations and lack of cellphone communication capabilities. Instrumentation at those sites include sensors for measuring subsurface temperature and moisture regimes, as well as sensors to monitor several atmospheric weather parameters (air temperature, relative humidity, precipitation, barometric pressure, incoming solar radiation, and wind speed) and water table depth. As noted previously, the water table depth and atmospheric weather parameters are being collected for use in evaluating SLR predictive models.

Due to the higher costs associated with satellite transmission of data, Maine DOT emphasized the value of establishing additional CRS&SI technology sites where cell modems could be used to transmit the data. Thus, a third site in Madison, Maine, was identified where cellular data transmission was viable. At that site, instrumentation consists primarily of sensors for measuring subsurface temperature and moisture regimes. Other than air temperature, atmospheric weather parameters are not being monitored at that site. The locations of the three field demonstration sites are shown in Figure 1. More detailed maps showing the locations of each site relative to the local routes are included in Appendices A, B and C (page A-3, page B-3 and page C-3). Site coordinates (latitude and longitude) and elevations were obtained with a hand-held Garmin GPS, and are included in tables on pages A-5, B-5 and C-5.

Initially, the research team investigated several different sensor technologies, data loggers and transmission systems for potential use in this project. Components were evaluated in terms of sensor accuracy, installation issues, data transmission, and power requirements. Additionally, the total package cost was considered in the final selection. For the two satellite transmission systems, the team evaluated equipment recommended by Campbell Scientific, Inc., Sutron Corporation, and Hoskins Scientific Limited, Canada. Ultimately, the instrumentation recommended by Hoskins Scientific was purchased. Their system contains components from a number of different manufacturers, with a total cost of approximately $10,600 per station. For the cellular transmission system, the research team also compared equipment produced by three different manufacturers: Onset Computer, Davis and INWUSA. The Onset equipment was identified as the best configuration for the price. The total cost of the Onset equipment purchased for the cell transmission site was about $4,000.

In addition to the sensors for measuring subsurface temperature and moisture regimes, all systems contain a data logger (enclosed in a waterproof box) and transmitter, a solar panel for recharging the power supply, and various miscellaneous cables and connectors. A listing of the major components of each system is included in Tables 1 and 2. Appendix J contains the specifications provided by the manufacturers for each of the sensors listed in Tables 1 and 2.

Figure 1. Location of 3 Demonstration Sites

Table 1. Equipment Purchased from Hoskin Scientific for Satellite Transmission Sites

Part #	Quantity	Item Description and Associated Details
SSLOG-IRD	1	Solar Stream Data logger / Iridium Satellite Transceiver Onset Smart Sensor Interface Iridium 9602 Transceiver with Integral Iridium Antenna Hoffman Nema 4 Enclosure 16"x14"x10" Pole Mount Bracket for Enclosure 20 A/hr. Sealed Lead Acid Battery 10 Watt Solar Panel Amphenol Military Circular Connector for Thermistor String Integral Iridium Antenna (12' Cable Length)
E317-3C395 T16	1	Smart Sensor Control Box with Modbus Interface to SSLOG
TS-1272-3F-4407-66	1	Thermistor String with 12 thermistors YSI 44007 Thermistor 5K @ 25C, +/-0.2C Interchangeability Polyurethane Injection Mold 72' total cable length (66' Tail Wire) Amphenol Mating Connector for Satellite Enclosure Kevlar Stranding Water Block Cable Fill
E348-S-SMC-M005	4	Soil Moisture Sensors - Decagon EC5
E317-2B41824	1	INW-Pressure Transducer (water table depth) PT12, 5 PSIg 316 Stainless - Standard Calibration Modbus Interface
E317-7A23540	1	Sensor Cable for Pressure Transducer PU 100 Submersible – 60 feet long
E348-S-ADAPT-X5-10	1	Smart Sensor 5-to-10 Input Expander Kit for SSLOG
E348-S-THB-M008	1	Temp/RH Sensor (12-bit) w/ 8m Cable
E348-RS3	1	Solar Radiation Shield (for use with temp/RH sensors)
E348-S-RGA-M002	1	Rain Gauge (.01") with 2m Cable
E348-S-LIB-M018	1	Silicon Pyranometer Sensor w/18m Cable
E348-M-LBB	1	Light Sensor Bracket
E348-S-BPA-CM10	1	Barometric Pressure Sensor
E348-S-WSA-M003	1	Wind Speed Sensor with 3m Cable
E348-S-EXT-M010	2	10m Smart Sensor Extension Cables for Rain & Wind Sensors
E348-S-EXT-CASE	2	Weatherproof Extension Cable Connector Housing

Table 2. Equipment Purchased from Onset Computer for Cellular Transmission Site

Part #	Quantity	Item Description and Associated Details
U30-GSM-000-10-S100-204	2	U30-GSM - Cellular communications
SOLAR-6W	2	6 Watt Solar Panel
BHW-PRO-CD	1	HOBOware Pro Mac/Win Software
S-TMB-M017	12	12-Bit Temp Smart Sensor (17 m cable)
S-SMC-M005	2	Soil Moisture Smart Sensor (Decagon EC 5)
S-TMB-M002	1	12-Bit Temp Smart Sensor (2m cable) for air temp.
RS3	1	Solar Radiation Shield (for air temp sensor)
S-EXT-M010	2	Smart Sensor Extension Cable - 10m length
S-EXT-CASE2	2	Weatherproof Housing for Extension Cables

It should be noted that miscellaneous costs associated with mounting data loggers and atmospheric sensors (i.e. pole and/or mast), installing water wells, etc., are not included in the costs quoted previously. Additionally, a data transmission plan must also be purchased for each system. Since these systems are still in their first year of operation, the annual data transmission costs have not yet been firmly established; however, the annual cost is estimated to range from a minimum of $300 (for cellular transmission) to a maximum of about $1,000 (for satellite transmission). The cost of data transmission will depend on several factors, including data logging rate and transmission interval.

The same soil moisture “smart sensors” were used at both the satellite and the cellular transmission sites. They combine the innovative ECH2O® Dielectric Aquameter probe from Decagon Devices, Inc. with Onset’s “smart sensor” technology. All sensor conversion parameters are stored inside the smart sensor adapter so that data is provided directly in soil moisture units without any programming or extensive user setup. They have a rated accuracy of ±0.031 m^3/m^3 (volumetric moisture content). Prior to installation in the field, a check of the sensor functionality was conducted in the UMass Dartmouth laboratory by checking the sensor readings both in air and in distilled water to confirm that the readings were within the tolerances specified by the manufacturer.

At the satellite transmission sites, thermistor “strings” (produced by INW) were selected for subsurface temperature measurements. These consist of a series of 12 thermistors (Yellow Springs Instrument, Inc. model 44007), with a rated accuracy of 0.2 ^{o}C. The bottom 9 thermistors were imbedded in a single cable. The deepest 4 sensors were placed at a spacing of 12 inches, and the remaining 5 were placed at a spacing of 6 inches, as shown in Figure 2a. Additionally, three “fly-out” thermistors were provided, which branched off of the main cable as shown in Figure 2b. The fly-out thermistors were designed to be placed at the pavement surface, bottom of pavement, and within the granular base course. At the cellular transmission site, 12 individual “Temperature Smart Sensors” (produced by Onset Computer) were selected for subsurface temperature measurements. These also had a rated accuracy of 0.2 ^{o}C. The individual thermistors were wrapped with electrical tape to maintain the desired spacing, as shown in Figure 3, and then attached to a wooden dowel as shown on page F-3 for installation/placement in the borehole.

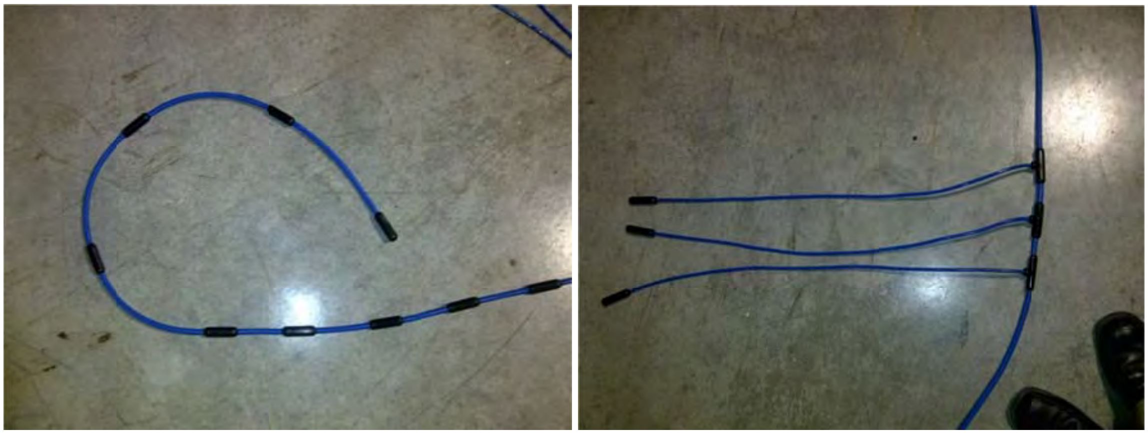


Figure 2. **INW thermistor string (a) bottom 9 thermistors; and (b) upper 3 fly-out thermistors**

Figure 3. **Onset thermistors**

Prior to installing the subsurface temperature sensors, they were calibrated in an ice bath to determine freezing temperature offsets. The thermistor strings purchased for the satellite transmission system were calibrated by Hoskin Scientific personnel, and the Onset thermistors (for the cellular transmission system) were calibrated in the lab at UMass Dartmouth. Crushed ice (made from distilled water) was placed in an insulated cooler. The container was then filled with distilled water to just below the level of the ice. The thermistor string (Hoskin) or individual probes (Onset) were then submerged in the ice bath, and were allowed to remain there long enough for the sensors to acclimate (and temperature readings to stabilize). At the Hoskin lab, a recirculating pump was available to maintain the ice bath at 32 ^{o}F during the stabilization period. In the UMass lab, a recirculating pump was not available, so the ice/water mixture was stirred around during the stabilization period in an effort to maintain a constant freezing temperature. Once the temperatures recorded by the thermistors had stabilized, the offset from 32 ^{o}F was recorded. These freezing temperature offsets are tabulated on pages A-6, B-6 and C-6.

3. Instrument Installation

General

For subsurface instrument installation (thermistors and moisture sensors), the NH and Maine DOTs provided a drill rig, backhoe, and crews with other miscellaneous tools. A borehole, approximately 7 feet deep, was drilled in the pavement for the thermistors, and soil samples were taken and logged for lab testing. Then a second borehole, approximately 3 feet deep, was drilled for installation of moisture sensors. A trench was excavated from the boreholes out beyond the roadway edge for running sensor cables to the pole/mast where the data logger and other associated instrumentation was mounted. After the thermistors and moisture sensors were installed, the trench was backfilled with the excavated soil/base materials and then cold patch and/or hot mix asphalt was placed in the trench.

Site details for the Warren Flats (WF) site, the Mariaville site, and the Madison site are included in Appendices A, B and C, respectively. Sketches showing the locations of the instrumentation at each site are included on page A-4, page B-4 and page C-4. Samples obtained from the boreholes for the thermistors were transported to the laboratory at UMass Dartmouth and subjected to sieve analysis, moisture content determination, and in some cases, hydrometer analysis and Atterberg Limits tests (liquid limit and plastic limit). Results from laboratory testing conducted on soil samples are included in Appendices G, H and I.

At each of the three primary demonstration sites, one thermistor was installed in the asphalt surface, one was installed immediately below the asphalt layer, and the remaining sensors were installed at approximately the following depths: 6, 12, 18, 24, 30, 36, 48, 60, 72 and 84 inches beneath the pavement surface. The placement of soil moisture sensors varied at each site, depending upon the thickness of the asphalt and base layers and existing moisture conditions. The maximum depth of moisture sensors did not exceed 40 inches. The exact depths (below top of pavement) and offsets (horizontal distances off roadway centerline) for all thermistors and moisture sensors are tabulated on page A-5, page B-5 and page C-5.

The three primary demonstration sites were all located in relatively open areas, in order to provide sufficient sunlight exposure so that the solar panels could provide sufficient power, and to avoid obstacles that might hinder the satellite and cellular transmission. Maine DOT personnel were concerned that frost/thaw patterns in adjacent shaded sections of roadway might differ significantly from the frost/thaw patterns recorded in those open areas. Therefore, near the two primary sites in Maine (designated Mariaville-1 and Madison-1), the research team installed a series of subsurface temperature sensor/data loggers at secondary sites (designated Mariaville-2 and Madison-2), located in shady areas of roadway within about a half mile distance from the primary demonstration sites. The locations of these secondary sites are shown on the maps on pages B-3 and C-3, respectively.

At these two shaded sites, a series of 10 subsurface temperature sensors were installed. One was installed in the asphalt surface, and the remaining sensors were installed at approximately the following depths: 6, 12, 18, 24, 30, 36, 42, 54, and 78 inches below the top of pavement. The exact depths of the temperature sensors are tabulated on pages B-7 and C-7. The sensors installed in the asphalt surface were Hobo Pro V2 sensors, purchased specifically for this project. The remaining temperature sensors at these sites consist of Hobo Pendant temperature sensors, which were used in a previous NH DOT/FS SLR study, and were loaned to the research team for this current project. All of the Hobo temperature sensors were manufactured by Onset Computer, and include internal data loggers. Specification sheets for these sensors are included in Appendix J. No real-time transmission of data occurs from these sensors. They were placed in a cased hole, which was covered with cold patch. At the conclusion of the 2013 spring thaw period, the cold patch will be removed, and the sensors will be withdrawn from the hole for data downloading. The cased hole will then be backfilled.

In addition to subsurface temperature and moisture sensors, at the two satellite transmission sites (Warren Flats and Mariaville-1), additional sensors were installed to monitor several atmospheric weather parameters (air temperature, relative humidity, precipitation, barometric pressure, incoming solar radiation, and wind speed) and water table depth. As noted previously, the water table depth and atmospheric weather parameters are being collected for use in evaluating SLR predictive models. The atmospheric sensors were mounted on a mast and/or wood post located off the edge of the road within the right of way. A pressure transducer for monitoring the depth to the groundwater table was placed in a well which was also installed off the edge of the roadway near the mast/wood post, as shown in the sketches on pages A-4 and B-4. Site-specific details, as well as photographs of the instrument installations at each site, are included in the appendix sections of this report.

Warren Flats (WF), NH Site Installation

This site is located on Route 25C in Warren, NH, as shown on pages A-2 and A-3. It was one of the nine field test sections incorporated in the previous NH DOT/FS SLR study conducted between 2006 and 2009. Some of the previous instrument installations are still in place in the westbound lane, thus the subsurface instrumentation for the current project was installed in the eastbound lane. A plan showing the locations of the former and current instrumentation locations is shown on page A-4.

At this site, the NH DOT had a utility pole in place that they wanted to utilize for the current project. The wind and air temperature sensors, as well as the solar panel and enclosure containing the data logger/transmitter and barometric pressure sensor, were mounted on a telescoping mast that was attached to the utility pole. The rain gauge and pyranometer (for measuring solar radiation) were attached directly onto the wooden utility pole. These devices were installed on August 7, 2012. Photographs of this installation are included in Appendix D, pages D-1 through D-3.

The atmospheric sensors were first attached to the mast with the mast laid out horizontally near the ground surface, and then the mast was hoisted and attached to the utility pole. Prior to attaching the mast, wooden spacers were lag bolted to the utility pole to provide sufficient space for the mounting hardware (for the sensors and data logger enclosure). After the mast was attached to the utility pole, the data logger enclosure was attached to the mast, and the electrical connections were made between the sensors and the data logger. The rain gauge and pyranometer were mounted on the utility pole, at a level where they could be accessed via a ladder (because a bucket truck was not available). They were shimmed and adjusted as necessary to maintain a level position. Figure 4 shows a photograph of this installation. During the fall of 2012 (after this photograph was taken), the NH DOT had a bucket truck available and utilized it to bolt the top of the mast to the utility pole (between the wind sensor and the air temperature sensor).

Figure 4. Warren Flats, NH Site

The subsurface sensors were to be installed at a later date (pending availability of a drill rig); however, the investigators wanted to have all of the electronics connected during the August 7, 2012 installation. Therefore, the thermistor string and the four moisture sensors were placed in a plastic bag and buried in a hole near the base of the utility pole, with the cables running up through PVC conduit and then connected to the data logger inside of the NEMA enclosure.

The NH DOT provided a drill rig, backhoe and associated crews to assist the research team with installation of a monitoring well and subsurface sensors on August 29, 2012. Photographs of these installations are included in Appendix D, pages D-4 through D-8. The monitoring well was installed first, and was located about 8 feet east of the utility pole. The well consisted of 5 feet of 2-inch diameter PVC slotted screen, with 10 feet of riser pipe (approximately 5 feet below ground and 5 feet stuck up above ground surface). The pressure transducer (for monitoring depth to groundwater table) was placed 14 feet below the top of the riser pipe. A notch was provided near the riser pipe juncture just below ground surface so that the transducer cable could exit and be buried in a trench between the well and the utility pole where the data logger was mounted. Holes were drilled in the top of the riser pipe to allow for venting, and a locking cap was installed (page D-4, top).

An elevation survey was conducted with an Engineer's level to determine the location of the riser pipe and pressure transducer relative to the top of the pavement surface where the subsurface sensors were installed. The depth to the water table was measured with an electronic water level meter as well as with a hand-held tape. Based upon the measured data, it was determined that the water table at the new well was located about 5.2 feet below the top of pavement on August 29, 2012.

A saw cut was then made to open a trench in the pavement surface as shown on the plan (page A-4). Because the roadway at this site had been badly cracked, it was reconstructed during the spring/summer of 2010. Rather than removing the existing pavement (which had been overlaid, in some locations, more than once), the NH DOT reconstructed the roadway as shown in Figure 5. A 14 inch layer of reclaimed asphalt mixed with crushed gravel was placed on top of the old asphalt concrete (AC) pavement, and then that new base layer was topped with about 4 inches of new AC pavement.

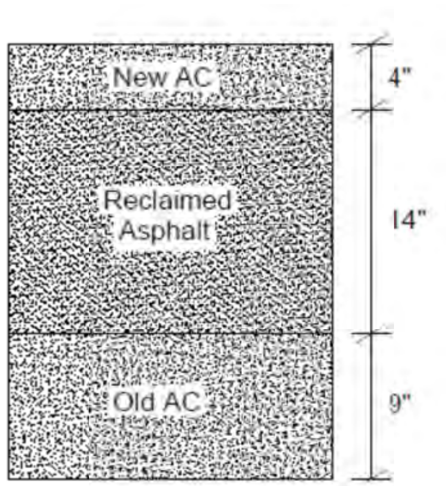


Figure 5. Cross-section of reconstructed roadway at Warren Flats site

A borehole, approximately 8 feet deep, was drilled through the old AC pavement layer (approximately between wheel paths) for the thermistor string. Due to the relatively shallow water table, it was necessary to advance the borehole with 3.5 inch OD steel casing to keep the hole open. Continuous split-spoon sampling along with standard penetration testing (SPT) was performed from the bottom of the old AC layer to the bottom of the borehole. Samples obtained from this borehole were logged by the research team and then transported to the laboratory at UMass Dartmouth for sieve analysis and moisture content determination. SPT N-values are included in Table 3, and a summary of results from the laboratory testing are included in Table 4, along with USCS and AASHTO soil classifications. Grain size distribution curves for the soil samples are included in Appendix G.

Table 3. SPT N-Values at Warren Flats Site

Depth (ft)	N-Value (Blows/ft)
2.33-4.33	10
4.33-6.33	26
6.33-8.33	25

Table 4. Results of Grain Size Analyses and Moisture Content Determinations at Warren Flats Site

	USCS Particle Size Distribution								
Depth (feet)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	Moisture Content (%)	AASHTO Symbol	USCS Symbol
2.25-2.42	0	12	11	18	40	20	14	A-2	SM
2.42-2.83	0	29	10	9	28	23	20	A-2	SM
3.00-3.50	0	1	5	23	59	12	9	A-2	SP-SM
5.29-5.63	4	25	12	25	29	5	13	A-1-b	SP-SM
5.63-6.00	0	0	2	27	63	7	13	A-3	SP-SM
6.00-6.33	0	0	8	32	53	7	14	A-3	SP-SM
7.21-7.46	0	0	6	23	52	18	17	A-2	SM
7.46-7.75	0	1	4	18	66	9	18	A-3	SP-SM
7.75-8.08	0	0	4	17	39	40	21	-	SM
8.08-8.33	0	0	0	3	52	45	23	-	SM
Reclaimed Base	9	22	14	31	21	3	-	A-1-b	SP

In order to keep the borehole open for thermistor installation, a PVC casing was placed inside of the steel casing used during the drilling operations. The steel casing was then removed, and the thermistor string placed inside of the PVC casing, as shown in Figure 6. The annulus between the borehole and the outside of the PVC casing, as well as the space between the thermistor string and inside of the PVC casing was backfilled with Holliston filter sand.

A second borehole, approximately 3 feet deep, was then drilled (closer to the outer wheel path) for installation of moisture sensors. Because there was about 9 inches of old AC pavement at the bottom of the trench, it was necessary to first core through that layer using a 6-inch diameter pavement core barrel, as shown in Figure 7. One moisture sensor was placed in the subgrade soil immediately below the old AC layer. A small notch was chiseled out in the side of the AC core that was removed (to accommodate the cable from the moisture sensor), and then the AC core was replaced. A bead of silicone was then placed around the perimeter of the upper part of that AC core to seal it.

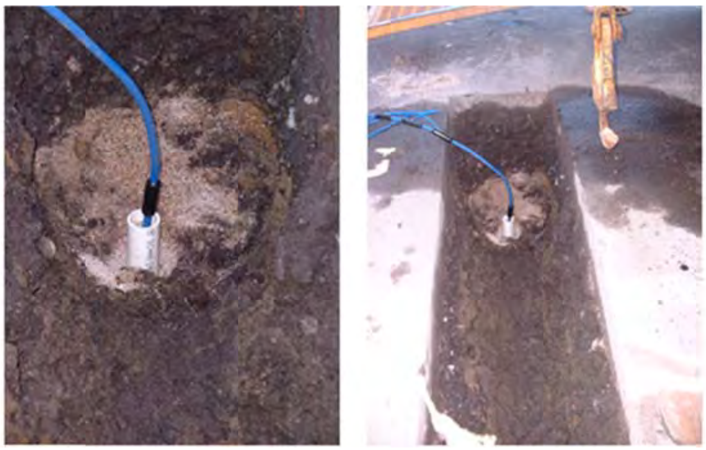


Figure 6. Installation of thermistor string at Warren Flats site

Figure 7. Coring old AC layer at Warren Flats site

The trench was then backfilled with the reclaimed asphalt/gravel mix which was compacted by hand with a tamper (Figure 8). The remaining three moisture sensors as well as 2 of the 3 fly thermistors were placed within the reclaimed asphalt/gravel mix. The third fly thermistor was placed in the asphalt layer (cold patch) that was placed to seal the top of the trench. The exact depths of the thermistors and moisture sensors at this site, as well as the location (horizontal offset from roadway centerline) are tabulated on page A-5.

Figure 8. Backfilling trench in roadway at Warren Flats site

Prior to backfilling the trench between the roadway and the utility pole, the soil moisture “smart sensors” were placed inside of a piece of PVC conduit, as shown in Figure 9. As the trench was backfilled, pieces of orange flagging were placed below the final lift of soil to indicate the location of wires/cables in case future excavation occurs at the site.

Figure 9. Backfilling trench in roadway at Warren Flats site

The NH DOT returned to the Warren Flats site on September 20, 2012 and replaced the cold patch with a layer (approximately 4 inches thick) of hot-mix asphalt (HMA). Great care was taken to replace the upper two thermistors in the new HMA layer (about 0.5 inches below the surface) and just below the HMA layer.

Mariaville, ME Site Installation(s)

The Mariaville-1 site is located in the southbound lane of Route 181 in Mariaville, ME, as shown on pages B-2 and B-3. As discussed previously, this primary site was located in an open/sunny section of roadway, and Maine DOT personnel were concerned that frost/thaw patterns in adjacent shaded sections of roadway might differ significantly from the frost/thaw patterns recorded in open/sunny areas. Therefore, the research team installed a series of subsurface temperature sensor/data loggers at a secondary site (designated Mariaville-2), located in a shady section of roadway just down the hill in the northbound lane of Route 181, just north of Mariaville 1.

Mariaville-1 is a satellite transmission site, so the same equipment that was installed at Warren Flats, NH, (listed in Table 1) was also installed at this site. Both the subsurface sensors and atmospheric sensors were installed on October 9, 2012 at this site, so research team members worked with Maine DOT personnel on various tasks in parallel in order to accomplish the installation in one day. Photographs of equipment installation at this site are included in Appendix E. A plan showing the location of instrumentation at the Mariaville-1 site is shown on page B-4.

Upon arrival at the site, two observations were made. First, the pavement surface was badly cracked, as shown in Figure 10. Second, just east of the roadway at the proposed site location, it appeared that there was ledge outcropping. Therefore, there was some concern that shallow bedrock might hinder the instrument installation.

Figure 10. Cracked pavement at Mariaville site (near top of hill facing north).

The water well was installed first, and drillers hit ledge at a depth of about 12 feet in that location. There was no groundwater observed in that borehole at that time, however the pressure transducer was placed in the well to monitor any potential rise in groundwater level that might occur in the future. The well consisted of 5 feet of 2-inch diameter PVC slotted screen, with 5 feet of riser pipe. The top of the riser pipe was placed just below the top of the existing ground surface. Holes were drilled in the top of the riser pipe to allow for venting, and a locking cap was provided at the top of the riser pipe. Maine DOT personnel had stipulated that they did not want a riser pipe sticking up above ground surface, so a steel monitoring well cover was placed over the well, flush with the ground surface. Photographs of the well installation are included on pages E-2 and E-3.

After the well was completed, a 4-inch by 6-inch wood post was installed adjacent to the well. Similar to what had been done at the Warren Flats, NH site, the team first assembled atmospheric sensors on a pop-up mast laid out on a tarp on the ground, and then attached the mast to the wood post, as shown in photos on pages E-4 and E-5.

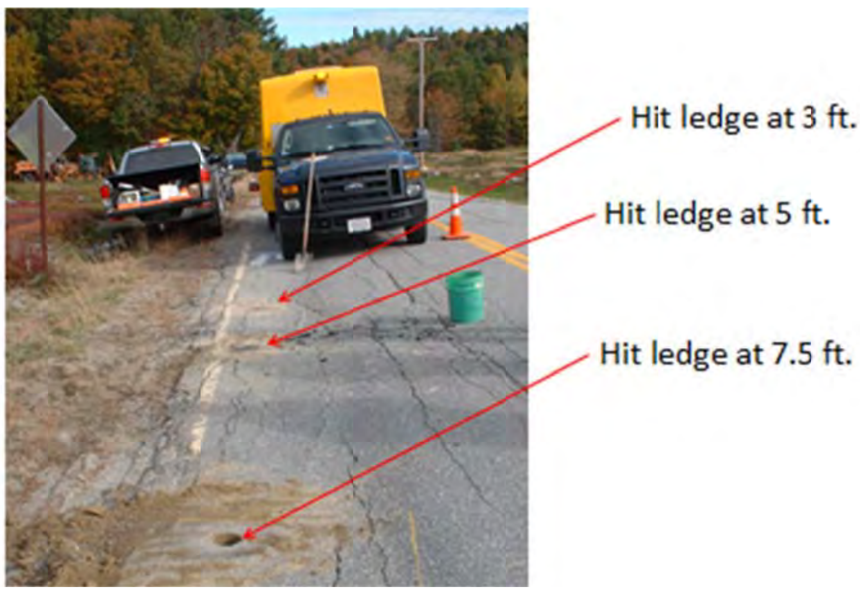


Figure 11. Refusal in three boreholes at Mariaville site

As some members of the team worked on atmospheric sensor assembly, the drillers simultaneously began work for thermistor installation. Due to shallow ledge at this site, it took three attempts to drill a hole deep enough for the thermistor installation, as shown in Figure 11. No soil samples or SPT tests were obtained from these “exploratory” boreholes. At the first borehole (drilled directly in front of the wood post), refusal was encountered at a depth of about three feet. The drillers moved up the hill slightly and hit ledge at a depth of about five feet. Finally, the drillers were able to advance a borehole to a depth of about 7.5 feet on the third attempt. After this borehole was completed, the pavement surrounding the borehole was cut and removed, and a trench was excavated between that borehole location and the wood post (shown on pages E-6 through E-8).

The drillers then advanced another borehole at that location for thermistor installation. The pavement at this location was about 5.5 inches thick. Soil samples were collected from this borehole and logged by Maine DOT personnel along with standard penetration test N-values. Soil samples were transported to the laboratory at UMass Dartmouth for sieve analysis and moisture content determination. SPT N-values are included in Table 5, and a summary of results from the laboratory testing are included in Table 6, along with USCS and AASHTO soil classifications. Grain size distribution curves for the soil samples are included in Appendix H.

Table 5. SPT N-Values at Mariaville-1 Site

Depth (ft)	N-Value (Blows/ft)
0.50-2.50	9
2.50-4.50	33
4.50-6.50	38

Table 6. Results of Grain Size Analyses and Moisture Content Determinations at Mariaville-1 Site

	USCS Particle Size Distribution								
Depth (feet)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	Moisture Content (%)	AASHTO Symbol	USCS Symbol
0.50-1.50	15	20	14	31	15	5	5	A-1-b	SW-SM
1.50-2.50	0	12	10	23	31	24	12	A-2	SM
2.50-4.50	21	11	8	23	22	14	8	A-1-b	SM
4.50-6.50	5	10	15	28	39	4	9	A-1-b	SP

Because groundwater was not encountered in boreholes at this site, and soils were fairly dense, it was not necessary to case the thermistor hole as was done at the Warren Flats, NH, installation. However, prior to installation, the thermistor string was tightly attached to a PVC dowel. This was done in an attempt to prevent potential damage that might occur to the thermistor cable if differential frost heaving occurs along the length of the cable. Photographs of the thermistor string and moisture sensor installation are included on pages E-9 through E-11. Page B-5 shows a tabulation of sensor locations (depths and offsets from centerline) installed at this site.

After the subsurface sensors were installed, the trench between the roadway and the wood post was backfilled, and the pavement was patched with HMA (page E-12 and E-13). With the assistance of a bucket truck, the rain gauge and pyranometer were shimmed and adjusted as necessary to maintain a level position (page E-14). The completed installation is shown in Figure 12.

Figure 12. Completed Installation at Mariaville-1 site

<u>Madison, ME Site Installation</u>

The Madison-1 site is located in the northbound lane of Route 43 in Madison, ME, as shown on pages C-2 and C-3. As discussed previously, the research team also installed a series of subsurface temperature sensor/data loggers at a secondary site (designated Madison-2), located in a shady section of roadway on Route 43 just past the intersection of Old County Road, as shown on page C-3.

Madison-1 is a cell transmission site, which was installed because Maine DOT had expressed an interest in a low-cost system primarily for monitoring subsurface temperature and moisture regimes. The equipment listed in Table 2 was purchased from Onset Computer and installed at the Madison-1 site. The only atmospheric sensor installed at this site was for air temperature, and no water well was installed. Due to the number of thermistors desired and their associated cable lengths, it was necessary to use two separate data logger/transmitters (and thus 2 separate solar panels), because the maximum total length of cable attached to the U-30 data logger/transmitter was limited to 328 feet (100 meters). Additional cost savings could be realized with this type of system if fewer subsurface monitoring points were used.

All equipment was installed on October 11, 2012 at this site. A plan showing the location of instrumentation at the Madison-1 site is shown on page C-4. Photographs of the installation are included in Appendix F. Again, team members worked in parallel; while some DOT personnel drilled a hole for the wood post, others removed pavement and advanced boreholes for thermistor and moisture sensor installation (pages F-1 through F-3). The pavement at this location was about 6 inches thick. Soil samples were collected from the 7-foot deep borehole (for thermistors) and logged by Maine DOT personnel along with standard penetration test N-values. Soil samples were transported to the laboratory at UMass Dartmouth for sieve analysis and moisture content determination. Hydrometer analysis and Atterberg Limits tests (liquid limit and plastic limit) were also performed on two of the three soil samples. SPT N-values are included in Table 7, and Atterberg limits are listed in Table 8. A summary of results from the sieve, hydrometer and moisture content testing is included in Table 9, along with USCS and AASHTO soil classifications. Grain size distribution curves for soil samples are included in Appendix H.

Table 7. SPT N-Values at Madison-1 Site

Depth (ft)	N-Value (Blows/ft)
0.50-2.00	34
3.00-5.00	9
5.00-7.00	11

Table 8. Atterberg Limits Data at Madison-1 Site

Depth (ft)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
3.00-5.00	37.4	20.2	17.2
5.00-7.00	36.9	23.8	13.2

Table 9. Results of Grain Size Analyses and Moisture Content Determinations at Madison-1 Site

	USCS Particle Size Distribution								
Depth (feet)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	Moisture Content (%)	AASHTO Symbol	USCS Symbol
0.50-2.00	7	18	10	38	20	6	7	A-1-b	SW-SM
3.00-5.00	0	0	0	5	9	86	24	A-6	CL
5.00-7.00	0	0	0	2	5	94	27	A-6	CL

Nine of the 12 thermistors were attached to a wood dowel (as shown in Figure 3 and on page F-3, top left). This was done to maintain the spacing of the individual thermistors, and also to prevent potential damage that might occur to the thermistor cables if differential frost heaving occurs along the lengths of those cables. The locations (depths and offsets from centerline) of those nine thermistors, as well as the 3 fly thermistors and two moisture sensors installed at this site, are tabulated on page C-5.

The two data logger/transmitters, two solar panels, and the air temperature sensor were mounted directly onto the 4-inch by 6-inch wood post, as shown on page F-4. The post was then hoisted into the pre-drilled hole (page F-5). A trench was excavated between the roadway and the wood post to bury the thermistor and moisture sensor cables (page F-5 and F-6**)**. The cables were then run up through protective PVC conduit. The Onset thermistors also had “smart sensors” **(**like the moisture sensors), which were located on the cable about a foot below the connector for the data logger (see Figure 13 (a)). After the sensor cables were connected to the data logger, the smart sensors and excess cable were placed into PVC conduit, and then duct tape was placed over the cables between the conduit and data logger enclosure Figure 13 (b and c).

(a) (b) (c)

Figure 13. Madison-1 site: (a) connecting thermistors to data logger (smart sensors shown hanging below enclosure); (b) smart sensors and excess cable placed into PVC conduit; (c) completed installation with duct tape placed over cables between conduit and data logger enclosure.

4. Data Obtained and Lessons Learned to Date

At this time, the three remote systems are logging, storing and transmitting data. Data is being transmitted and stored at the DataGarrison server (for satellite systems at Warren Flats and Mariaville-1) and at the Onset “Hobolink” server (for the cellular transmission system, Madison-1). The web address and login information for these servers is as follows:

https://datagarrison.com/

user ID: 300234010074300

Password: data

www.Hobolink.com

name: research

password: umassd

The link between those servers and the UMass Dartmouth Decision Support System (DSS) is anticipated to be established in the near future.

Several problems have been encountered with the two satellite transmission systems since their installation. The first problem was observed at the Warren Flats site in early October. The voltage on the battery seemed to be steadily declining; then problems with some of the transmitted data were noted on about October 13, and the system went down completely on Oct 18, 2012. On November 2, Robert Eaton (Frost Associates, sub-consultant to UMass) visited the Warren Flats site and observed water in the NEMA enclosure. It was not clear whether the moisture was due to condensation, or due to a crack in the box which had occurred during shipping (and which was caulked over prior to mounting in the field). In any case, Mr. Eaton dried out the inside of the enclosure and pressed the manual reset button on the system; however the system still did not function properly.

Simultaneously (during the first week in November), problems were observed in the wind speed, rain and air temperature data being transmitted from the Mariaville-1 site. The research team discussed these problems with Doug Calvert (Hoskin Scientific) and Tom Stalcup (Upward Innovations and DataGarrison). Tom Stalcup kindly offered to visit the two test sites and troubleshoot the systems. Tom first visited the Mariaville-1 site on November 10, 2012. Tom concluded that the sensor problems at the Mariaville-1 site appear to have been caused by water getting into the “smart sensor” in-line PVC tubes, which contain sensor electronics and mount outside the enclosure. These tubes have thick rubber grommets that compress against the sensor cables in an effort to create a water-tight seal. However, water got in, most likely because of pressure differentials building up inside the tubes which can literally suck water in during rain events. Figure 14 (a) shows the wind sensor's in-line tube and water that poured out when Tom opened it up back at his office.

(a) **(b)**

Figure 14. (a) water found in the in-line PVC tube (b) protective tape wrapped over in-line tube
(Photographs provided by Mr. Tom Stalcup)

Tom replaced the wind speed sensor and mounted the in-line tube horizontally, and underneath the enclosure, to help prevent water from getting in again. Since the in-line tube on the air temperature sensor could not be mounted horizontally (due to the limited cable length), Tom wrapped electrical tape around the tube to prevent water from building up near where the wires enter that tube (Figure 14 b).

Tom Stalcup then visited the Warren Flats (WF) site on November 13, 2012. At that time, it could not be determined whether the battery at the WF site went dead due to (1) water infiltration into a sensor in-line tube, shorting out that sensor and draining battery power; and/or (2) water infiltration into enclosure, shorting out the power switch. Due to the concern that water may have been entering the NEMA enclosure through the crack, Tom replaced the enclosure with a new one. The battery was also replaced, and the WF station began transmitting again, but there appeared to be possible issues with the wind speed sensor and at least one of the soil moisture sensors. Monitoring of that site over the next several days suggested that there was still a significant power drain, so there was concern that water infiltration into a sensor in-line tube was still causing problems.

Tom spoke to Onset technical representatives about the issues with water getting into their sensor electronics and they said they are in the process of redesigning rubber grommets to make a tighter fit around the cable going into the sensor tubes. In the meantime, Onset agreed to provide free replacements for any failed sensors in our systems; however, the replacements will not be the new design. Therefore, Tom designed a “PVC Jacket” that could be added to the existing smart sensor in-line tubes. These jackets essentially consist of a PVC tube with an inner diameter larger than the smart sensor tube's outside diameter. They are sealed at the top, but open at the bottom. The open bottom will prevent pressure differentials that could suck water through the top seal. The top is a commercially obtained cord grip specifically designed for weather-proofing cables as they enter enclosures. It screws into a PVC cap which was threaded to accept the cord grip. The cord grip has an O-ring which seals it against the PVC cap. The cap fits tightly over the 12 inch long plastic jacket with PVC cement applied beforehand. The jacket was then covered with electrician’s tape which survives well in sunlight. The materials used for constructing these prototype PVC jackets are shown in Figure 15 (a); a temperature sensor without the PVC jacket is shown in Figure 15 (b), and that same sensor with a jacket installed is shown in Figure 16.

(a)

(b)

Figure 15. (a) PVC jacket materials (b) Onset temperature sensor without jacket

(Photographs provided by Mr. Tom Stalcup)

Figure 16. Onset temperature sensor with PVC jacket installed over smart sensor tube
(Photograph provided by Mr. Tom Stalcup)

Tom Stalcup returned to the Warren Flats site on December 3, 2012. He removed the old wind sensor and put up a new one (with the newly designed PVC jacket attached) on a different bracket. The new wind sensor is much lower than the original wind sensor. Tom noted that there was some water in the sensor tube going to the original wind speed sensor, which was most likely the cause of its failure. He also noted that one soil moisture sensor at that site is not responding properly, probably for a similar reason. Tom isolated the non-working soil moisture sensor and disconnected it. To help prevent a total system shutdown in the future due to this potential water ingress issue, Tom activated a feature to the firmware that will shut down sensors if they cause too much of a current drain. This is better than the whole site going down, but losing a sensor(s) is not ideal. Therefore, for any future installations, the water ingress issue will need to be addressed further if Onset soil moisture sensors are to be used. Tom's prototype PVC jackets should work for exterior installations such as the atmospheric sensors mounted on the pole/mast, but not for in-line smart sensor tubes that are buried beneath the ground surface and/or pavement.

At the cellular transmission site (Madison-1), one of the two data loggers continues to transmit data; however, no data has been received from the second data logger/transmitter since December 9, 2012. To date, the research team has not been able to visit that site and/or to troubleshoot that system. It is possible that one of the Onset sensors went bad (perhaps due to water ingress issues, as discussed in the previous paragraphs), and that may have shorted out something that shut the data logger/transmitter down. Further investigation of this problem is planned for the near future.

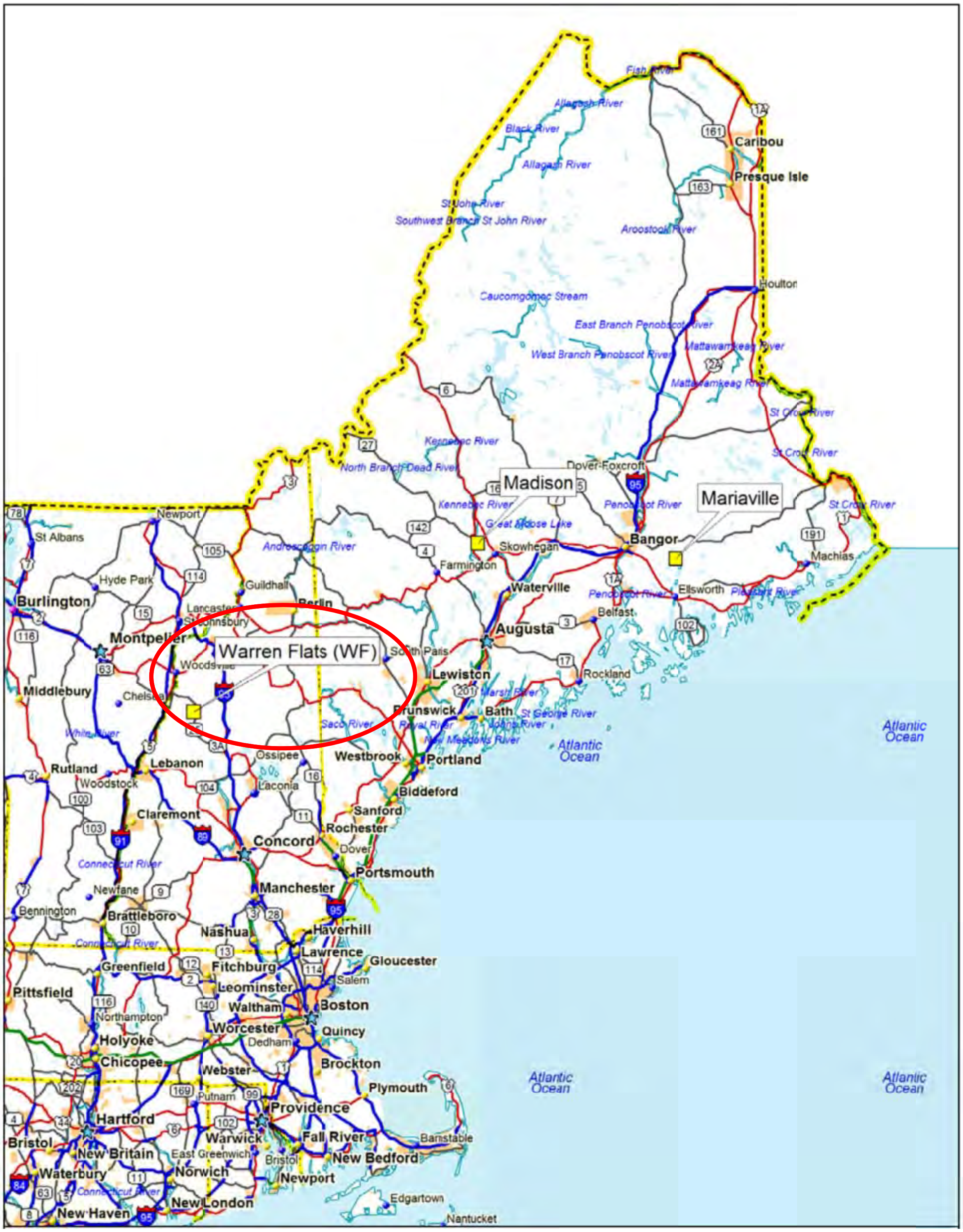
So, in summary, data is being collected and transmitted from all three field test sites, however not all components are fully functional at the sites. At the cellular transmission site (Madison-1), data is currently being collected from six of the subsurface temperature sensors, one of the two moisture sensors, and the air temperature sensor. At the Mariaville-1 satellite transmission site, all 26 sensors are currently transmitting data, however, the wind, rain and air temperature sensor appear to be giving erroneous readings. Tom Stalcup has indicated that he may be able to get up to that site later this month (January 2013) to fix those sensors. The sensors that failed have either the inline sensor tubes that appear vulnerable to water infiltration (see above) or in the case of the rain buckets, have sensor electronics outside the enclosure within the bucket itself that also appear vulnerable. Stalcup plans to replace the sensors, adding sensor jackets where necessary and by replacing the rain buckets with different models that do not have sensitive sensor electronics outside the enclosure. At the Warren Flats satellite transmission site, 25 of the 26 sensors are currently transmitting data; however, the rain sensor at that site also appears to be giving erroneous readings. As noted previously, Tom Stalcup isolated one of the soil moisture sensors that was not functioning properly and disconnected it on his 12/3/12 visit to that site.

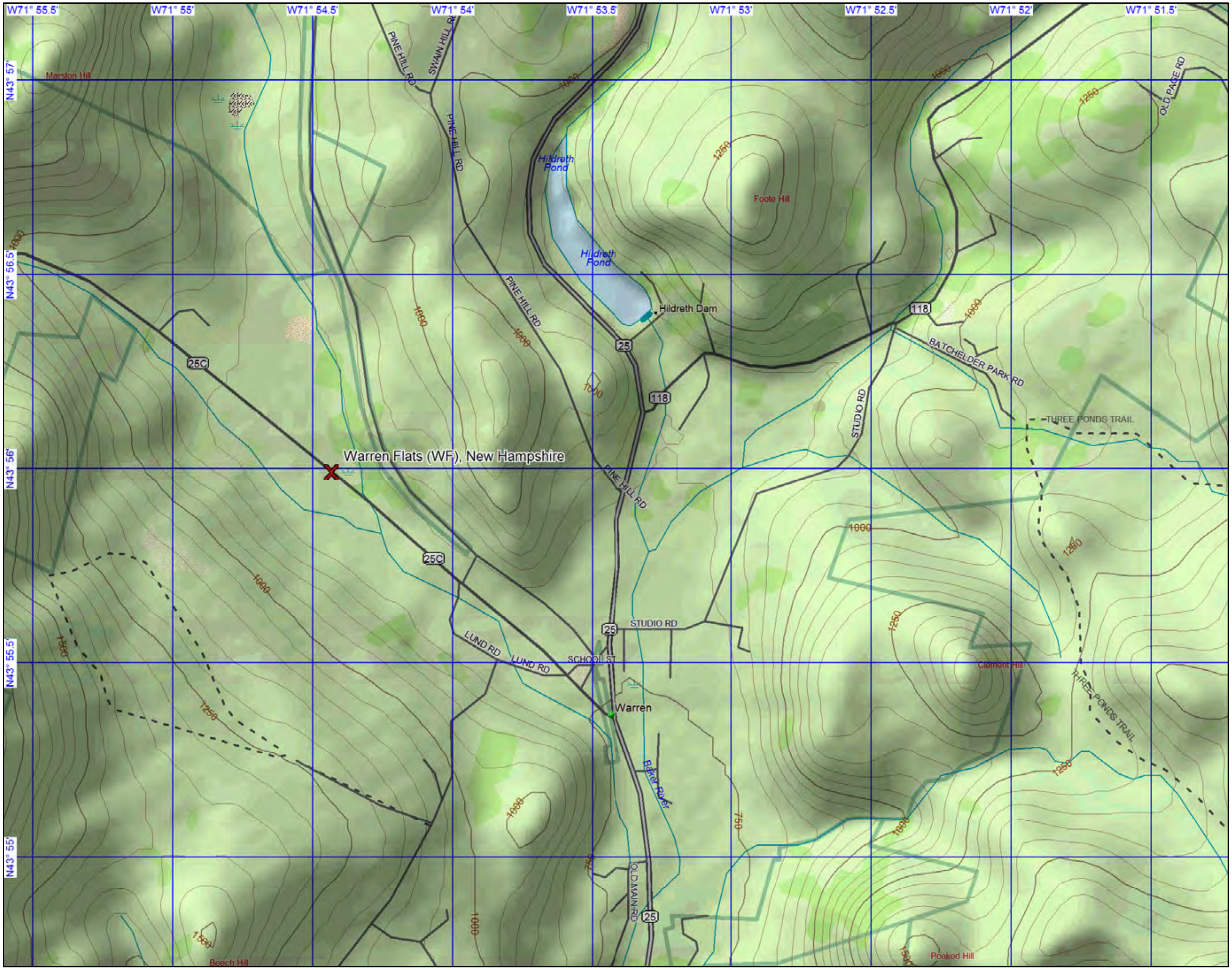
Data is being transmitted and stored at the DataGarrison server (for satellite systems) and at the Onset "Hobolink" server (for the cellular transmission system). The link between those servers and the UMass Dartmouth Decision Support System (DSS) is anticipated to be established in the near future. Updates regarding the UMass DSS will be provided in upcoming project Quarterly Reports, as well as in the project Task 6 report.

Appendix A

Warren Flats, NH

Site Plans & Equipment Details (Serial Numbers, Offsets, etc.)


Madison
Mariaville
Warren Flats (WF)



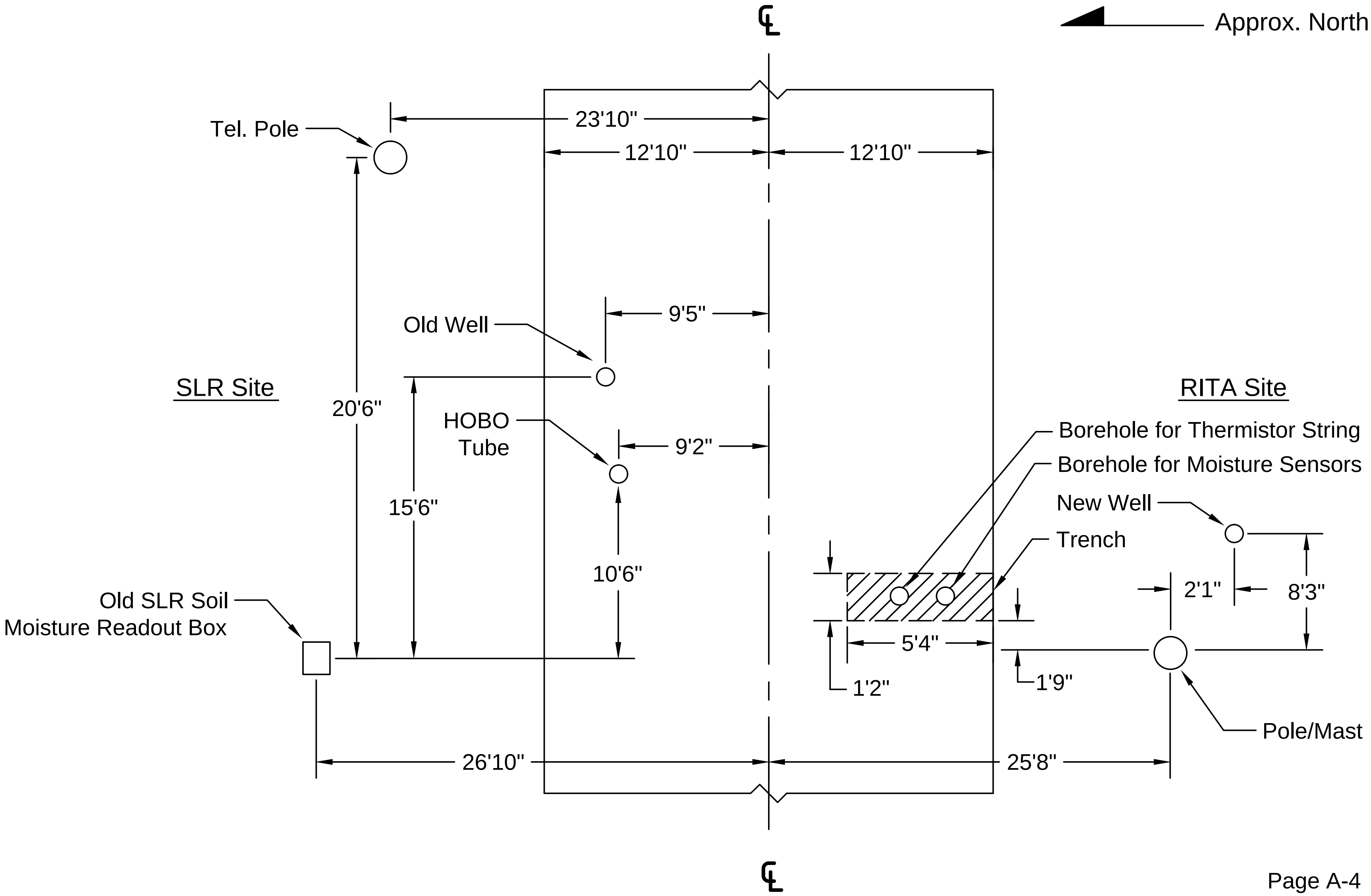
© 2001 DeLorme. Topo USA® 3.0

Scale: 1 : 25,000 Zoom Level: 13-0 Datum: WGS84 Map Rotation: 0° Magnetic Declination: 16.0°W

2,000 ft

Rte 25C, Warren, NH, Warren Flats (WF) Site

(Drawing not to Scale)



Site Name & Location	Elev. (ft)	Coordinates	
Warren Flats (WF), NH	766	**Lat.**	**Long.**
Date atmospheric sensors installed: 8/7/12		N 43° 55.99'	W 71° 54.43'
Date subsurface sensors installed: 8/29/12			

Instrumentation at this site provided by Hoskin Scientific with satellite transmission provided by Upward Innovations/DataGarrison

*Distances measured off Centerline (CL)

**Depths measured from Top of Existing Pavement

			Measured		
		Modbus Address (S.N.)	**Depth (in)	*Distance (in)	Comments
MOISTURE SENSOR		Modbus_10050943_na	33.0	108.0	Prongs installed in vertical orientation in bottom of borehole below old (original) pavement
MOISTURE SENSOR		Modbus_10050944_na	14.5	97.0	Prongs installed in horizontal orientation in trench
MOISTURE SENSOR		Modbus_10002281_na	9.0	99.0	ditto
MOISTURE SENSOR		Modbus_9996269_na	5.0	99.0	ditto
THERMISTOR-Fly 1	T-12	Modbus_3_3_na	0.5		9/20/12 Replaced cold patch with HMA; sensor moved to 7" south of the NE corner of the trench against the east side of the trench.
THERMISTOR-Fly 2	T-11	Modbus_3_2_na	3.0		9/20/12 sensor moved to 4" south of the NE corner of the trench against the east side of the trench.
THERMISTOR-Fly 3	T-10	Modbus_3_1_na	7.5	81.0	Located in reclaimed asphalt mix, between new and old pavement (at borehole location)
THERMISTOR	T-1	Modbus_2_0_na	14.0	81.0	Located in borehole (approx. center of trench)
THERMISTOR	T-2	Modbus_2_1_na	20.0	81.0	ditto
THERMISTOR	T-3	Modbus_2_2_na	26.0	81.0	ditto
THERMISTOR	T-4	Modbus_2_3_na	32.0	81.0	ditto
THERMISTOR	T-5	Modbus_2_4_na	38.0	81.0	ditto
THERMISTOR	T-6	Modbus_2_5_na	50.0	81.0	ditto
THERMISTOR	T-7	Modbus_2_6_na	62.0	81.0	ditto
THERMISTOR	T-8	Modbus_2_7_na	74.0	81.0	ditto
THERMISTOR	T-9	Modbus_3_0_na	86.0	81.0	ditto

Site Name & Location
Warren Flats (WF), NH

Hoskin Modbus Address	Freezing Temp. Offset +/- (°F)	Sensor Depth** (specified in inches below pavement surface)
3-3	0.050	pavement surface
3-2	-0.118	4.0
3-1	0.047	7.5
2-0	-0.127	14.0
2-1	0.140	20.0
2-2	0.032	26.0
2-3	0.035	32.0
2-4	-0.073	38.0
2-5	0.083	50.0
2-6	0.020	62.0
2-7	0.101	74.0
3-0	0.038	86.0

Site Name & Location
Warren Flats (WF), NH
Date Hobo sensors installed: 9/20/12

Onset Serial #	Freezing Temp. Offset +/- (^oF)	Sensor Depth (specified in inches below pavement surface)
1104871	0.0	7.0
1104858	0.2	13.0
1104862	0.2	19.0
1104835	-0.2	25.0
1104839	0.0	31.0
2254693	-0.2	37.0
1104850	0.0	43.0
2254696	-0.4	55.0
2254694	-0.4	79.0

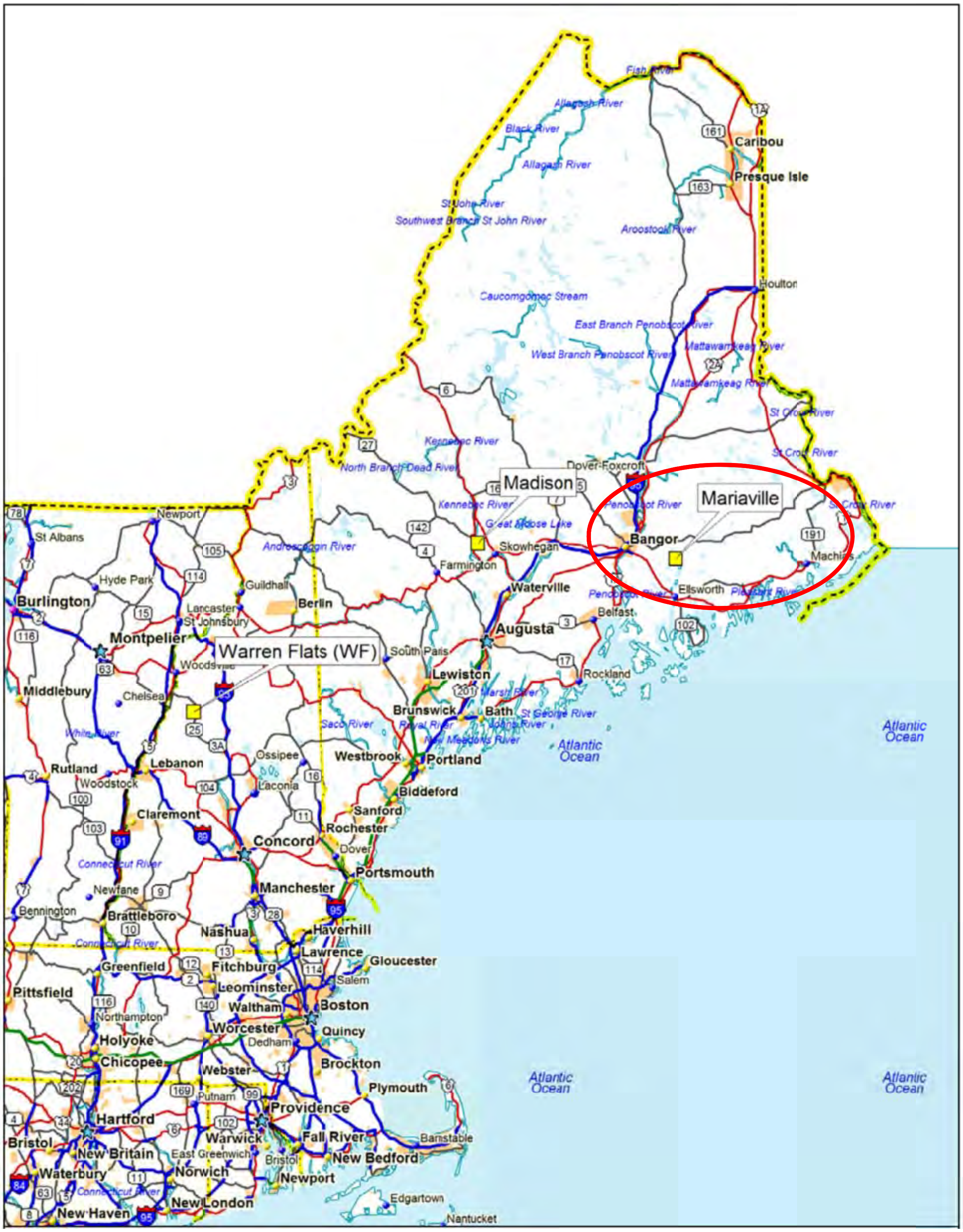
Hobo sensors installed in cased hole from previous NH DOT SLR study.

Instrumentation at this site consists of Hobo temperature sensors with internal data loggers (produced by Onset Computer). No real-time transmission of data occurs from these sensors. These HOBO tubes are installed in the fall and removed and downloaded in the spring.

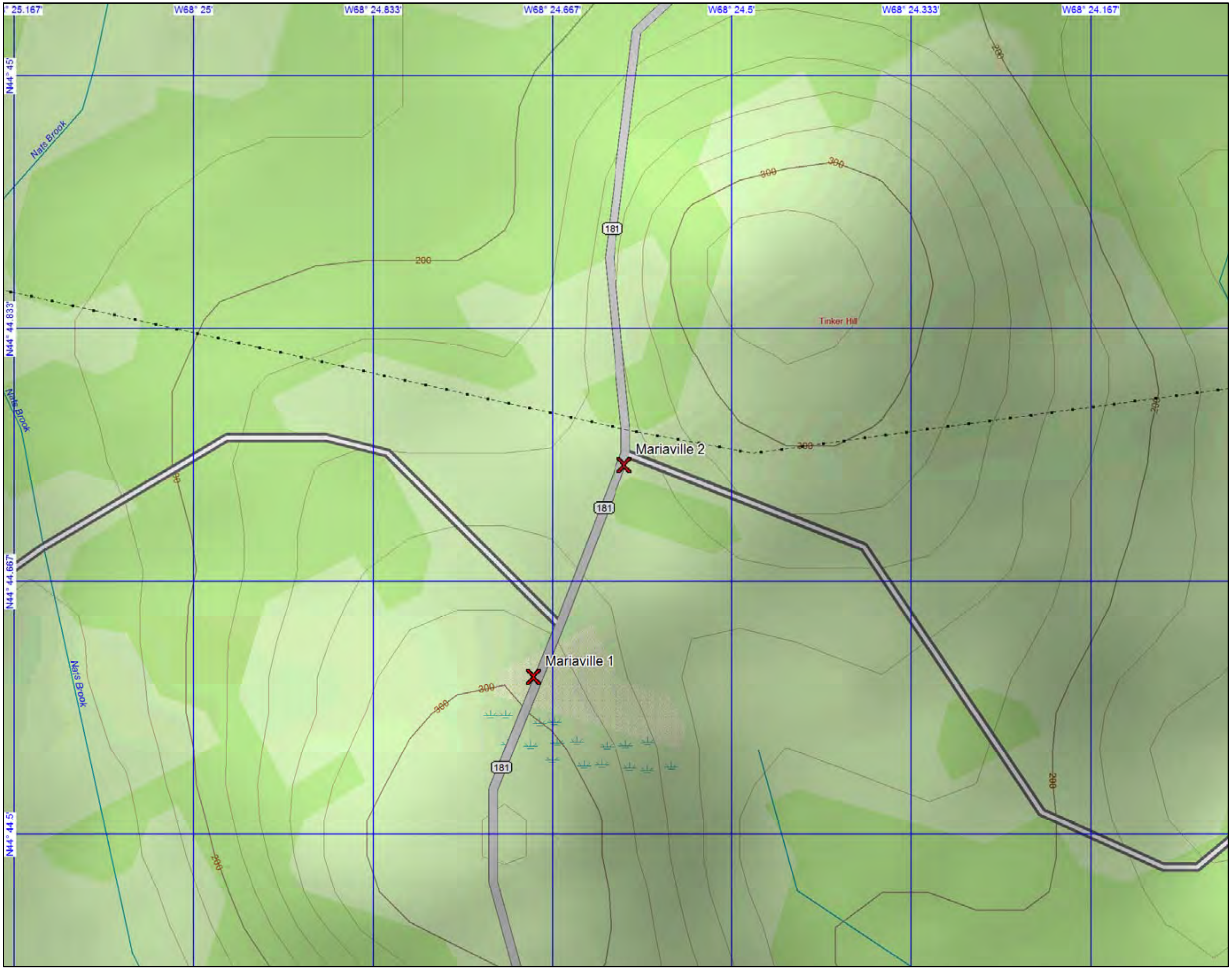
Appendix B

Mariaville, Maine

Site Plans & Equipment Details (Serial Numbers, Offsets, etc.)



Madison
Mariaville
Warren Flats (WF)
Caribou
Presque Isle
Houlton
Dover-Foxcroft
Bangor
Machias
Ellsworth
Belfast
Rockland
Skowhegan
Farmington
Waterville
Augusta
Lewiston
Brunswick
Bath
Portland
Westbrook
Biddeford
Sanford
Rochester
Dover
Portsmouth
Concord
Manchester
Nashua
Haverhill
Lawrence
Gloucester
Salem
Boston
Quincy
Brockton
Plymouth
Providence
Fall River
New Bedford
Newport
Barnstable
Edgartown
Nantucket
Worcester
Waltham
Leominster
Fitchburg
Dedham
Webster
Putnam
Warwick
Bristol
East Greenwich
Norwich
New London
New Haven
Waterbury
New Britain
Hartford
Chicopee
Holyoke
Northampton
Greenfield
Pittsfield
Brattleboro
Newfane
Bennington
Claremont
Lebanon
Woodstock
Rutland
Middlebury
Chelsea
Montpelier
Burlington
St Albans
Newport
Hyde Park
Lancaster
St Johnsbury
Guildhall
Berlin
Woodsville
South Paris
Ossipee
Laconia
Atlantic Ocean

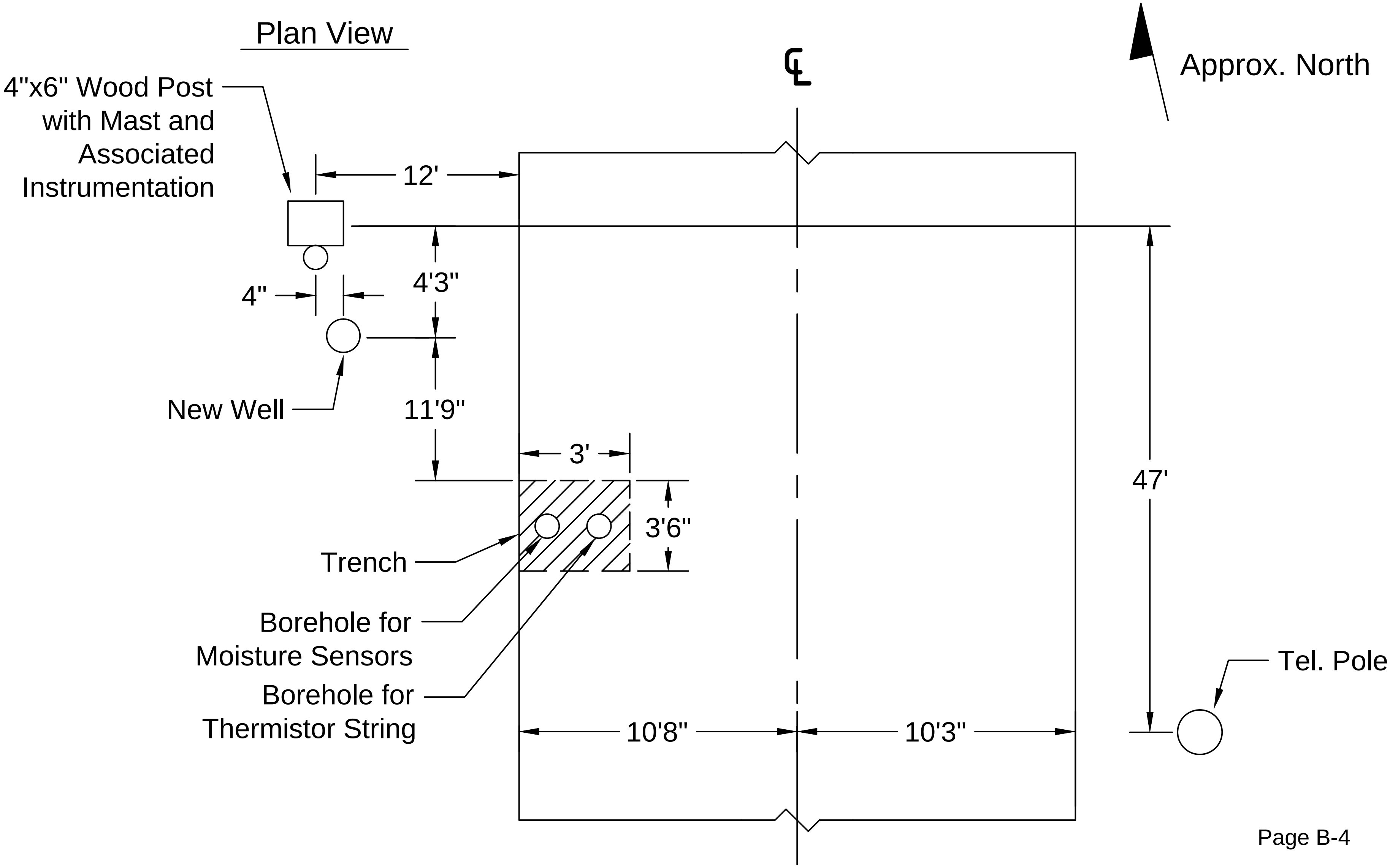


Scale: 1 : 6,400 Zoom Level: 15-0 Datum: WGS84 Map Rotation: 0° Magnetic Declination: 18.1°W

500 ft

Rte 181, Mariaville, ME Site

(Drawing not to Scale)



Site Name & Location	Elev. (ft)	Coordinates	
Mariaville 1, ME	289	**Lat.**	**Long.**
Date atmospheric sensors installed: 10/9/12		N 44° 44.601’	W 68° 24.694’
Date subsurface sensors installed: 10/9/12			

Instrumentation at this site provided by Hoskin Scientific with satellite transmission provided by Upward Innovations/DataGarrison

*Distances measured off Centerline (CL)

**Depths measured from Top of Existing Pavement

			Measured		
		Modbus Address (S.N.)	**Depth (in)	*Distance (in)	Comments
MOISTURE SENSOR	#31	10002280	39.5	112.0	6" south of north edge of trench (prongs vertical in bottom of borehole)
MOISTURE SENSOR	#41	10050941	29.0	112.0	6" south of north edge of trench (prongs horizontal in sidewall of borehole)
MOISTURE SENSOR	#45	10050945	22.0	112.0	ditto
MOISTURE SENSOR	#37	10050947	12.0	112.0	ditto
THERMISTOR-Fly 1	T-12	Modbus_3_3_na	0.5		placed in HMA surface at north edge of trench
THERMISTOR-Fly 2	T-11	Modbus_3_2_na	6.0	102.0	placed just below asphalt at north edge of trench
THERMISTOR-Fly 3	T-10	Modbus_3_1_na	9.0	102.0	placed at north edge of trench
THERMISTOR	T-1	Modbus_2_0_na	12.0	96.0	29" south of north edge of trench (in borehole)
THERMISTOR	T-2	Modbus_2_1_na	18.0	96.0	ditto
THERMISTOR	T-3	Modbus_2_2_na	24.0	96.0	ditto
THERMISTOR	T-4	Modbus_2_3_na	30.0	96.0	ditto
THERMISTOR	T-5	Modbus_2_4_na	36.0	96.0	ditto
THERMISTOR	T-6	Modbus_2_5_na	48.0	96.0	ditto
THERMISTOR	T-7	Modbus_2_6_na	60.0	96.0	ditto
THERMISTOR	T-8	Modbus_2_7_na	72.0	96.0	ditto
THERMISTOR	T-9	Modbus_3_0_na	84.0	96.0	ditto

Site Name & Location
Mariaville 1, ME

Hoskin Modbus Address	Freezing Temp. Offset +/- (^{o}F)	Sensor Depth** (specified in inches below pavement surface)
3-3	0.227	pavement surface
3-2	NA	6.0
3-1	0.056	9.0
2-0	0.000	12.0
2-1	0.017	18.0
2-2	-0.001	24.0
2-3	0.011	30.0
2-4	0.032	36.0
2-5	-0.013	48.0
2-6	-0.004	60.0
2-7	-0.040	72.0
3-0	0.005	84.0

Site Name & Location	Elev. (ft)	Coordinates	
Mariaville 2, ME	249	**Lat.**	**Long.**
Date subsurface sensors installed: 10/9/12		N 44° 44.744’	W 68° 24.601’

Onset Serial #	Freezing Temp. Offset +/- (°F)	Sensor Depth (specified in inches below pavement surface)
1104864	-0.2	78.0
2262473	-0.6	54.0
2262474	-0.2	42.0
1104860	0.0	36.0
1104855	0.0	30.0
1104840	-0.4	24.0
1104832	0.2	18.0
1104875	0.2	12.0
1104874	NA	6.0
10136218	NA	surface

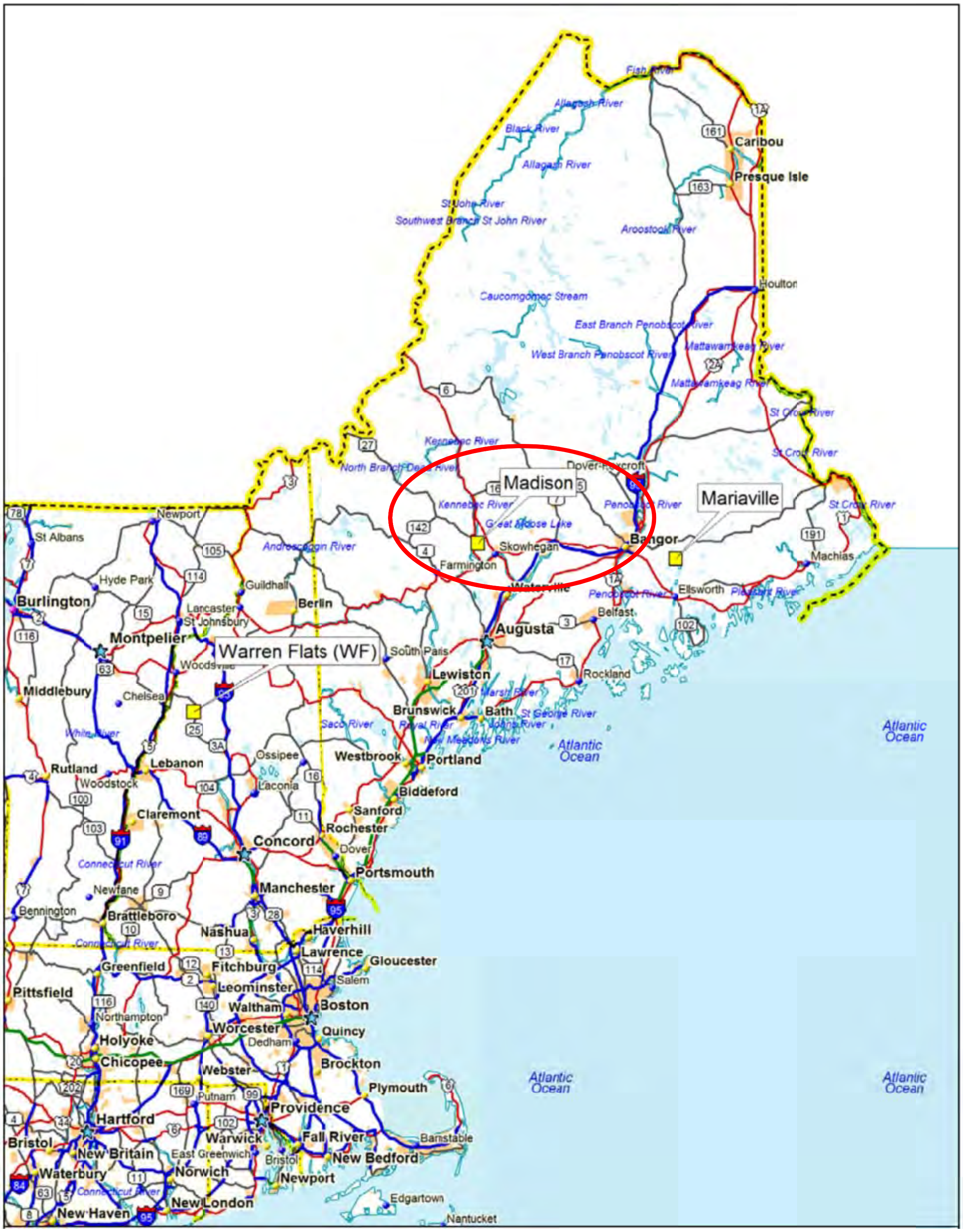
Site located just south of Orrin Road in NB lane 3’ from right edge of pavement.

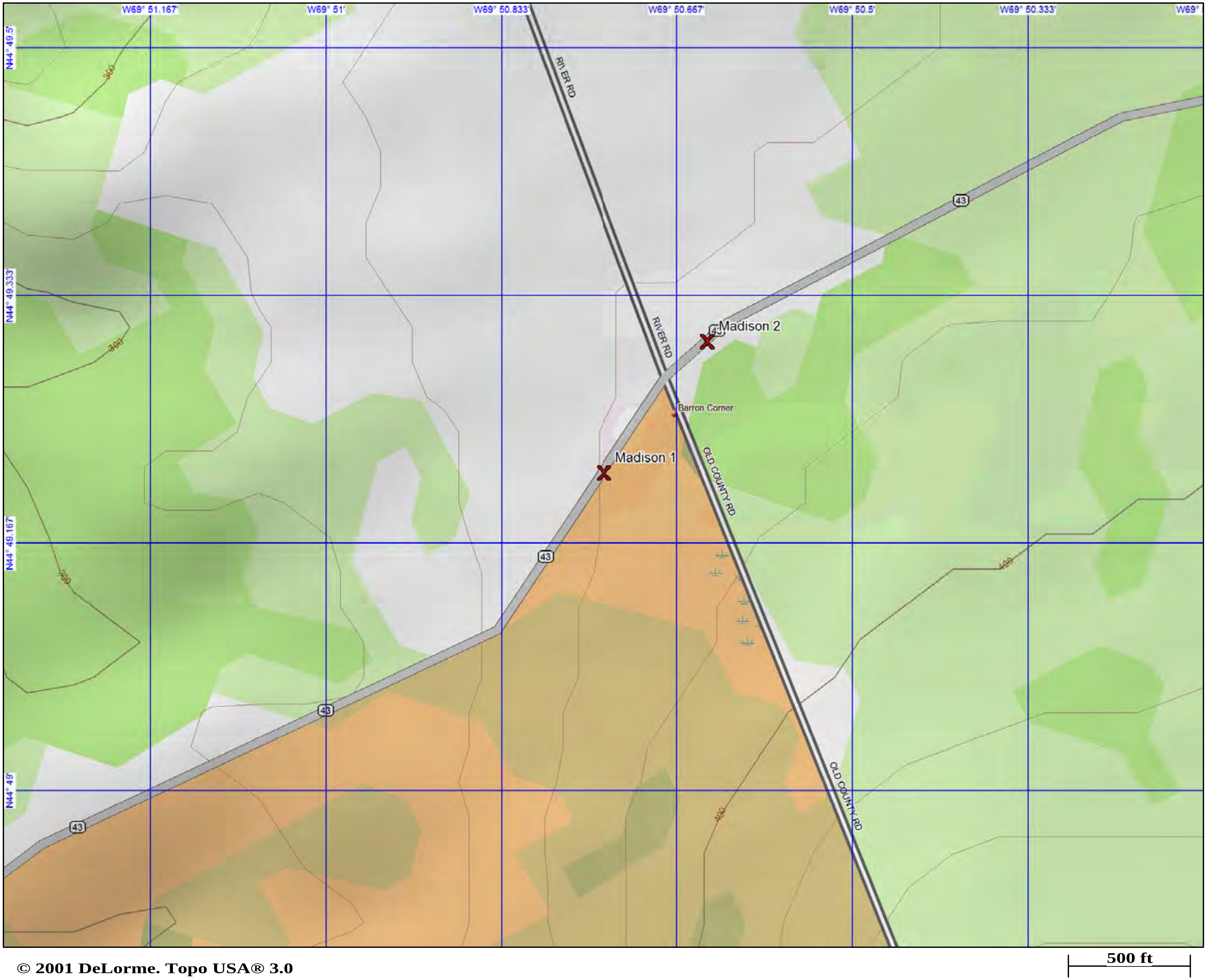
Instrumentation at this site consists of Hobo temperature sensors with internal data loggers (produced by Onset Computer). No real-time transmission of data occurs from these sensors. These HOBO tubes are installed in the fall and removed and downloaded in the spring.

<u>Appendix C</u>

Madison, Maine

Site Plans & Equipment Details (Serial Numbers, Offsets, etc.)


Madison
Mariaville
Warren Flats (WF)
Caribou
Presque Isle
Houlton
Bangor
Skowhegan
Farmington
Augusta
Belfast
Ellsworth
Machias
Rockland
Lewiston
Brunswick
Bath
Portland
Westbrook
Biddeford
Sanford
Rochester
Dover
Portsmouth
Concord
Manchester
Nashua
Haverhill
Lawrence
Gloucester
Salem
Boston
Quincy
Brockton
Plymouth
Providence
Fall River
New Bedford
Newport
Barnstable
Edgartown
Nantucket
Worcester
Waltham
Leominster
Fitchburg
Dedham
Webster
Putnam
Warwick
Bristol
East Greenwich
Norwich
New London
New Haven
Waterbury
New Britain
Hartford
Chicopee
Holyoke
Northampton
Springfield
Greenfield
Pittsfield
Bennington
Brattleboro
Newfane
Claremont
Lebanon
Woodstock
Rutland
Middlebury
Chelsea
Montpelier
Burlington
St Albans
Hyde Park
Newport
Lancaster
St Johnsbury
Guildhall
Berlin
South Paris
Ossipee
Laconia
Dover-Foxcroft
Atlantic Ocean
Fish River
Allagash River
Black River
St John River
Southwest Branch St John River
Aroostook River
Caucomgomoc Stream
East Branch Penobscot River
West Branch Penobscot River
Mattawamkeag River
St Croix River
Kennebec River
Great Moose Lake
Androscoggin River
Penobscot River
Saco River
Connecticut River
White River



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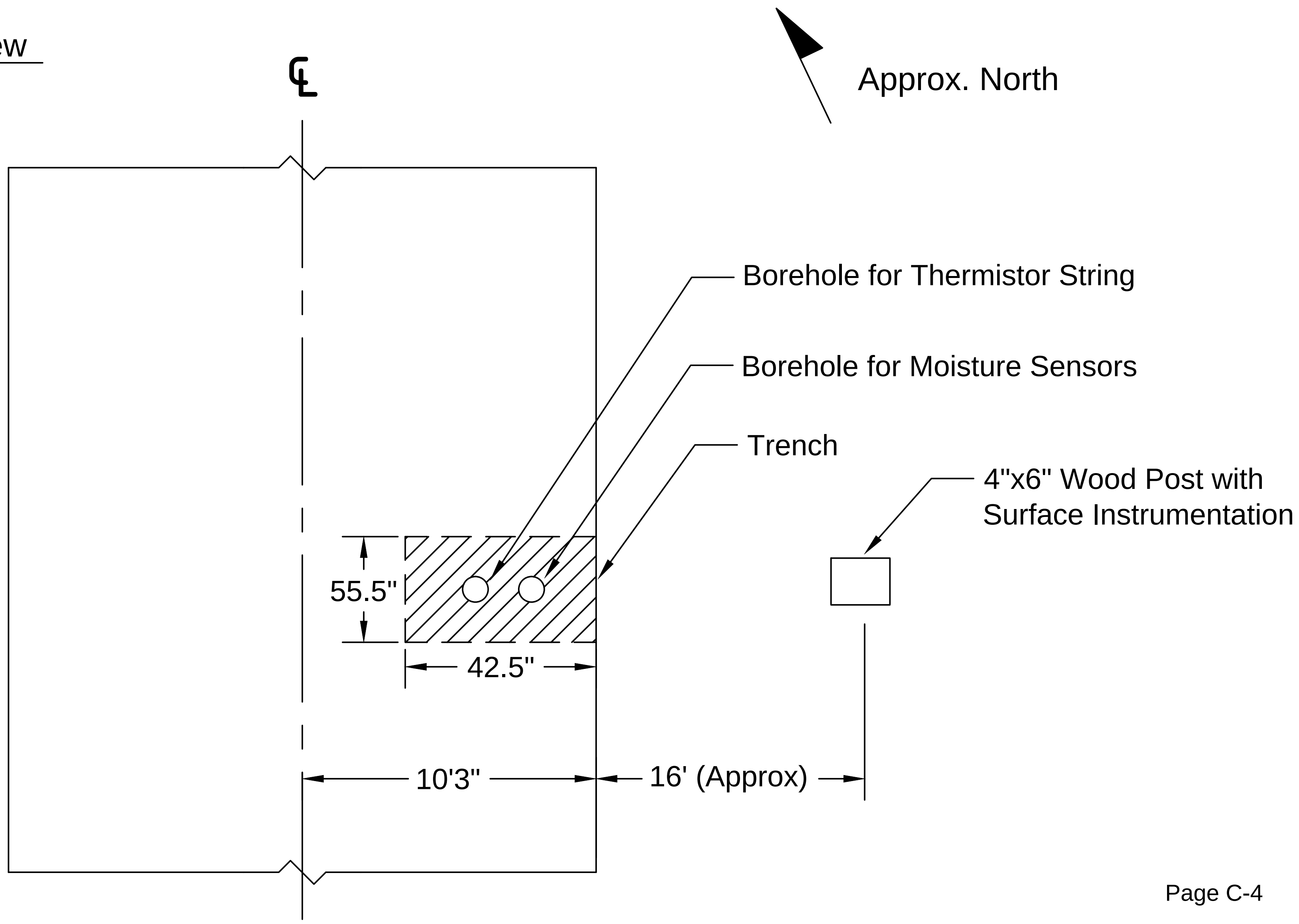
Rte 43, Madison, ME Site (Drawing not to Scale)

Plan View



Site Name & Location	Elev. (ft)	Coordinates	
Madison 1, Maine	360	**Lat.**	**Long.**
Date air temperature sensor installed: 10/11/12		N 44° 49.212’	W 69° 50.747’
Date subsurface sensors installed: 10/11/12			

Instrumentation at this site provided by Onset Computer with cell transmission provided by Onset HoboLink (AT&T and T Mobile Servers)

*Distances measured off Centerline (CL)

**Depths measured from Top of Existing Pavement

		Serial Number	Measured **Depth (in)	Measured *Distance (in)	Comments
MOISTURE SENSOR	#33	10160933	23.0	108.0	32" south of northeast edge of trench (prongs vertical in borehole)
MOISTURE SENSOR	#34	10160934	33.0	108.0	32" south of northeast edge of trench (prongs vertical in borehole)
THERMISTOR	Fly-1	10135846			Located along N.E. edge of trench in asphalt surface
THERMISTOR	Fly-2	10135857	4.5	100.0	Located along N.E. edge of trench
THERMISTOR	Fly-3	10135856	7.0	100.0	Located along N.E. edge of trench
THERMISTOR		10135855	12.0	96.0	Located in borehole (approx. center of trench)
THERMISTOR		10135854	18.0	96.0	ditto
THERMISTOR		10135853	24.0	96.0	ditto
THERMISTOR		10135852	30.0	96.0	ditto
THERMISTOR		10135851	36.0	96.0	ditto
THERMISTOR		10135850	48.0	96.0	ditto
THERMISTOR		10135849	60.0	96.0	ditto
THERMISTOR		10135848	72.0	96.0	ditto
THERMISTOR		10135847	84.0	96.0	ditto

AIR TEMP SENSOR	10161720

Site Name & Location
Madison 1, ME

Onset Serial #	Freezing Temp. Offset +/- (^oF)	Sensor Depth** (specified in inches below pavement surface)
10135846	-0.142	pavement surface
10135847	-0.142	84"
10135848	0.032	72"
10135849	-0.293	60"
10135850	-0.193	48"
10135851	-0.092	36"
10135852	-0.092	30"
10135853	-0.092	24"
10135854	-0.243	18"
10135855	-0.018	12"
10135856	-0.043	7"
10135857	-0.142	4.5"

Site Name & Location	Elev. (ft)	Coordinates	
Madison 2, ME	364	**Lat.**	**Long.**
Date Subsurface sensors installed: 10/11/12		N 44° 49.298’	W 69° 50.637’

Onset Serial #	Freezing Temp. Offset +/- (°F)	Sensor Depth (specified in inches below pavement surface)
2262477	NA	78.5
2262476	-0.2	54.5
2262475	-0.4	42.5
1104847	0.2	36.5
1104848	0.0	30.5
1104868	-0.2	24.5
1104853	0.0	18.5
1104861	-0.2	12.5
1104825	-0.2	6.5
10136219	NA	surface

Site located just north of Old County Road in NB lane on Route 43, 3’ from right edge of pavement.

Instrumentation at this site consists of Hobo temperature sensors with internal data loggers (produced by Onset Computer). No real-time transmission of data occurs from these sensors. These HOBO tubes are installed in the fall and removed and downloaded in the spring.

Appendix D

Warren Flats, NH

Photographs of Equipment Installation

Fig D-1. Looking SW

Fig D-2. Looking SE

Fig D-3. Wind Speed Sensor

Fig D-4. Solar Panel and Air Temperature Sensor

Fig D-5. Looking West

Fig D-6. Environmental Sensors

Fig D-7. Looking West

Fig D-8. Looking North

Fig D-9. Drilling Temperature Sensors Hole (Water Well Standpipe on Right)

Fig D-10. Drilling Temperature Sensor Holes   Fig D-11. Temperature Sensor Installation

Fig D-12. Subsurface Sensor Hole   Fig D-13. Temperature Sensor Flies

Fig D-14. Soil Moisture Sensor Borehole   Fig D-15. Pavement Core

Fig D-16. Temperature Sensor Flies

Fig D-17. Temperature Sensor Flies

Fig D-18. Placing Sensor Flies

Fig D-19. Backfilling

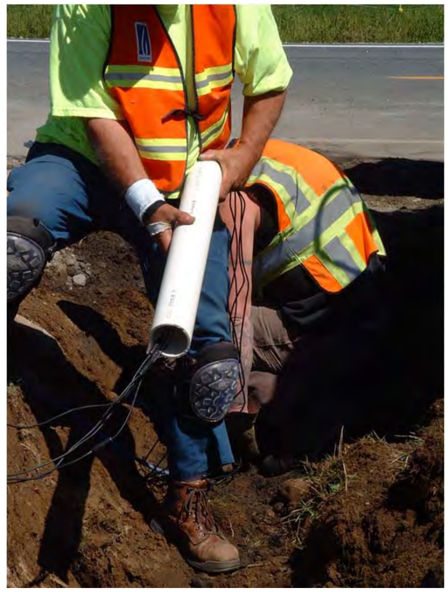


Fig D-20. Smart Sensor Modules

Fig D-21. Protective Casing for Modules

Flagging placed in trench
prior to final backfilling

Fig D-22. Flagging Sensor Casing

Fig D-23. Backfilling Instrumentation Wires Trench

Fig D-24. Placing Temporary Cold Patch Pavement

Fig D-25. Compacting Cold Patch

<u>Appendix E</u>

Mariaville, Maine

Photographs of Equipment Installation

Fig E-1. Cracked Pavement Just North of Installation

Fig E-2. Drilling Water Well

Fig E-3. Water Well Pressure Transducer

Fig E-4. Pressure Transducer Cable Coming Out of Top of Casing

Fig E-5. Water Well Protective Casing

Fig E-6. Water Well Completed Installation at Ground Level

Fig E-7. Drilling Instrumentation Readout Post Borehole

Fig E-8. Installing Readout Post

Fig E-9. Vertical Alignment of Readout Post

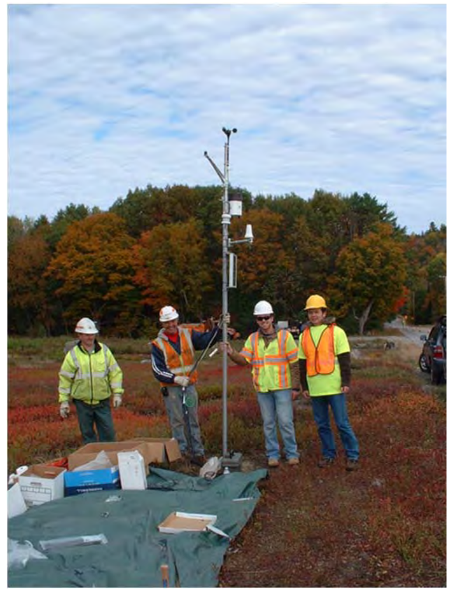


Fig E-10. Mounting Instrumentation to Pole Fig E-11. Checking Locations on Pole

Fig E-12. Set off Blocks for Mounting Fig E-13. Attaching Pole to Wooden Post

Fig E-14. Exploratory Boring for Ledge

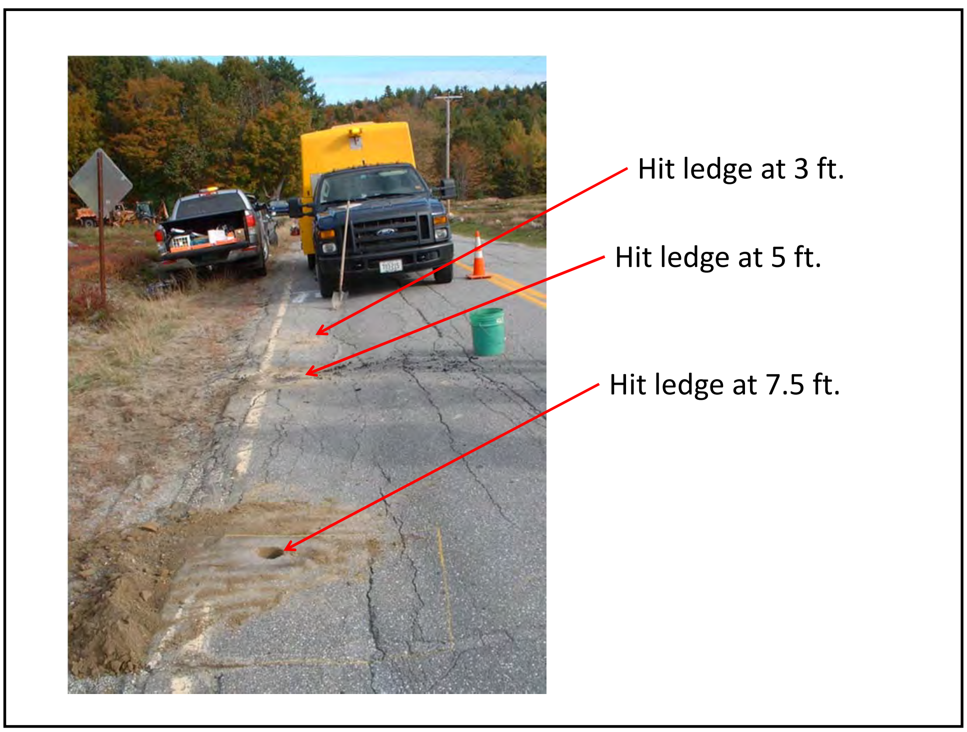
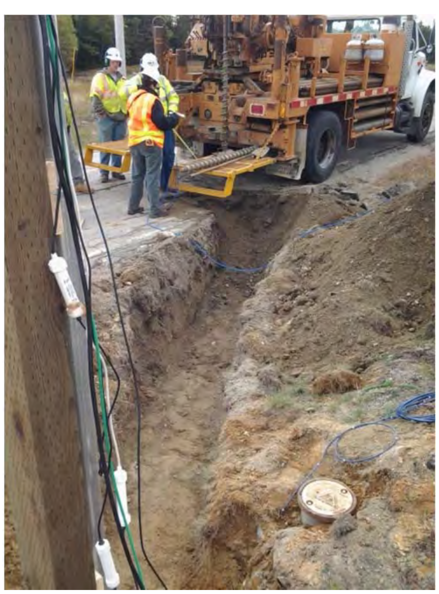


Fig E-15. Depths to Ledge

Fig E-16. Saw Cutting Pavement

Fig E-17. Removing Pavement for Trench

Fig E-18. Trenching for Subsurface Instrumentation Wires



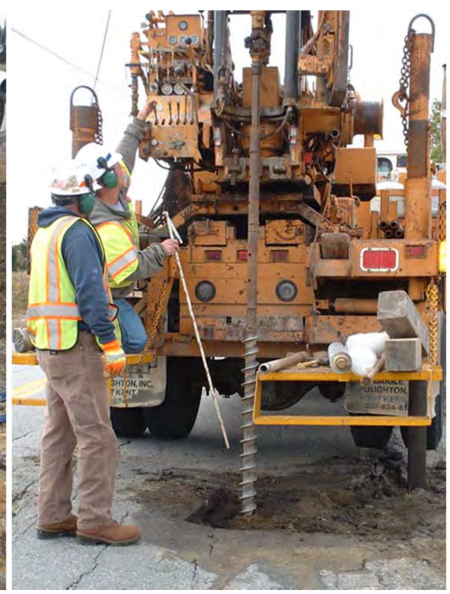


Fig E-19. Completed Trench

Fig E-20. Soil Moisture Sensors Borehole

Fig E-21. Thermistor Cables Mounted on Wooden Dowel

Fig E-22. Thermistor Flies for Top 3 Temperature Measurements

Fig E-23. Setting Top Surface Temperature Sensors

Fig E-24. Third Soil Moisture Sensor from Bottom of Borehole

Fig E-25. Running Instrumentation Cables to Readout Box

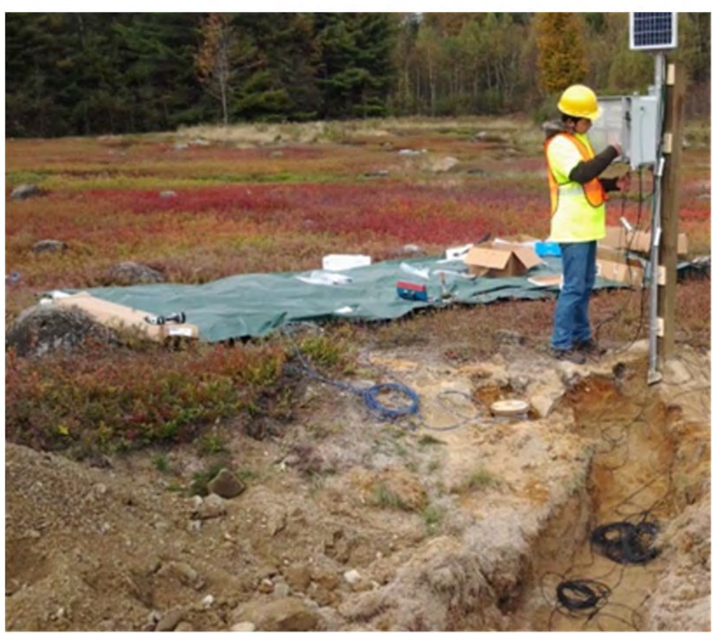


Fig E-26. Connecting Instrumentation to Readout Box

Fig E-27. Backfilling Trench

Fig E-28. Finishing Ditch Line

Fig E-28. Hot Asphalt Pavement Patching Trench

Fig E-29. Compacting Hotmix

Fig E-30. Looking at Water Well

Fig E-31. Environmental Sensors

Fig E-32. Levelling Rain Gauge

Fig E-33. Levelling Solar Radiation Sensor

Appendix F

Madison, Maine

Photographs of Equipment Installation

Fig F-1. Drilling Hole for Readout Box Post

Fig F-2. Removing Pavement from Road Trench for Instrumentation Installation

Fig F-3. Drilling Hole for Soil Samples

Fig F-4. Cable from Installed Temperature Sensors in Borehole

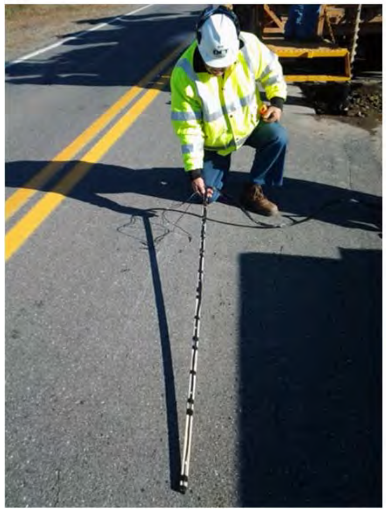


Fig F-5. Thermistors on Wooden Dowel   Fig F-6. Soil Moisture Sensor

Fig F-7. Surface Temperature Sensor in Pavement Crack to be Sealed

Fig F-8. Mounting Solar Panels to Wooden Post

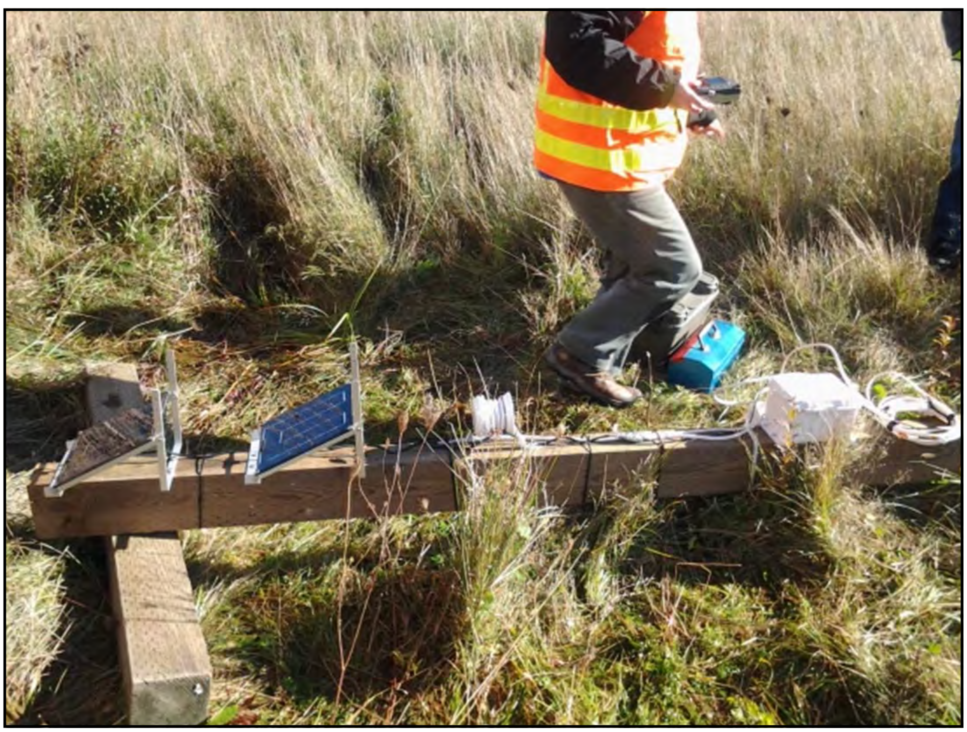


Fig F-9. Sensors and Readout Box Mounted on Post

Fig F-10. Checking Vertical Alignment of Post

Fig F-11. Digging Trench from Road to Post

Fig F-12. Running Instrumentation Wires from Road to Readout Post

Fig F-13. Backfilling Trench

Fig F-14. Configuring Sensors

Fig F-15. Completed Installation

Fig F-16. Heather Miller and Bob Eaton at Completed Installation

Appendix G

Warren Flats, NH

Results of Laboratory Tests on Soil Samples

The following USCS definitions of particle size ranges are used in this Appendix:

COMPONENT	DESCRIPTION	Size Range (mm)	Size Range (Sieve Number)
GRAVEL	Coarse (C.)	75 to 19	
GRAVEL	Fine (F.)	19 to 4.74	Greater than #4
SAND	Coarse (C.)	4.75 to 2.0	#4 to #10
SAND	Medium (M.)	2.0 to 0.425	#10 to #40
SAND	Fine (F.)	0.425 to 0.075	#40 to #200
Fines		Less than 0.075	Less than #200

Additional terms and equations used in this Appendix include:

D_{60} = Diameter that corresponds to 60% passing

D_{30} = Diameter that corresponds to 30% passing

D_{10} = Diameter that corresponds to 10% passing

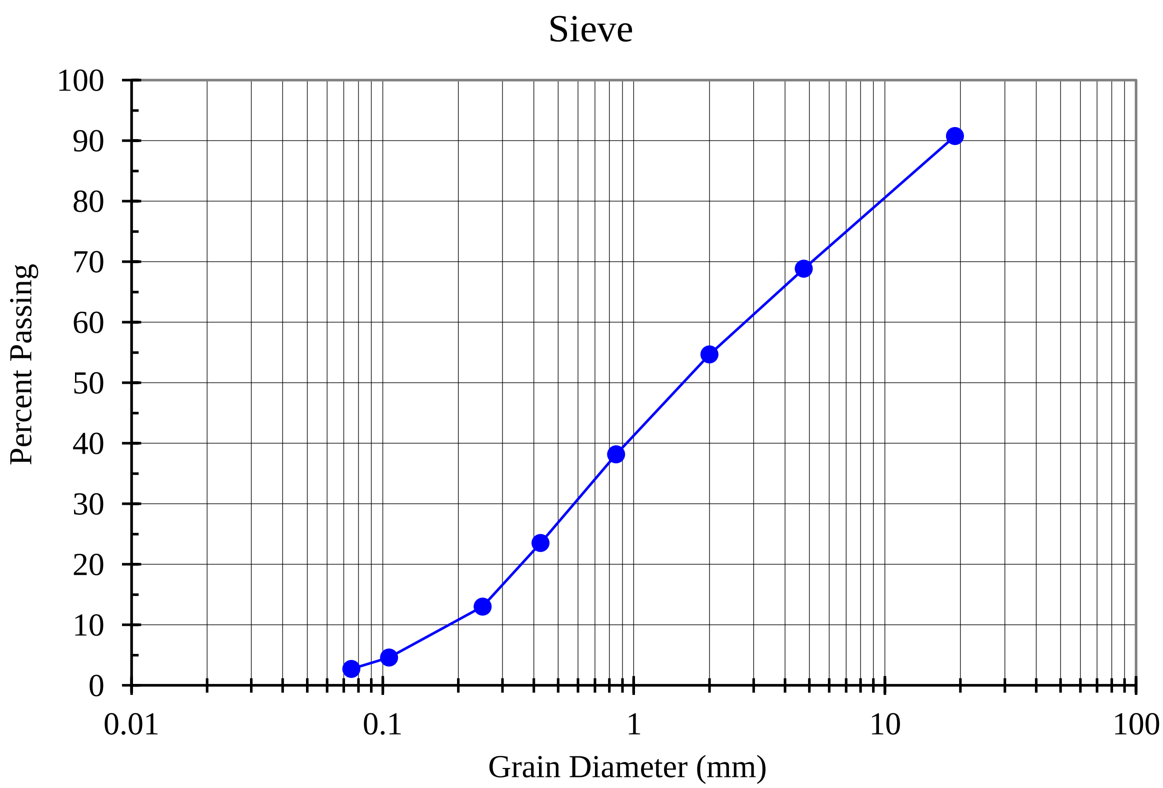
Coefficient of Uniformity, C_u

$$C_u = \frac{D_{60}}{D_{10}}$$

Coefficient of Curvature, C_c

$$C_c = \frac{[D_{30}]^2}{(D_{10})(D_{60})}$$

Site:	Warren Flats, NH
Date:	8/29/12
Boring #	WF-2012-1
Sample #	Reclaimed Base Mix
Depth:	-



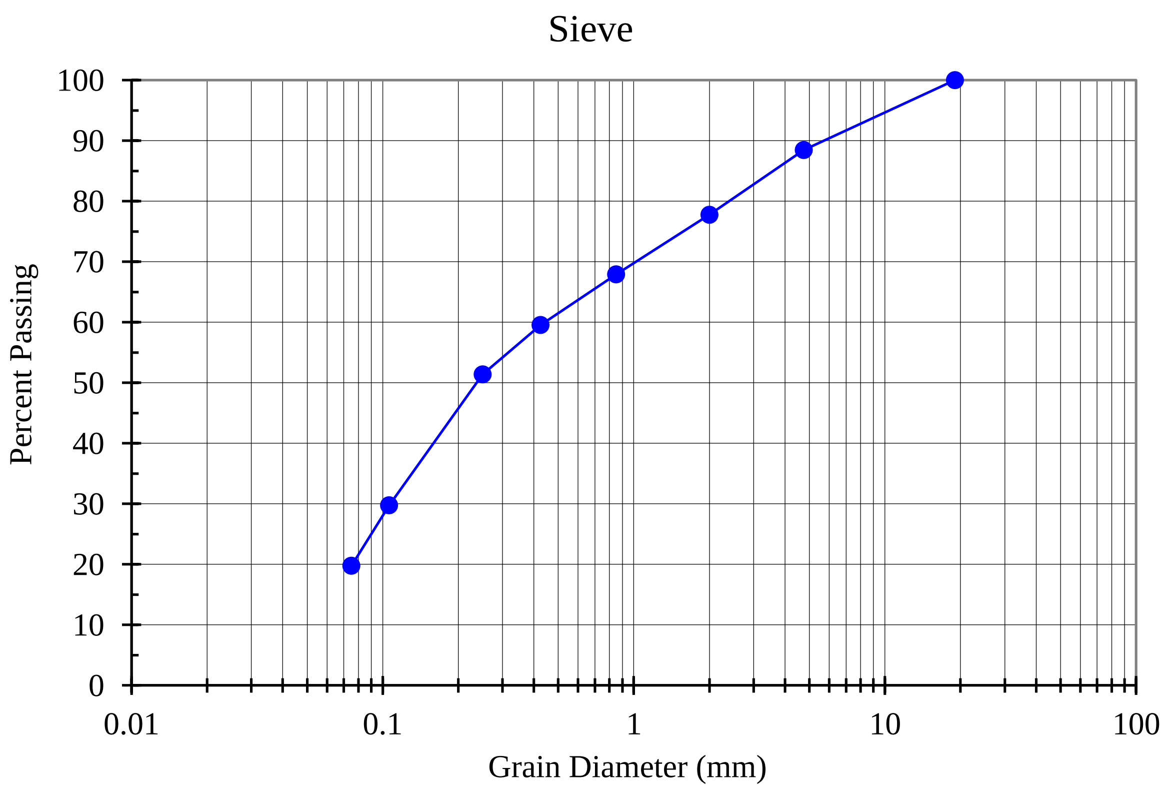
C. Gravel =	9
F. Gravel =	22
C. Sand =	14
M. Sand =	31
F. Sand =	21
Fines =	3

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.18	0.59	2.80	15.56	0.69

USCS	SP
AASHTO	A-1-b

Site: Warren Flats, NH
Date: 8/29/12
Boring # WF-2012-1
Sample # S-1c
Depth: 27"-29"

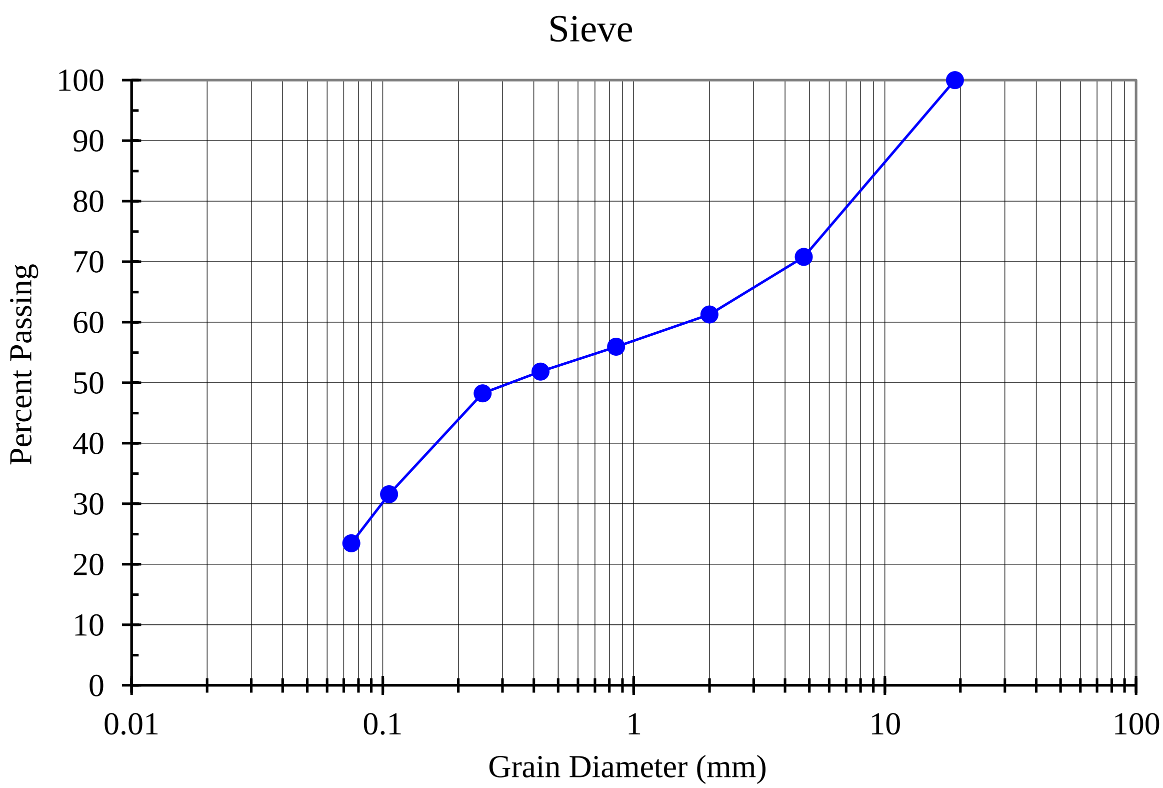


C. Gravel = 0
F. Gravel = 12
C. Sand = 11
M. Sand = 18
F. Sand = 40

Fines = 20

USCS	SM
AASHTO	A-2

Site: Warren Flats, NH
Date: 8/29/12
Boring # WF-2012-1
Sample # S-1a
Depth: 29"-34"

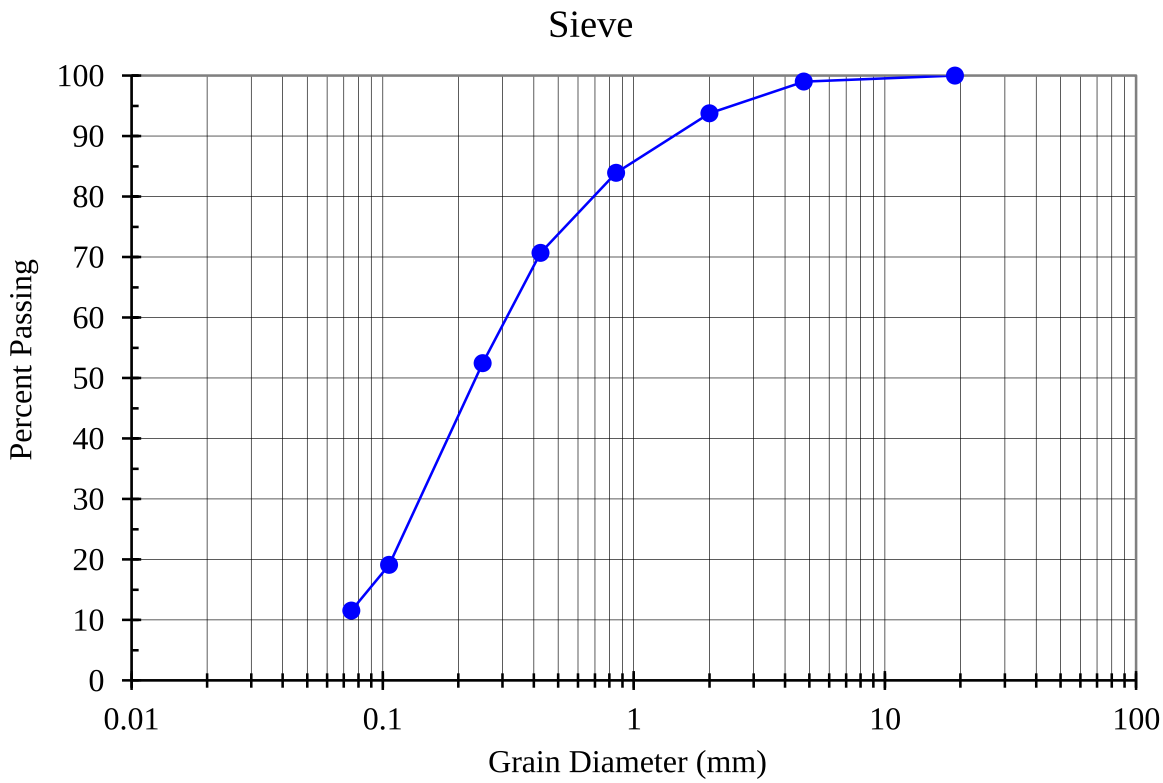


C. Gravel = 0
F. Gravel = 29
C. Sand = 10
M. Sand = 9
F. Sand = 28

Fines = 23

USCS	SM
AASHTO	A-2

Site:	Warren Flats, NH
Date:	8/29/12
Boring #	WF-2012-1
Sample #	S-1b
Depth:	36"-42"



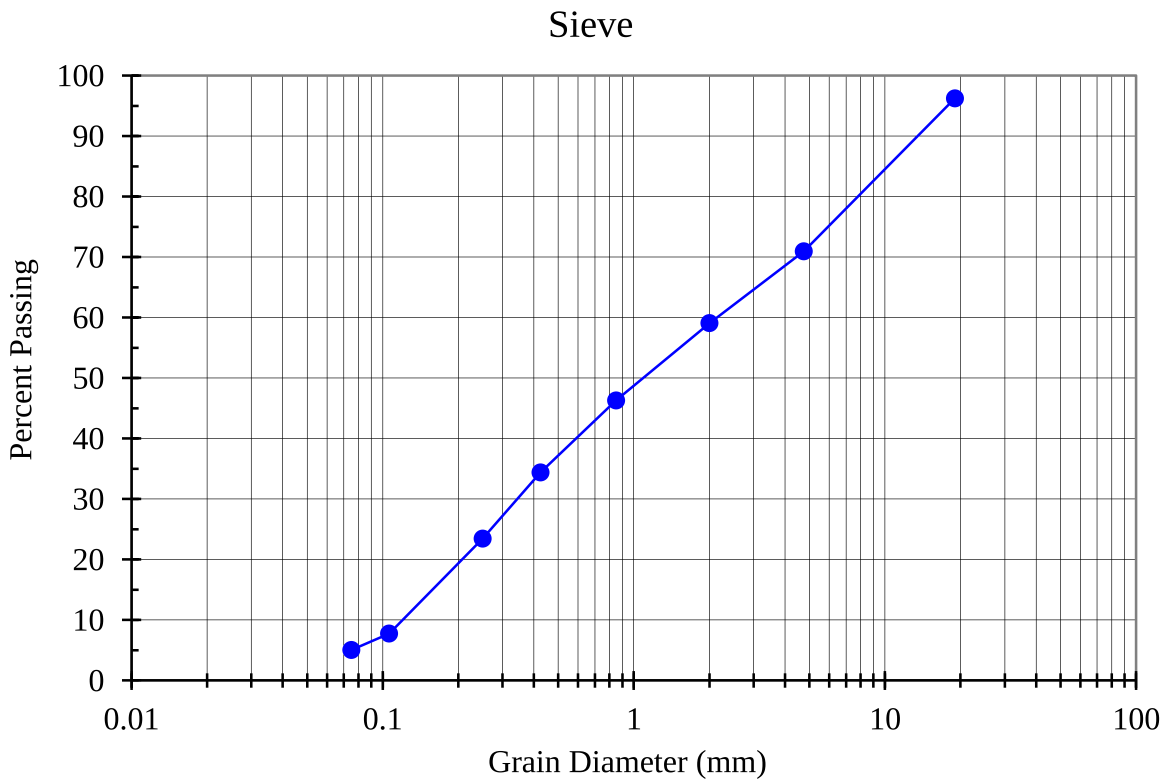
C. Gravel =	0
F. Gravel =	1
C. Sand =	5
M. Sand =	23
F. Sand =	59
Fines =	12

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.07	0.14	0.31	4.43	0.90

USCS	SP-SM
AASHTO	A-2

Site:	Warren Flats, NH
Date:	8/29/12
Boring #	WF-2012-1
Sample #	S-2c
Depth:	63.5"-67.5"



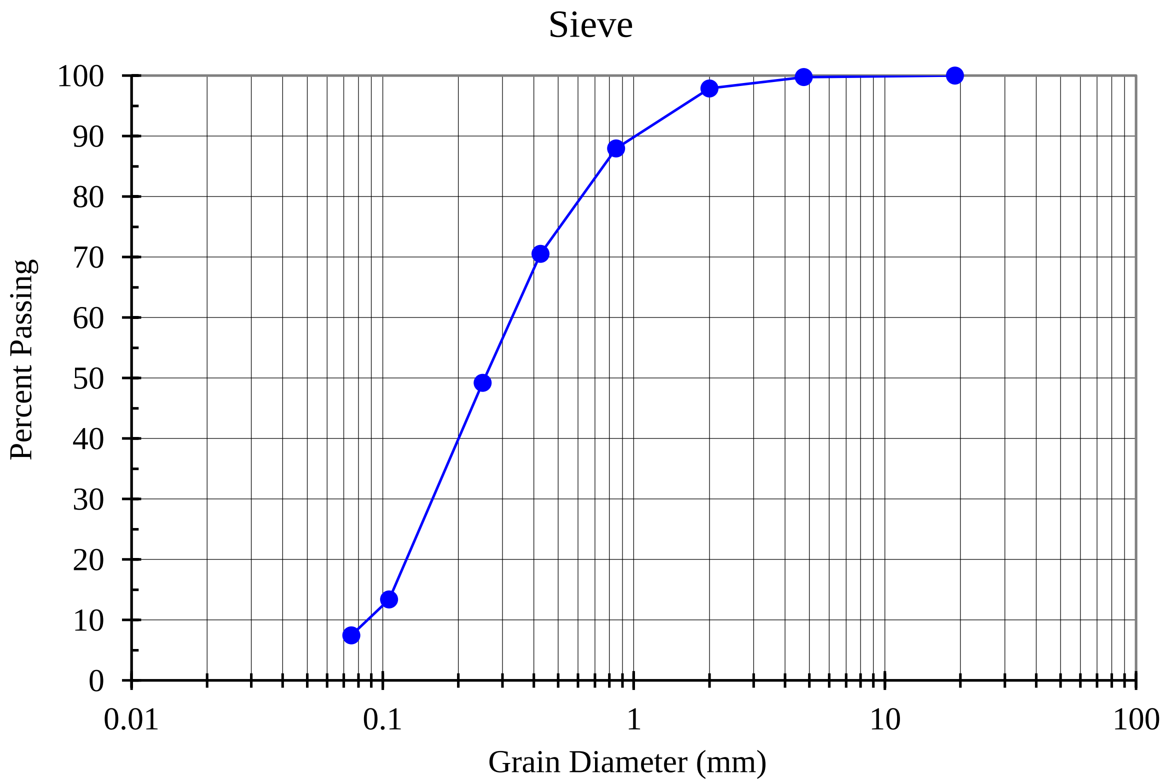
C. Gravel =	4
F. Gravel =	25
C. Sand =	12
M. Sand =	25
F. Sand =	29
Fines =	5

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.11	0.34	2.10	19.09	0.50

USCS	SP-SM
AASHTO	A-1-b

Site:	Warren Flats, NH
Date:	8/29/12
Boring #	WF-2012-1
Sample #	S-2b
Depth:	67.5"-72"



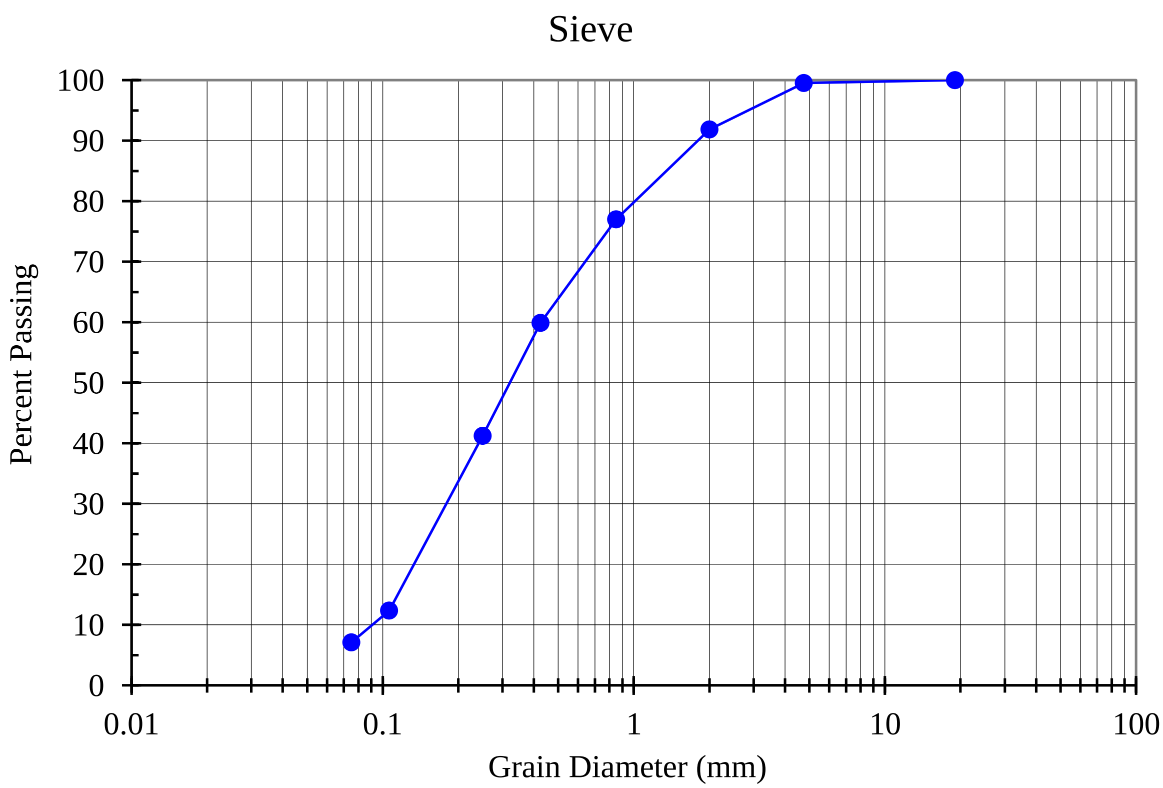
C. Gravel =	0
F. Gravel =	0
C. Sand =	2
M. Sand =	27
F. Sand =	63
Fines =	7

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.09	0.15	0.31	3.65	0.85

USCS	SP-SM
AASHTO	A-3

Site: Warren Flats, NH
Date: 8/29/12
Boring # WF-2012-1
Sample # S-2a
Depth: 72"-76"



C. Gravel = 0
F. Gravel = 0
C. Sand = 8
M. Sand = 32
F. Sand = 53

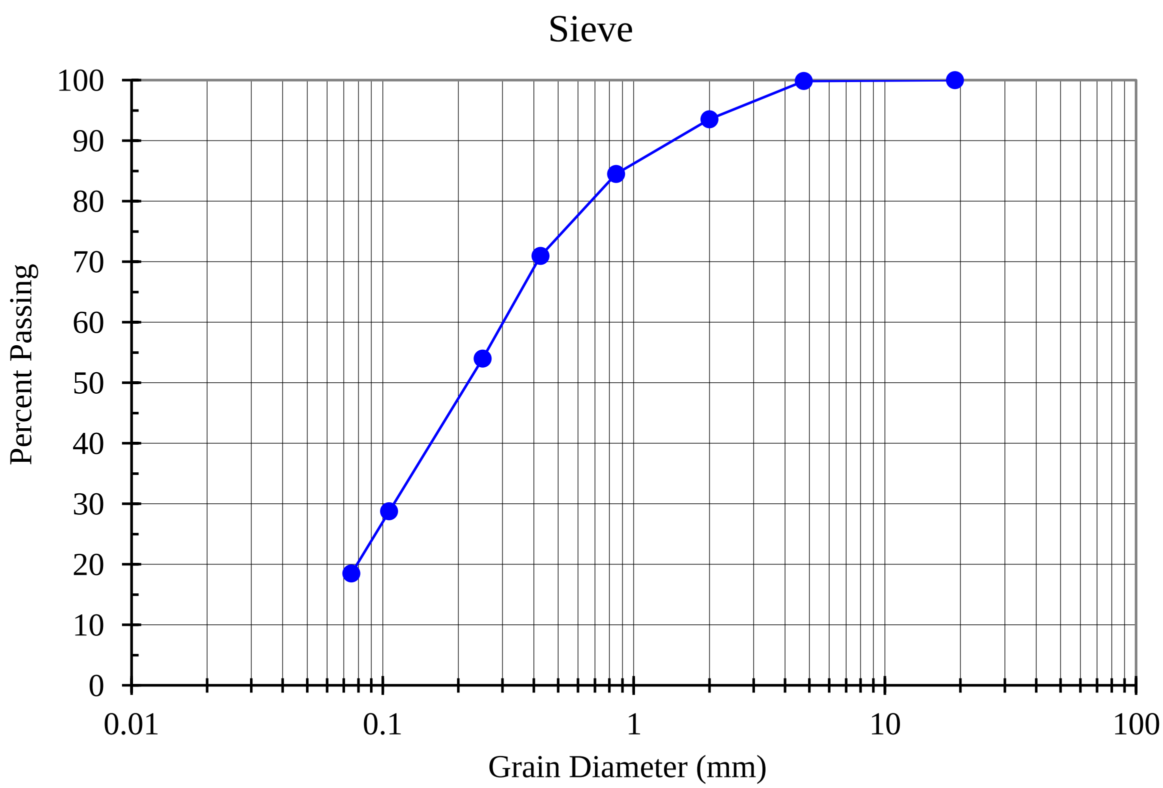
Fines = 7

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.09	0.18	0.41	4.56	0.88

USCS	SP-SM
AASHTO	A-3

Site: Warren Flats, NH
Date: 8/29/12
Boring # WF-2012-1
Sample # S-3d
Depth: 86.5"-89.5"

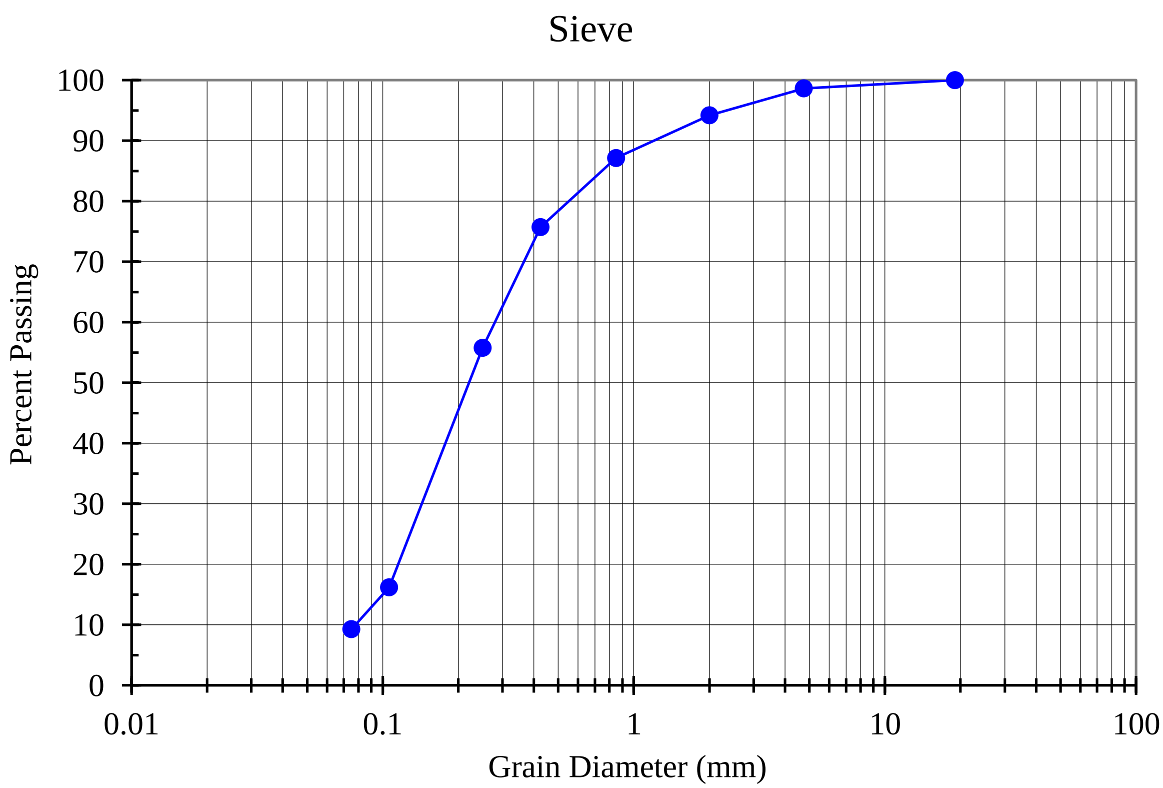


C. Gravel = 0
F. Gravel = 0
C. Sand = 6
M. Sand = 23
F. Sand = 52

Fines = 18

USCS	SM
AASHTO	A-2

Site:	Warren Flats, NH
Date:	8/29/12
Boring #	WF-2012-1
Sample #	S-3c
Depth:	89.5"-93"



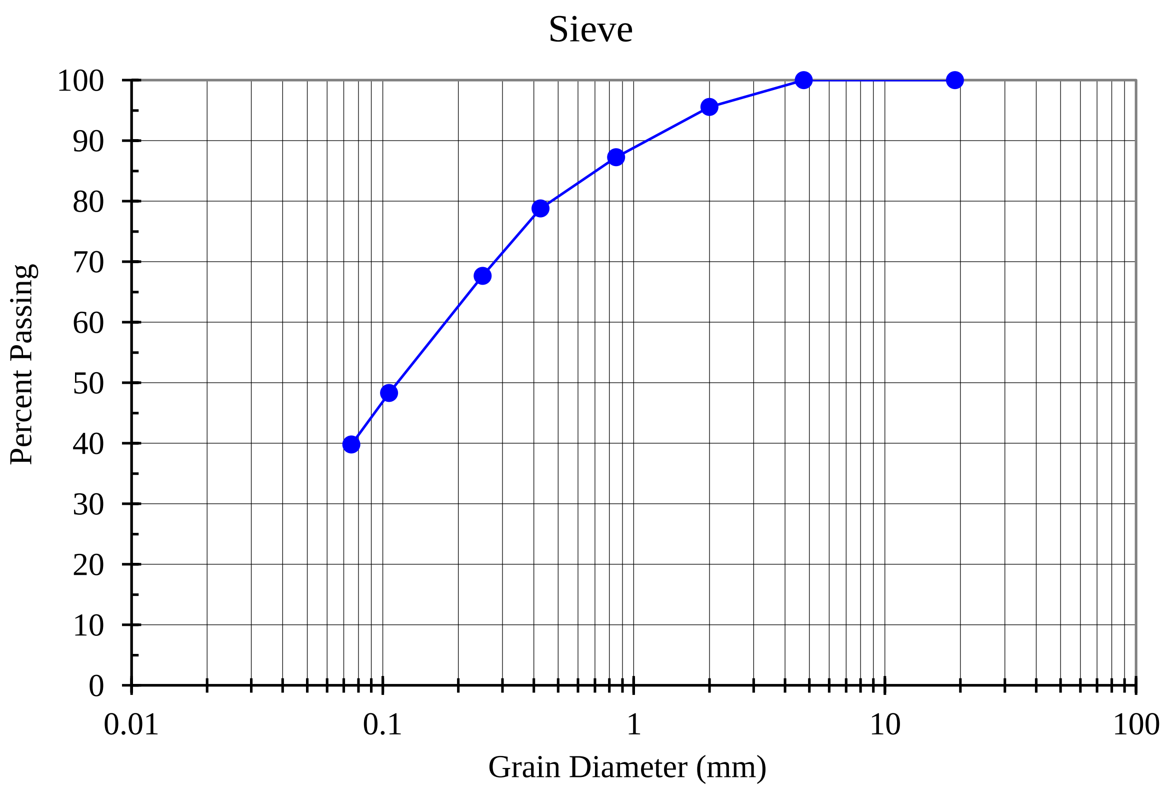
C. Gravel =	0
F. Gravel =	1
C. Sand =	4
M. Sand =	18
F. Sand =	66
Fines =	9

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.08	0.14	0.28	3.50	0.88

USCS	SP-SM
AASHTO	A-3

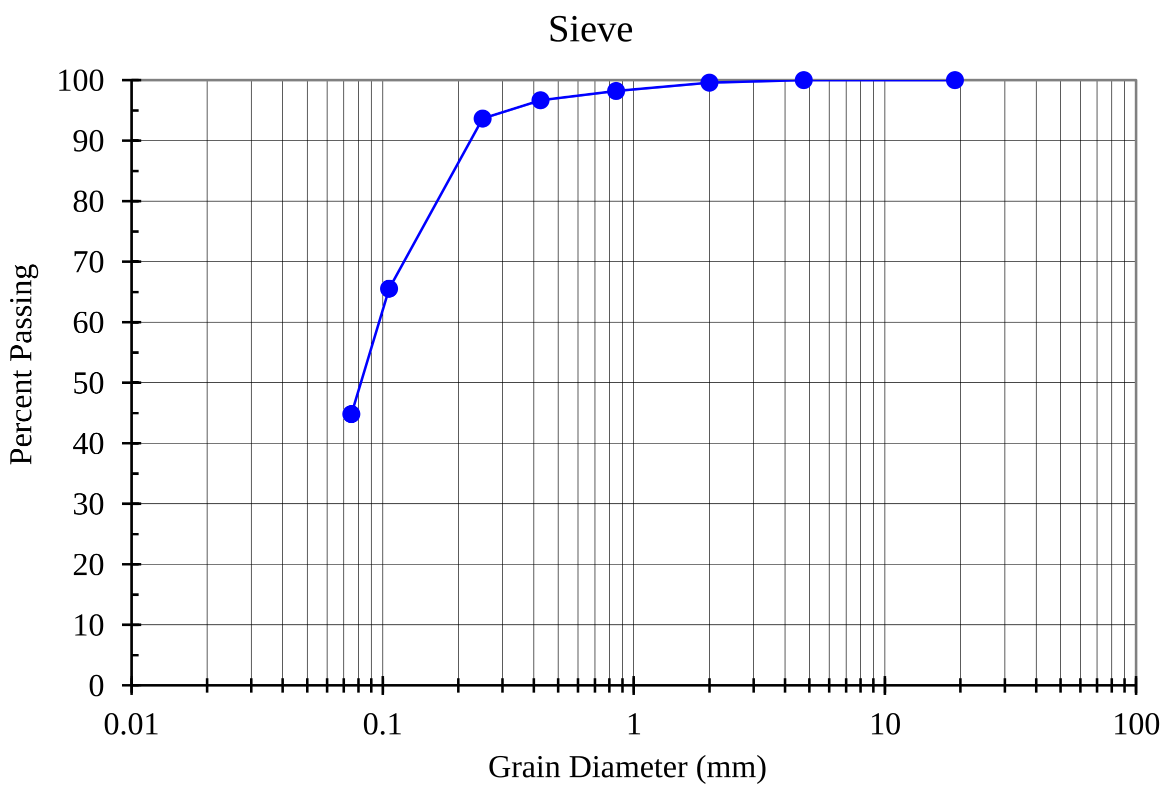
Site:	Warren Flats, NH
Date:	8/29/12
Boring #	WF-2012-1
Sample #	S-3b
Depth:	93"-97"



C. Gravel =	0
F. Gravel =	0
C. Sand =	4
M. Sand =	17
F. Sand =	39
Fines =	40

USCS	SM
AASHTO	Need Atterburg Limits

Site: Warren Flats, NH
Date: 8/29/12
Boring # WF-2012-1
Sample # S-3a
Depth: 97"-100"



C. Gravel = 0
F. Gravel = 0
C. Sand = 0
M. Sand = 3
F. Sand = 52

Fines = 45

USCS	SM
AASHTO	Need Atterburg Limits

Appendix H

Mariaville, Maine

Results of Laboratory Tests on Soil Samples

The following USCS definitions of particle size ranges are used in this Appendix:

COMPONENT	DESCRIPTION	Size Range (mm)	Size Range (Sieve Number)
GRAVEL	Coarse (C.)	75 to 19	
GRAVEL	Fine (F.)	19 to 4.74	Greater than #4
SAND	Coarse (C.)	4.75 to 2.0	#4 to #10
SAND	Medium (M.)	2.0 to 0.425	#10 to #40
SAND	Fine (F.)	0.425 to 0.075	#40 to #200
Fines		Less than 0.075	Less than #200

Additional terms and equations used in this Appendix include:

D_{60} = Diameter that corresponds to 60% passing

D_{30} = Diameter that corresponds to 30% passing

D_{10} = Diameter that corresponds to 10% passing

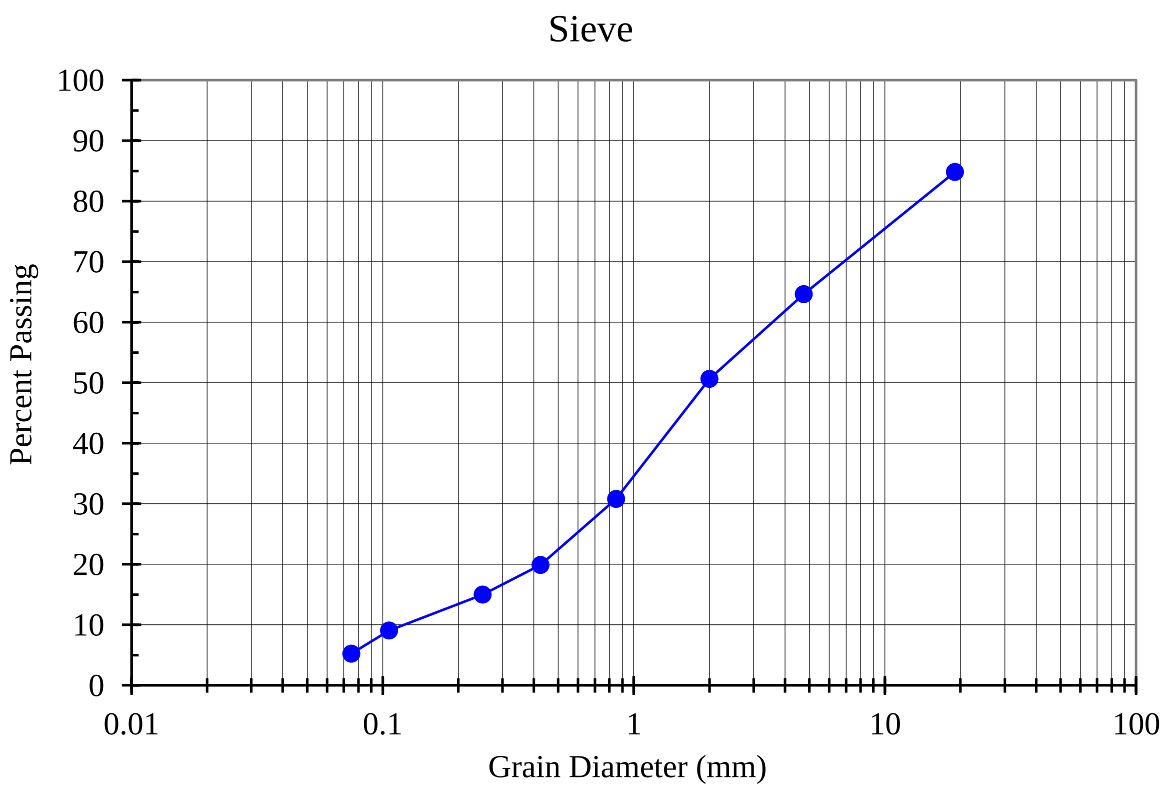
Coefficient of Uniformity, C_u

$$C_u = \frac{D_{60}}{D_{10}}$$

Coefficient of Curvature, C_c

$$C_c = \frac{[D_{30}]^2}{(D_{10})(D_{60})}$$

Site:	Mariaville, ME
Date:	10/9/12
Boring #	MR-2012-1
Sample #	S-1
Depth:	0.5'-1.5'



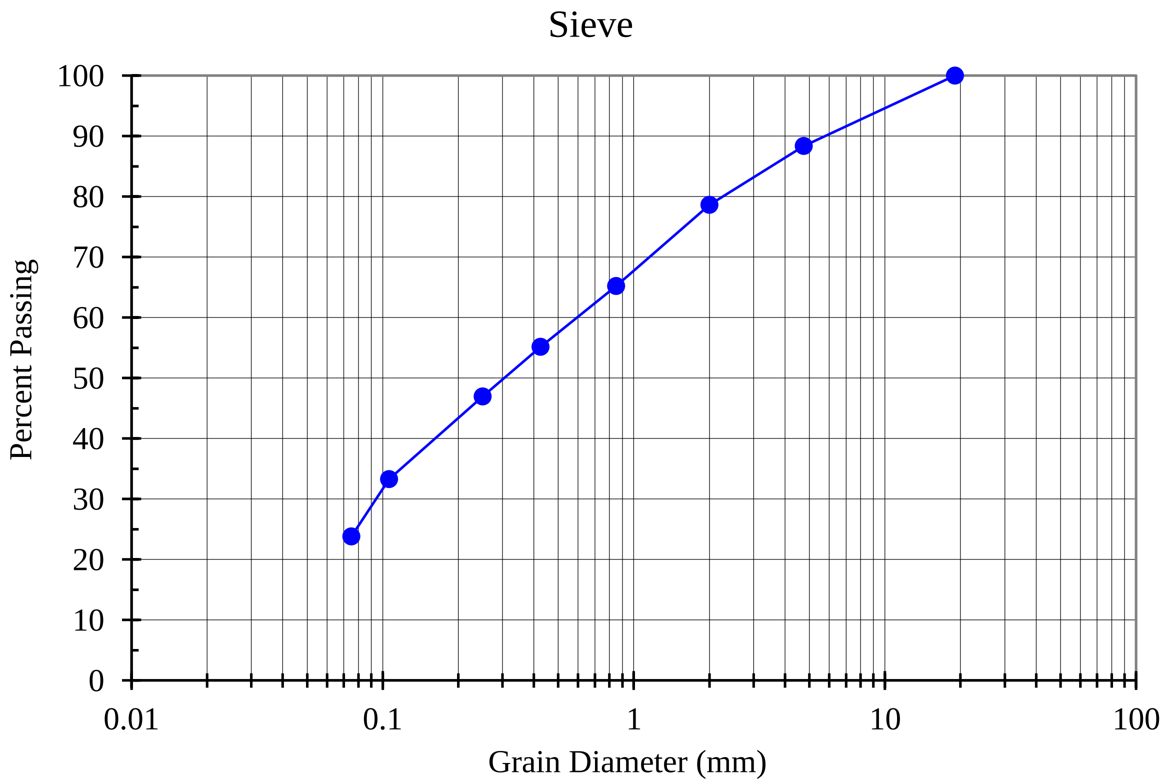
C. Gravel =	15
F. Gravel =	20
C. Sand =	14
M. Sand =	31
F. Sand =	15
Fines =	5

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.11	0.85	3.60	32.73	1.82

USCS	SW-SM
AASHTO	A-1-b

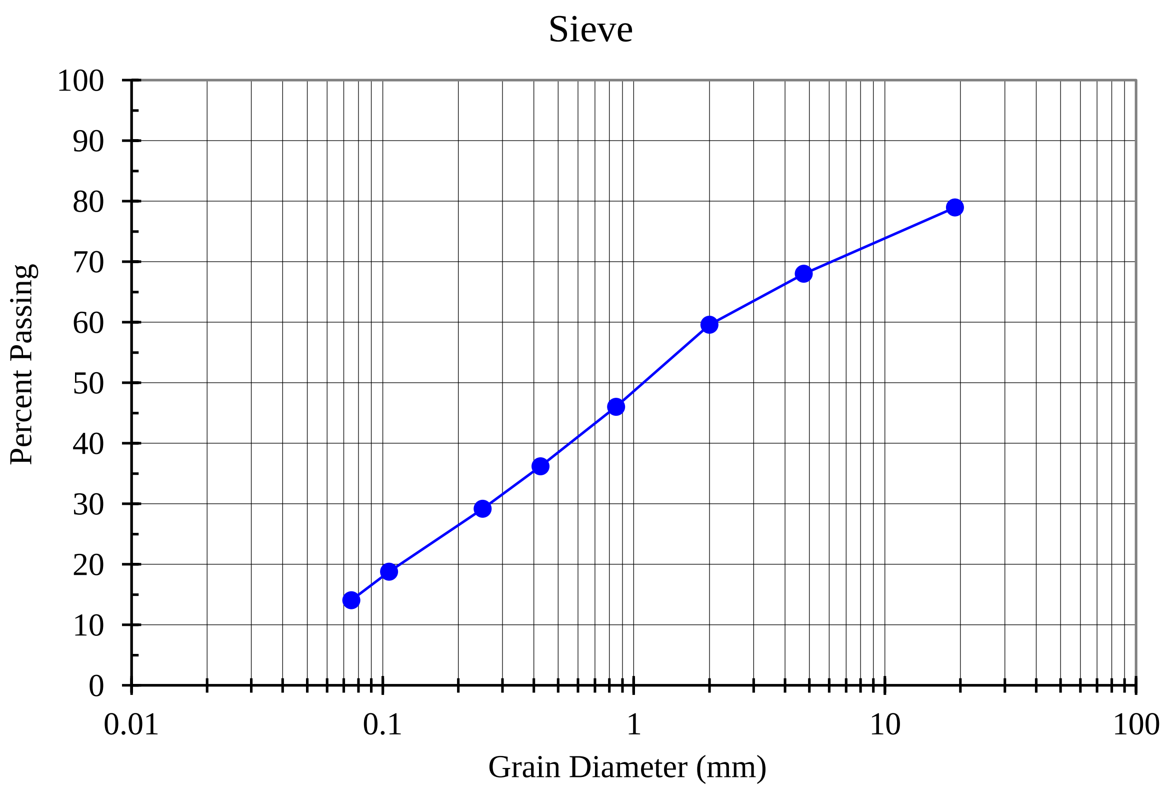
Site:	Mariaville, ME
Date:	10/9/12
Boring #	MR-2012-1
Sample #	S-2
Depth:	1.5'-2.5'



C. Gravel =	0
F. Gravel =	12
C. Sand =	10
M. Sand =	23
F. Sand =	31
Fines =	24

USCS	SM
AASHTO	A-2

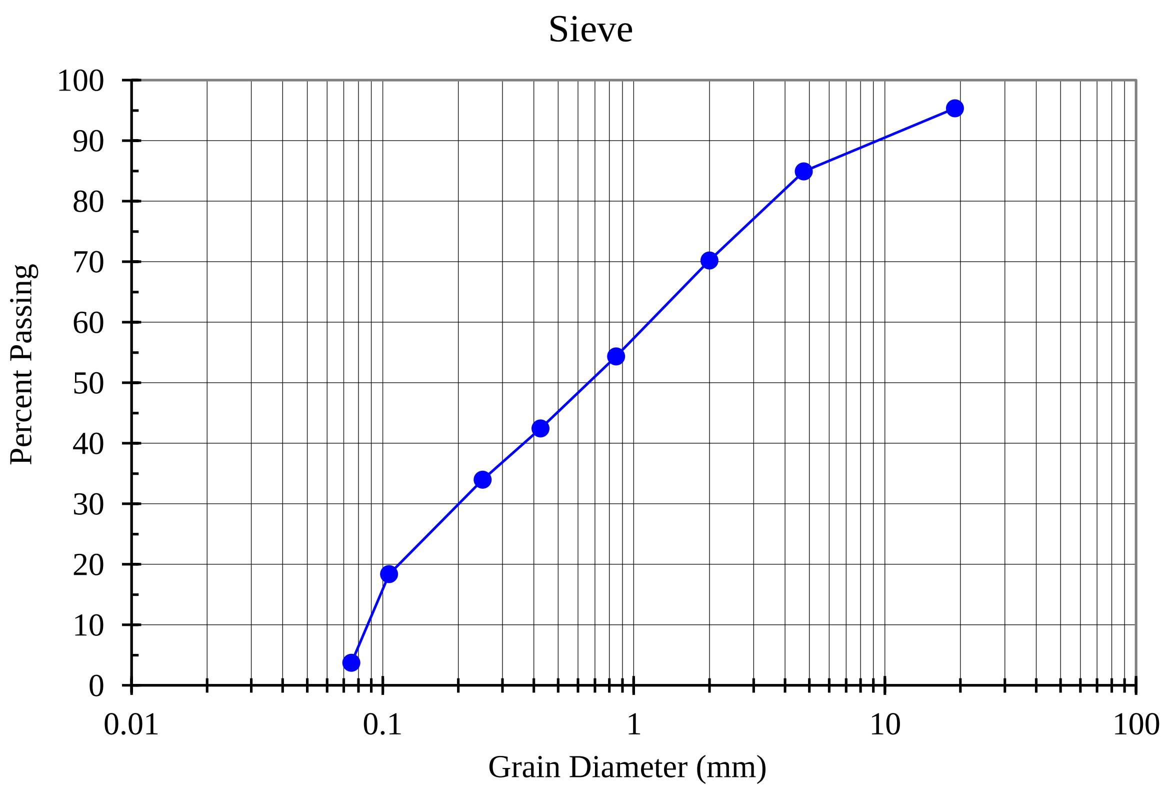
Site:	Mariaville, ME
Date:	10/9/12
Boring #	MR-2012-1
Sample #	S-3
Depth:	2.5'-4.5'



C. Gravel =	21
F. Gravel =	11
C. Sand =	8
M. Sand =	23
F. Sand =	22
Fines =	14

USCS	SM
AASHTO	A-1-b

Site: Mariaville, ME
Date: 10/9/12
Boring # MR-2012-1
Sample # S-4
Depth: 4.5'-6.5'



C. Gravel =	5
F. Gravel =	10
C. Sand =	15
M. Sand =	28
F. Sand =	39
Fines =	4

If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.09	0.20	1.10	12.94	0.43

USCS	SP
AASHTO	A-1-b

Appendix I

Madison, Maine

Results of Laboratory Tests on Soil Samples

The following USCS definitions of particle size ranges are used in this Appendix:

COMPONENT	DESCRIPTION	Size Range (mm)	Size Range (Sieve Number)
GRAVEL	Coarse (C.)	75 to 19	
GRAVEL	Fine (F.)	19 to 4.74	Greater than #4
SAND	Coarse (C.)	4.75 to 2.0	#4 to #10
SAND	Medium (M.)	2.0 to 0.425	#10 to #40
SAND	Fine (F.)	0.425 to 0.075	#40 to #200
Fines		Less than 0.075	Less than #200

Additional terms and equations used in this Appendix include:

D_{60} = Diameter that corresponds to 60% passing

D_{30} = Diameter that corresponds to 30% passing

D_{10} = Diameter that corresponds to 10% passing

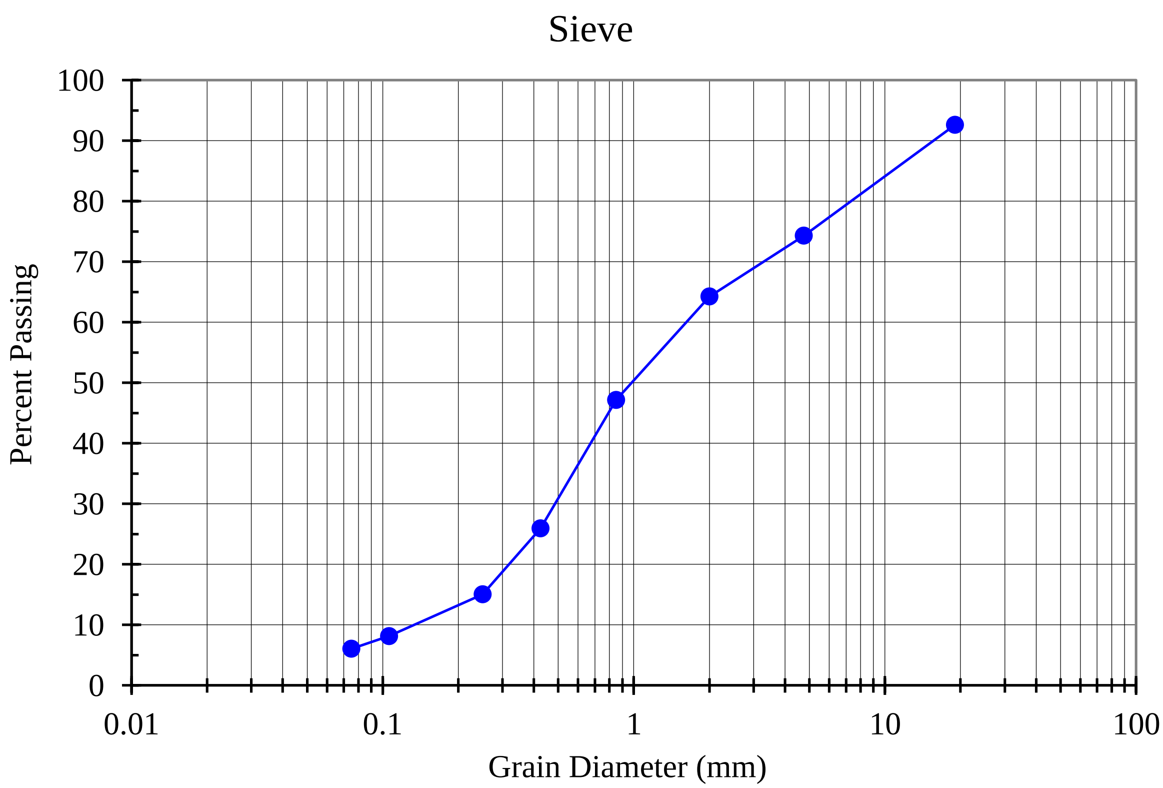
Coefficient of Uniformity, C_u

$$C_u = \frac{D_{60}}{D_{10}}$$

Coefficient of Curvature, C_c

$$C_c = \frac{[D_{30}]^2}{(D_{10})(D_{60})}$$

Site:	Madison, ME
Date:	10/11/12
Boring #	MD-2012-1
Sample #	S-1
Depth:	0.5'-2'



C. Gravel =	7
F. Gravel =	18
C. Sand =	10
M. Sand =	38
F. Sand =	20
Fines =	6

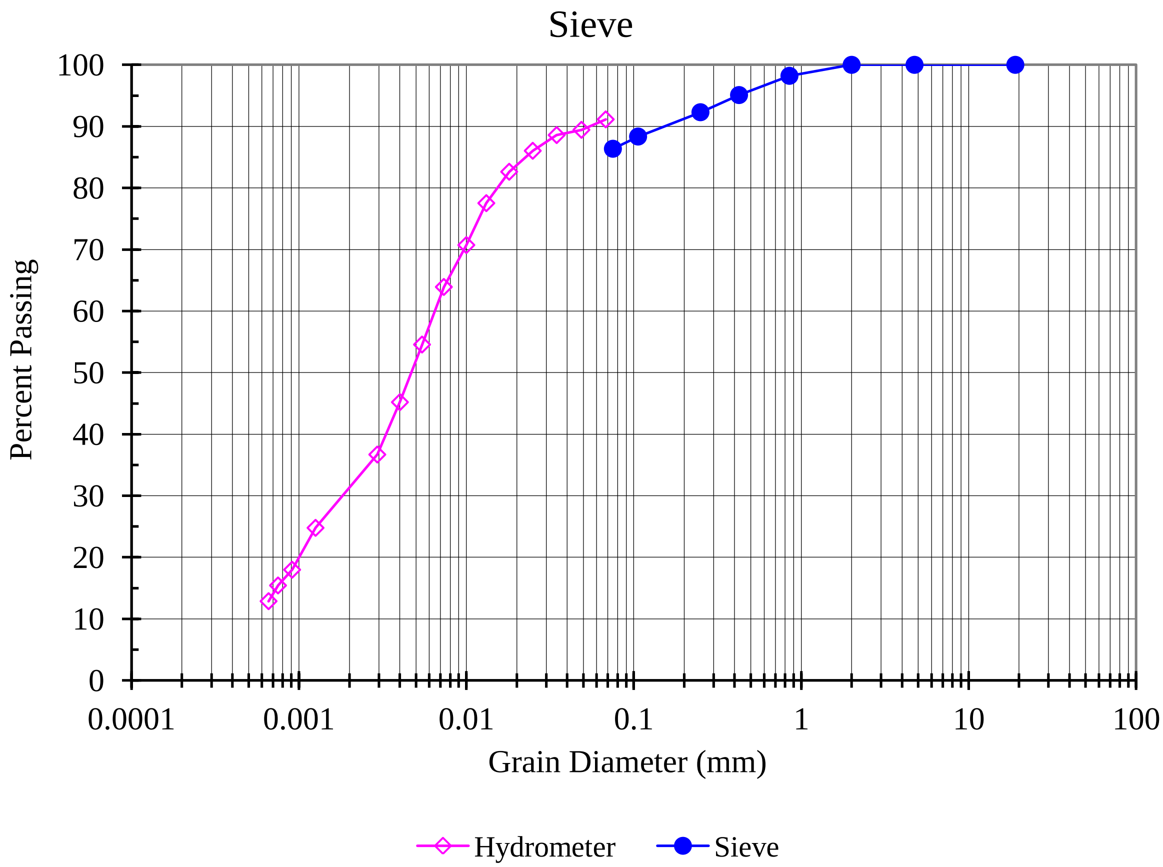
If Required for USCS Classification:

D_{10}	D_{30}	D_{60}	C_u	C_c
0.13	0.50	1.70	13.08	1.13

USCS	SW-SM
AASHTO	A-1-b

Sieve Analysis Sample 3'-5'

Site:	Madison, ME
Date:	10/11/12
Boring #	MD-2012-1
Sample #	S-2
Depth:	3'-5'

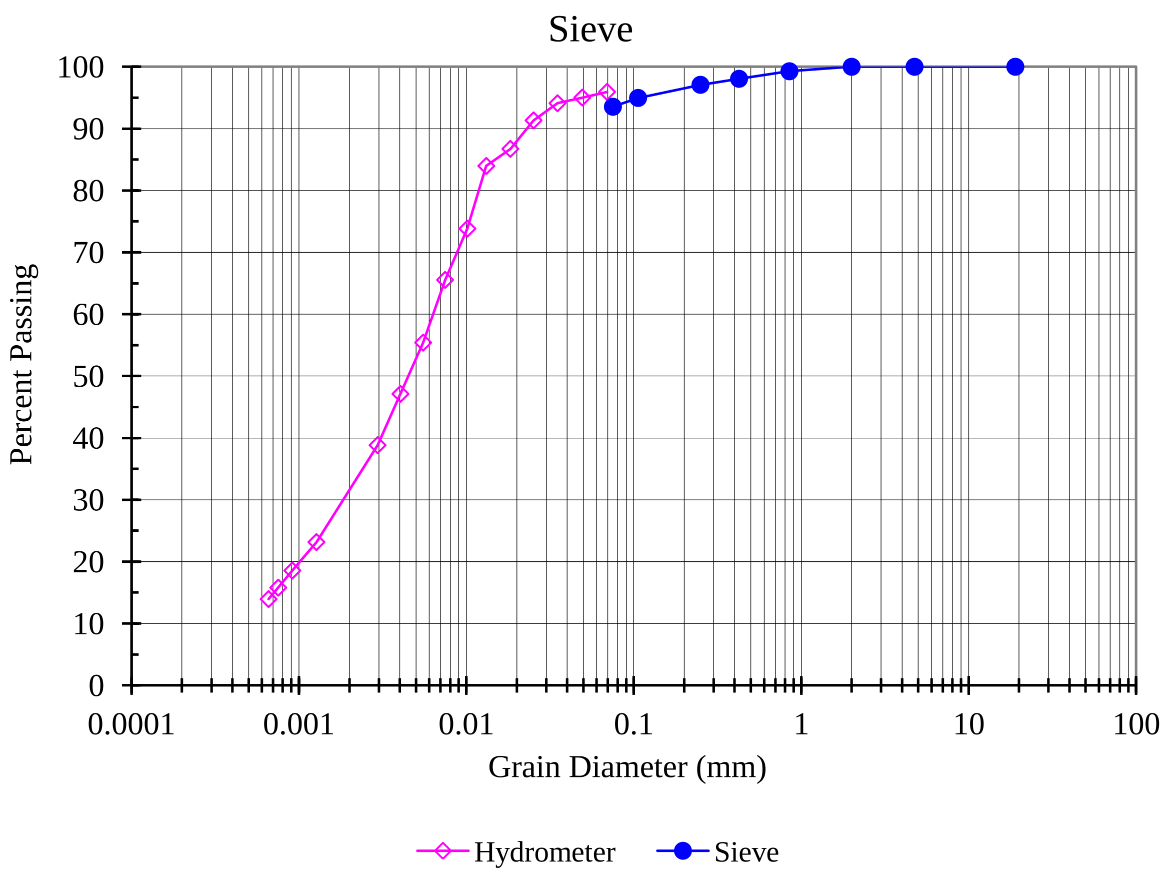


C. Gravel =	0		AASHTO Particle Size Limits:	
F. Gravel =	0		% Sand	14
C. Sand =	0		% Silt	55
M. Sand =	5		% Clay	31
F. Sand =	9			
		% Finer than 0.02 mm		85
Fines =	86	% Finer than 0.002 mm		31

USCS	CL
AASHTO	A-6

Sieve Analysis Sample 5'-7'

Site:	Madison, ME
Date:	10/11/12
Boring #	MD-2012-1
Sample #	S-3
Depth:	5'-7'



C. Gravel =	0		AASHTO Particle Size Limits:	
F. Gravel =	0		% Sand	6
C. Sand =	0		% Silt	63
M. Sand =	2		% Clay	31
F. Sand =	5			
		% Finer than 0.02 mm		88
Fines =	94	% Finer than 0.002 mm		31

USCS	CL
AASHTO	A-6

Appendix J

Equipment Specification & Operation Sheets

(Provided by Manufacturers)

Soil Moisture Smart Sensors (S-SMx-M005)

Soil moisture smart sensors are used for measuring soil water content and are designed to work with smart sensor-compatible HOBO® data loggers. They combine the innovative ECH_2O® Dielectric Aquameter probe from Decagon Devices, Inc. with Onset's smart sensor technology. All sensor conversion parameters are stored inside the smart sensor adapter so data is provided directly in soil moisture units without any programming or extensive user setup.

Specifications	S-SMC-M005	S-SMD-M005*
Measurement Range	In soil: 0 to 0.550 m^3/m^3 (volumetric water content)	In soil: 0 to 0.570 m^3/m^3 (volumetric water content)
Extended range	-0.401 to 2.574 m^3/m^3; see Note 1	-0.659 to 0.6026 m^3/m^3; see Note 1
Accuracy	±0.031 m^3/m^3 (±3%) typical 0 to 50°C (32° to 122°F) for mineral soils up to 8 dS/m ±0.020 m^3/m^3 (±2%) with soil specific calibration; see Note 2	±0.033 m^3/m^3 (±3%) typical 0 to +50°C (+32° to 122°F) for mineral soils up to 10 dS/m ±0.020 m^3/m^3 (±2%) with soil specific calibration; see Note 3
Resolution	±0.0007 m^3/m^3 (±0.07%)	±0.0008 m^3/m^3 (±0.08%)
Volume of Influence	0.3 liters (10.14 oz)	1 liter (33.81 oz)
Sensor Frequency	70 MHz	70 MHz
Soil Probe Dimensions	89 x 15 x 1.5 mm (3.5 x 0.62 x 0.06 in.)	160 x 32 x 2 mm (6.5 x 1.25 x 0.08 in.)
Weight	180 grams (6.3 oz)	190 grams (6.7 oz)
Decagon ECH_2O Probe Part No.	EC-5	10HS

***** HOBOware® 3.2.1 or greater is required for the S-SMD-M005 model only.

Specifications	Both models
Sensor Operating Temperature	0° to 50°C (32° to 122°F). Although the sensor probe and cable can safely operate at below-freezing temperatures (to -40°C/F) and the smart sensor tube (the white portion of the sensor cable that houses the electronics) can be exposed to temperatures up to 70°C (158°F), the soil moisture data collected at these extreme temperatures is outside of the sensor's accurate measurement range. Extended temperatures above 50°C (122°F) will decrease logger battery life when using the S-SMD-M005 smart sensor.
Bits per Sample	12
Number of Data Channels**	1
Measurement Averaging Option	No
Cable Length Available	5 m (16 ft)
Length of Smart Sensor Network Cable **	0.5 m (1.6 ft)

****** A single smart sensor-compatible HOBO logger can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables). Note that the S-SMD-M005 smart sensor uses more battery power than other models. Therefore, when connecting the S-SMD-M005 smart sensor to H21-00x loggers that use 4 AA batteries, attach no more than 6 of these sensors to maintain battery life of one year.

Note 1: The sensor is capable of providing readings outside the standard volumetric water content range. This is helpful in diagnosing sensor operation and installation. See the Operation section below for more details.

Note 2: This is a system level accuracy specification and is comprised of the probe's accuracy of ±0.03 m^3/m^3 typical (±0.02 m^3/m^3 soil specific) plus the smart sensor adapter accuracy of ±0.001 m^3/m^3 at 25°C (77°F). There are additional temperature accuracy deviations of ±0.003 m^3/m^3 / °C maximum for the probe across operating temperature environment, typical <0.001 m^3/m^3 / °C. (The temperature dependence of the smart sensor adapter is negligible.)

Note 3: This is a system level accuracy specification and is comprised of the probe's accuracy of ±0.03 m^3/m^3 typical (±0.02 m^3/m^3 soil specific) plus the smart sensor adapter accuracy of ±0.003 m^3/m^3 at 25°C (77°F). There are additional temperature accuracy deviations of ±0.003 m^3/m^3 / °C maximum for the probe across operating temperature environment, typical <0.001 m^3/m^3 / °C. (The temperature dependence of the smart sensor adapter is negligible.)

Inside this Package

- Soil Moisture Smart Sensor

Installation

This sensor measures the water content in the space immediately adjacent to the probe surface. Air gaps or excessive soil compaction around the probe can profoundly influence soil water content readings. Do not mount the probes adjacent to large metal objects, such as metal poles or stakes. Maintain at least 8 cm (3 inches) of separation between the probe and other objects. Any objects, other than soil, within 8 cm (3 inches) of the probe can influence the probe's electromagnetic field and adversely affect output readings. The S-SMC-005 sensor must be installed at least 3 cm (1.18 inches) from the surface and the S-SMD-005 sensor must be installed at least 10 cm (3.94 inches) from the surface to obtain accurate readings.

It is important to consider the particle size of the medium in which you are inserting the sensor because it is possible for sticks, tree bark, roots, or other materials to get stuck between the sensor prongs, which will adversely affect readings. Be careful when inserting these sensors into dense soil as the prongs can break if excessive sideways force is used to push them into the soil.

To install the soil moisture sensors, follow these guidelines:

- Good soil contact with the sensor probes is required.
- Install the sensor probes into undisturbed soil where there aren't any pebbles in the way of the probes.
- Use a soil auger to make a hole to the desired depth (an angled hole is best) and push the probes into undisturbed soil at the bottom of the hole. Alternatively, dig a hole and push the probes into the side of the hole.
- If the probe has a protective cap on the end, remove it before placing the probe into the hole.
- To push the probe into the soil, use a PVC pipe with slots for the sensor and a longer slot for the cable.
- Thoroughly water the soil around the sensor after it is installed with the hole partially backfilled to cause the soil to settle around the sensor.
- As the hole is back-filled, try to pack the soil to the same density as the undisturbed soil.
- Secure the sensor cable to the mounting pole or tripod with cable ties.
- The white tube on the sensor cable that houses the smart sensor electronics is weatherproof; mount it to the pole or tripod outside the logger enclosure with cable ties.

- Use conduit to protect the cable against damage from animals, lawn mowers, exposure to chemicals, etc.

If you need to calibrate your probe for the soil, you may want to gather soil samples from each sample depth at this time.

When removing the probe from the soil, **do not pull it out of the soil by the cable!** Doing so may break internal connections and make the probe unusable.

Connecting

To start using the Soil Moisture smart sensor, stop the logger and insert the sensor's modular jack into an available port on the logger. If a port is not available use a 1-to-2 adapter (Part # S-ADAPT), which allows you to plug two sensors into one port. The next time you use the logger, it will automatically detect the new smart sensor. Note that the logger supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly. See the logger user's guide for more details about connecting smart sensors to the logger.

Operating Environment

The Soil Moisture smart sensor provides accurate readings for soil between 0 and 50°C (32° and 122°F). The sensor will not be damaged by temperatures as low as -40°C (-40°F); it is safe to leave the sensor in the ground year-round for permanent installation. The smart sensor adapter electronics (housed in the white tube on the sensor cable) are rated to 70°C (158°F) and are mounted outside the logger enclosure and secured to the mounting pole. The cable and smart sensor adapter are weatherproof.

Operation

The Soil Moisture smart sensor measures the dielectric constant of soil in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m^3/m^3 are possible. A value of 0 to 0.1 m^3/m^3 indicates oven-dry to dry soil respectively. A value of 0.3 or higher normally indicates a wet to saturated soil. Values outside the operating range may be a sign that the sensor is not properly installed (poor soil contact or foreign objects are adjacent to the sensor) or that a soil-specific calibration is required. Note that sudden changes in value typically indicate that the soil has settled or shifted, which are signs that the sensor may not be installed properly or that it has been altered or adjusted during deployment. This sensor does not support measurement averaging. (See your logger user's guide for more information about measurement averaging.)

Maintenance

The Soil Moisture smart sensor does not require any regular maintenance. If cleaning, rinse the sensor with mild soap and fresh water.

Calibration

The Soil Moisture smart sensor comes pre-calibrated for most soil types. If, however, your soil type has high sand or salt content, the standard calibration will not be accurate. In such cases, you will need to convert the data provided by the probe with a specific calibration for your individual soil type. To determine the soil specific calibration formula, refer to the *Calibrating ECH_2O Soil Moisture Probes* application note, available at:

http://www.onsetcomp.com/files/support/pdfs/Soil_calibration.pdf

Verifying Sensor Functionality

To quickly check sensor functionality before deployment, perform the following two tests:

1. Wash the probe with water and let it dry.
2. Plug the sensor into the logger.
3. Open the logging software and go to the status screen.
4. Conduct an air test: Hold the sensor by the cable letting the sensor hang freely in the air, and compare the value in the status screen with the table below.

Sensor	Air	Water
S-SMC-M005	-0.193 to -0.139	+0.521 to +0.557
S-SMD-M005	-0.473 to -0.134	+0.474 to +0.692

5. Distilled water test: Insert the probe in a room temperature container of fresh water, completely covering the entire ECH_2O probe. Compare the value in the status screen with the table above.

If these tests pass, your sensor is working normally. If not, please contact Onset for assistance. If you believe your sensor is defective or broken, you can send the smart sensor back to Onset for testing if needed. Contact Onset or your place of purchase for a Return Merchandise Authorization (RMA) number and associated costs before sending it.

T8

SMART THERMISTOR STRING

WITH DATA LOGGING

FEATURES

- RS485 interface
- Temperature & time
- Up to 8 channels
- Variety of thermistors available
- 52,000+ records / non-volatile
- Polyethylene, polyurethane and Tefzel® cable options
- MODBUS® protocol
- Easy export to spreadsheets and databases
- Compatible with WaveData® Wireless Data Collection Systems
- Compatible with Aqua4Push auto-polling software

DESCRIPTION

The AquiStar® T8 Smart Sensor is a submersible multi-channel temperature sensor and datalogger. The T8 Smart Sensor records over 52,000 records of temperature and time data, operates on low power, and features easy-to-use software with powerful features.

The T8 consists of an internally powered, 8-channel recorder housed in a small weather-proof box. Thermistors are embedded in strings of multi-conductor cable, up to 8 thermistors per string. Several strings can be attached to a single control box, up to a total of 8 thermistors per box.

Several T8s, or a combination of T8s, PT2X Pressure/Temperature Smart Sensors, and pH Smart Sensors can be networked together and controlled from one location, either directly from a single computer or via a WaveData™ Wireless Data Collection System.

OPERATION

The T8 is powered internally with two AA batteries or can be powered with an auxiliary 9 - 13 VDC supply for data intensive applications.

The T8 comes with powerful, easy-to-use, Windows®-based Aqua4Plus software, affording the user extensive control, including real time monitoring, flexible programming, tabular and graphing displays, and a delayed start feature.

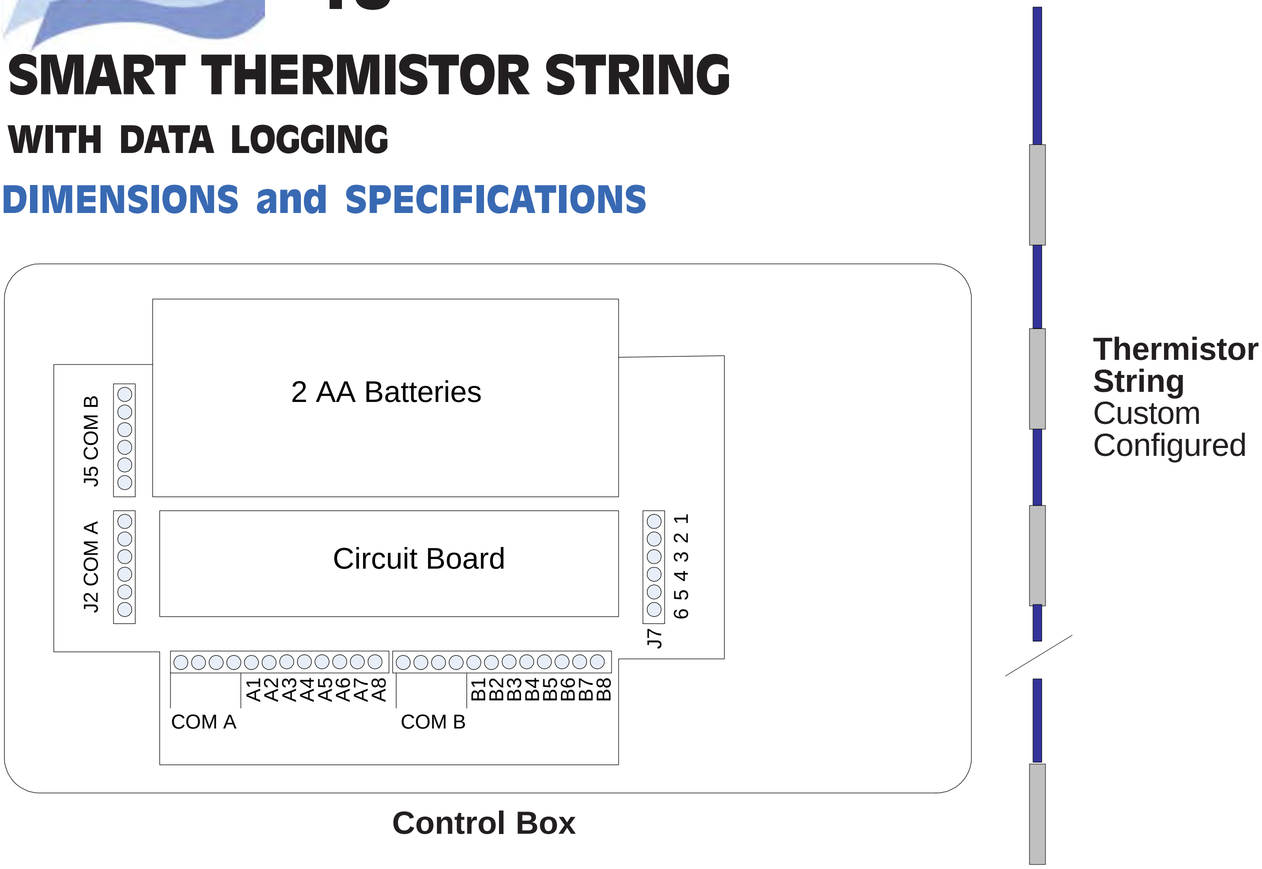
Instrumentation
Northwest, Inc.
1-800-776-9355
http://www.inwusa.com

T8

SMART THERMISTOR STRING

WITH DATA LOGGING

DIMENSIONS and SPECIFICATIONS



MECHANICAL

ENCLOSURE

Enclosure Material	ABS - IP66/67
Dimensions (box)	5.5” x 3.1” x 2.6” (14 x 7.9 x 6.6 cm)
Dimensions (incl connectors)	6.0” x 3.1” x 2.6” (15.2 x 7.9 x 6.6 cm)
Wire Seal Materials	Fluorocarbon and Buna N

CABLE

Standard Cables	9- or 12-conductor shielded cable with polyurethane, polyethylene or Tefzel® cable
Cable diameter	.280” (0.7 cm)
Thermistor node diameter	.50” (1.3 cm)

OPERATING SPECIFICATIONS

TEMPERATURE

Accuracy	± 0.2° (at 25° C)
Resolution	0.1° C
Temperature Range	-35° C to 105 ° C *(depending on thermistor)*

POWER SUPPLY

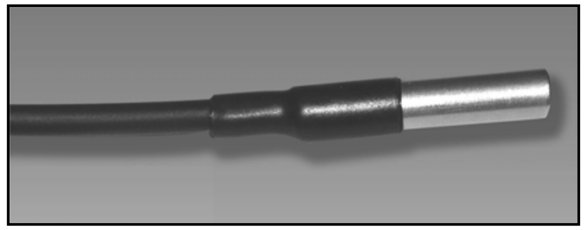
Internal	2 AA Alkaline Batteries
Auxiliary	6 - 13 VDC, 15 mA

Instrumentation Northwest, Inc.
Sales and Service Locations
8902 122nd Avenue NE, Kirkland • Washington 98033 USA
(425) 822-4434 • (425) 822-8384 FAX • info@inwusa.com
4620 Northgate Boulevard, Suite 170 • Sacramento, California 95834
(916) 922-2900 • (916) 648-7766 FAX • inwsw@inwusa.com

1-800-776-9355
http://www.inwusa.com

12-Bit Temperature Smart Sensor (Part # S-TMB-M0XX)

The 12-Bit Temperature smart sensor is designed to work with HOBO® Stations. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without any programming or extensive user setup.



Specification	12-Bit Temperature Smart Sensor
Measurement Range	-40° to +100°C (-40° to +212°F) – sensor tip
Accuracy	< ±0.2°C from 0° to +50°C (< ±0.36°F from +32° to +122°F), see Figure 1
Resolution	< 0.03°C from 0° to +50°C (< 0.054°F from +32° to +122°F), see Figure 1
Drift	< 0.1°C (0.18°F) per year
Response Time	< 2 minutes typical, in 2 m/sec (4.5 mph) moving air flow < 1 minute typical in stirred water bath
Operating Temperature Range (in-cable electronics)	-40° to +75°C (-40° to +167°F)
Environmental Rating	Sensor tip and cable jacket: Immersion in water up to +50°C (+122°F) for 1 year
Housings	Stainless steel waterproof sensor tip; weatherproof PVC housing for smart sensor adapter
Dimensions	Temperature probe: 7 x 38 mm (0.28 x 1.5 in.)
Weight	2 meter: .09 g (3.3 oz) 6 meter: .14 g (5.2 oz) 17 meter: .30 g (11.2 oz)
Bits per Sample	12
Number of Data Channels *	1
Measurement Averaging Option	Yes
Cable Lengths Available	2 m (6.6 ft) S-TMB-M002 6 m (19.7 ft) S-TMB-M006 17 m (55.8 ft) S-TMB-M017
Length of Smart Sensor Network Cable *	0.5 m (1.6 ft) for all models
Part Number	S-TMB-M002 (2 meter cable) S-TMB-M006 (6 meter cable) S-TMB-M017 (17 meter cable)
CE Specification	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

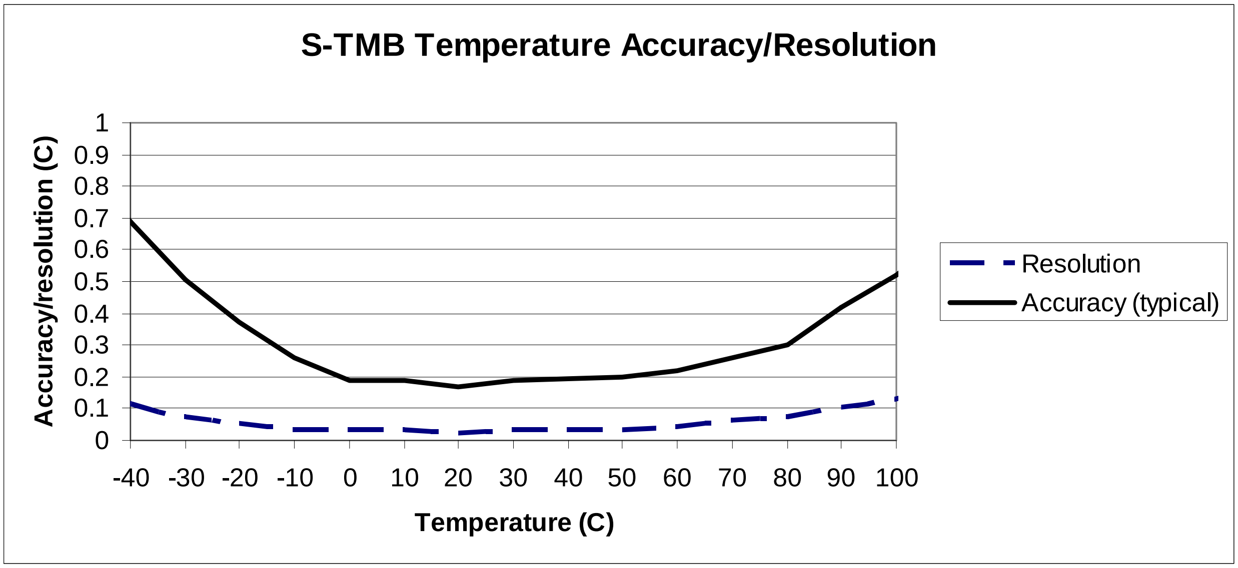


Figure 1: 12-Bit Temperature Smart Sensor Accuracy and Resolution

Inside this package

- 12-Bit Temperature Smart Sensor

Mounting

Mounting Considerations

- Mount the sensor so that at least 10 cm (4 inches) of the sensor cable is placed in the medium that is being measured. The temperature sensor is approximately 0.32 cm (1/8 inch) from the end of the stainless steel tip.
- If the sensor cable is left on the ground, it is recommended that you use conduit to protect against animals, lawn mowers, exposure to chemicals, etc.
- If you are mounting the sensor in water, place the sensor cable on the side of the mounting post facing downstream. This helps protect the sensor cable from getting damaged by floating debris.
- The Solar Radiation Shield (Part # M-RSA) is strongly recommended when measuring outdoor air temperatures. Solar radiation can significantly affect the air temperature readings.
- To minimize measurement errors due to ambient RF, use the shortest possible probe cable length and keep the probe cable as far as possible from other cables.
- Refer to the *HOBO Station Tri-pod Setup Guide* for more information about setting up complete HOBO Stations.

Optional Accessories

- Solar Radiation Shield (Part # M-RSA)

Installing the temperature sensor into the solar radiation shield

Use the ¼ inch cable clamp, washer, and screw (included with the solar radiation shield) to secure the sensor in the solar radiation shield as shown below.

1. Remove the bottom two shield plates by removing the three wing nuts.
2. Install the temperature sensor using the small black loop clamp, washer, and screw (see Figure 23).

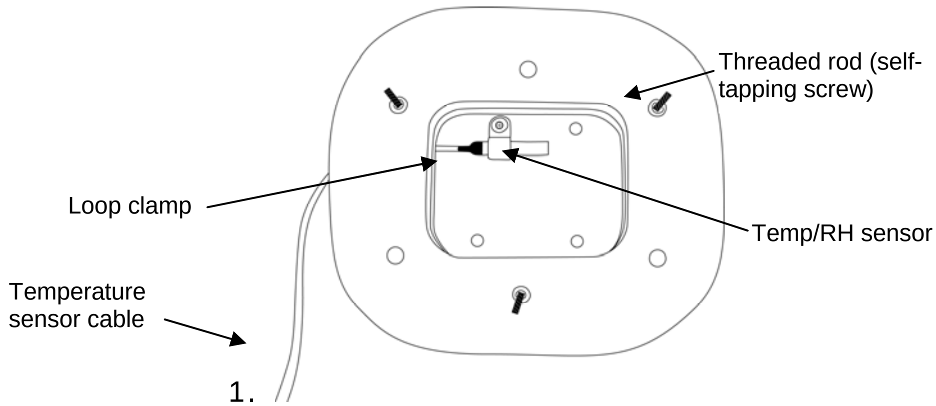


Figure 2: Temperature sensor inside solar radiation shield

Mounting the Solar Radiation Shield to the Tri-pod Mast

1. Mount the white solar radiation shield assembly onto the upper mast using the two U-bolts provided (see Figure 3).
2. Position the solar radiation shield to the desired height and tighten the U-bolt assemblies. Optimum orientation of the solar radiation shield is to face it into the direction of the predominant wind.
3. Feed the cable out through the third and fourth shield plates (see Figure 3).

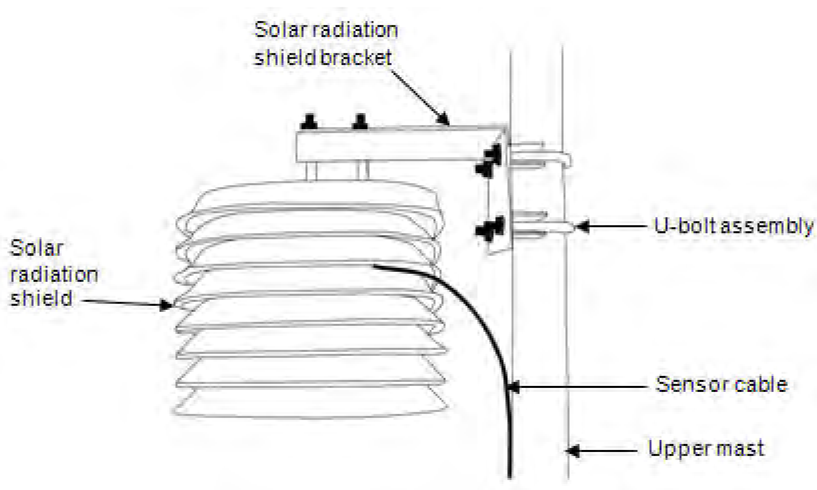


Figure 3: Mounting Solar Radiation Shield

4. Replace the bottom two shield plates.

Connecting the Sensor to a Logger

To use the 12-Bit Temperature smart sensor, stop the HOBO Station logger and insert the sensor's modular jack into an available port on the logger. If a port is not available, use a 1-to-2 adapter (Part # S-ADAPT), which allows you to plug two sensors into one port. The next time you use the HOBO Weather Station, it will automatically detect the new smart sensor. Note that the HOBO Weather Station supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly.

Operating Environment

The 12-Bit Temperature smart sensor can be used in air, soil, or water. The sensor is designed to last at least one year in water as warm as +50°C (+122°F). If the smart sensor is continually exposed to water for more than a year, it will eventually drift. Exposure to water above +50˚C (+122°F) is not recommended and may significantly reduce the life of the sensor.

Response Time

The 12-Bit Temperature smart sensor has 90% response times of < 2 minutes in 2 m/sec (4.5 mph) moving air flow (< 1 minute typical in stirred water bath). Faster sensor response times are not always better because they are more likely to be affected by transient conditions. Ideally the response time of a sensor should be the same order of magnitude as the logging interval. For typical logging intervals of 10 to 30 minutes, this smart sensor's response time of < 2 minutes is an acceptable match, however, measurement averaging may be useful for longer logging intervals (see the *Operation* section below).

Operation

The 12-Bit Temperature smart sensor supports measurement averaging. When measurement averaging is enabled, data is sampled more frequently than it is logged. The multiple samples are then averaged together and the average value is stored for the interval. For example, if the logging interval is set at 10 minutes and the sampling interval is set at 1 minute, each recorded data point will be the average of 10 measurements. Measurement averaging is useful for reducing noise in the data and preventing aliasing, which can occur when the temperature varies more rapidly than it is being measured. It is recommended that you use measurement averaging whenever the 12-Bit Temperature smart sensor is placed in an area where the temperatures can change quickly with respect to the logging interval, for example, placed in front of a cycling air vent while using a relatively long logging interval. Note that fast sampling intervals (less than 1 minute) may significantly reduce battery life.

Maintenance

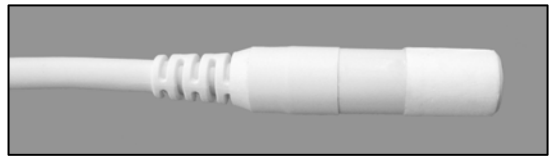
The 12-Bit Temperature smart sensor does not require any maintenance other than an occasional cleaning. If necessary, rinse the sensor and cable with mild soap and fresh water.

Verifying Sensor Accuracy

It is recommended that you check the accuracy of the 12-Bit Temperature smart sensor annually. The 12-Bit Temperature smart sensor cannot be calibrated. Onset® uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it may be damaged or worn out if it has been in use for several years. If you are unsure of the smart sensor's accuracy, you can send it back to Onset for re-certification. Contact Onset or your place of purchase for a Return Merchandise Authorization (RMA) number and associated costs prior to sending it.

Temperature/RH Smart Sensor (S-THB-M00x)

The Temperature/RH smart sensor is designed to work with smart sensor-compatible HOBO® data loggers. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without any programming, calibration or extensive user setup.



Specifications	**Temperature**	**RH**
Measurement Range	-40°C to 75°C (-40°F to 167°F)	0-100% RH at -40° to 75°C (-40° to 167°F); exposure to conditions below -20°C (-4°F) or above 95% RH may temporarily increase the maximum RH sensor error by an additional 1%
Accuracy	0.2°C over 0° to 50°C (0.36°F over 32° to 122°F); see Figure 1	+/- 2.5% from 10% to 90% RH (typical), to a maximum of +/- 3.5%. See Figure 2 for full range.
Resolution	0.02°C at 25°C (0.04°F at 77°F); see Figure 1	0.1% RH at 25°C (77°F)
Bits Per Sample	12	10
Drift	< 0.1°C (0.18°F) per year	< 1% per year typical; hysteresis 1%
Response Time	5 minutes in air moving 1 m/sec	5 minutes in air moving 1 m/sec with protective cap
Operating Temperature Range	-40°C to +75°C (-40°F to +167°F)	
Environmental Rating	Weatherproof: 0 to 100% RH intermittent condensing environments. For best results, the Temp/RH Smart Sensor should be mounted inside a protective enclosure, such as a solar radiation shield.	
Housing	PVC cable jacket with ASA styrene polymer RH sensor cap; modified hydrophobic polyethersulfone membrane	
Sensor Dimensions	10 x 35 mm (0.39 x 1.39 in)	
Weight	S-THB-M002 - 110 g (3.88 oz); S-THB-M008 - 180 g (6.35 oz)	
Number of Data Channels *****	2	
Measurement Averaging Option	No	
Cable Lengths Available	2.5 m (8.2 ft); 8 m (26.2 ft)	
Length of Smart Sensor Network Cable *****	0.5 m (1.6 ft); 6 m (19.6 ft)	
Part Numbers	S-THB-M002, S-THB-M008	
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).	

***** A single smart sensor-compatible HOBO logger can accommodate 15 data channels and up to 100 m (325 ft) of smart sensor cable (the digital communications portion of the sensor cables).

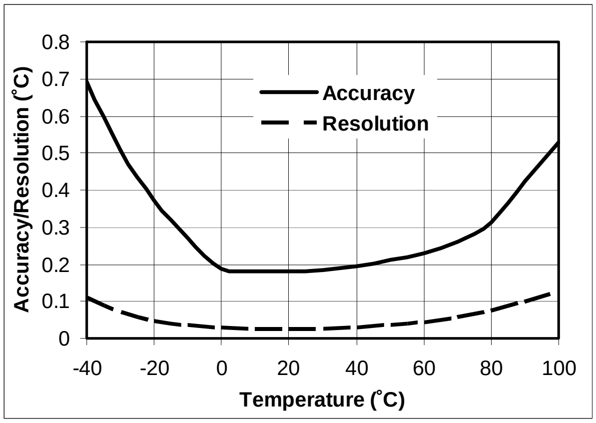


Figure 1: Temperature Accuracy and Resolution

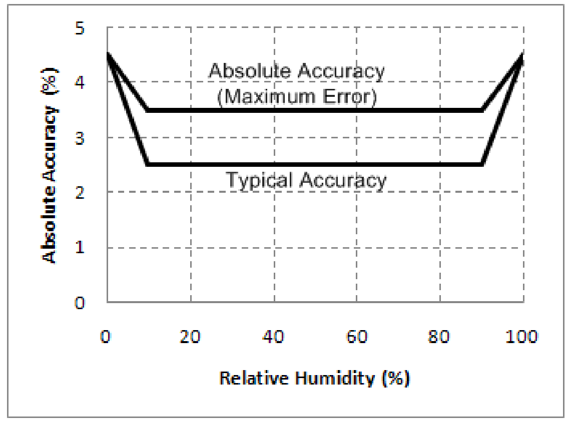


Figure 2: Relative Humidity Accuracy

Inside this Package

- Temp/RH Smart Sensor

Mounting

Accessories

Solar Radiation Shield (part # M-RSA or RS3)
Replacement RH Sensor (part # HUM-RHPCB-2)

Typical Mounting

- Solar Radiation Shield: Use the washer and screw (included with the M-RSA radiation shield) or cable clamps (included with the RS3 radiation shield) to secure the smart sensor in the radiation shield as shown in Figures 3 and 4.

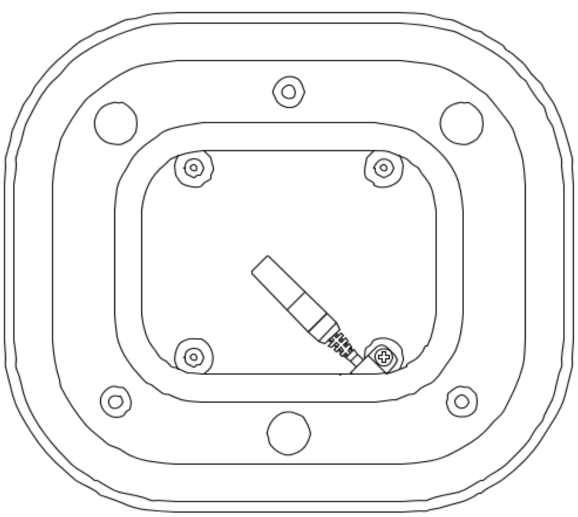


Figure 3: Temp/RH Sensor mounted in the Solar Radiation Shield M-RSA

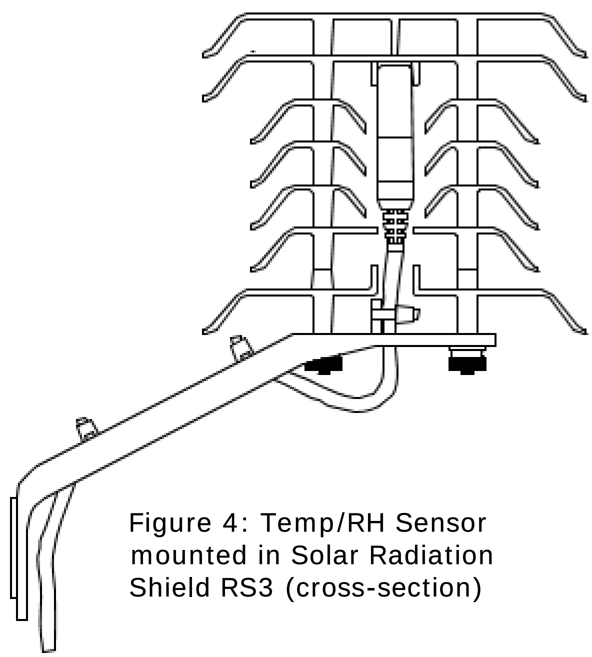


Figure 4: Temp/RH Sensor mounted in Solar Radiation Shield RS3 (cross-section)

Mounting Considerations

- A solar radiation shield is strongly recommended when measuring air temperature in direct sunlight. Solar radiation can be a significant source of error in the temperature and RH readings.
- When mounting the probe, care should be taken to thermally isolate the sensor from the mounting surface to ensure accurate air temperature and humidity readings. The probe's temperature sensor is at the end of the cable, just below the cup.
- It is recommended that the probe be protected from direct exposure to the weather. This will prolong the sensors' accuracy.
- If you are running sensor cables along the ground, it is recommended that you use conduit to protect against animals, lawn mowers, exposure to chemicals, and so on.
- The protective housing on the cable contains the smart sensor's electronics. It is waterproof, but it is not designed for prolonged submergence in puddles, saturated soils, etc.
- Refer to the logger user's guide for more information regarding setting up complete weather stations.

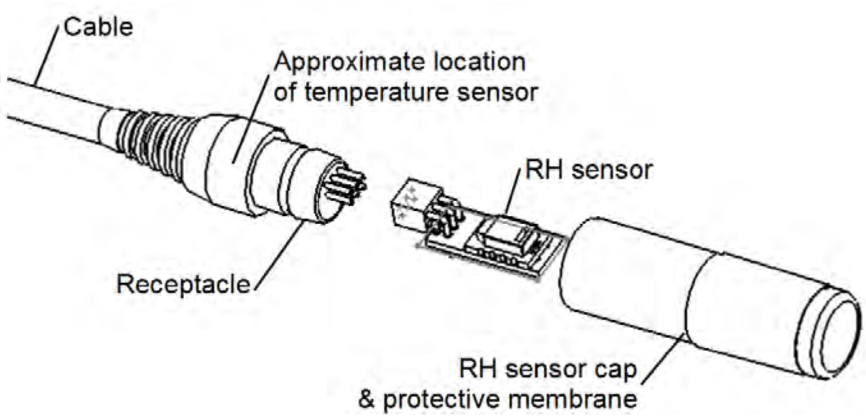
Connecting

To use the sensor with the smart sensor-compatible HOBO logger, stop the logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adapter (Onset Part # S-ADAPT). The next time you launch the logger, it will automatically detect the new sensor. Note that the logger supports a maximum of 15 data channels. Use the software to launch the logger and verify the sensor is functioning correctly. See the logger user's guide for more details about connecting HOBO smart sensors to loggers.

Replacing the RH sensor

The RH sensor is protected by an ASA styrene polymer cap and a modified hydrophobic polyethersulfone fluid barrier membrane that allows vapor to penetrate while protecting the sensor from condensation. RH sensor performance may degrade over time. To replace the RH sensor, take the following steps:

1. Remove the tape fastening the sensor cap to the receptacle. Discard the tape.
2. Grasp the cap and membrane and pull firmly to remove them. Discard them.
3. **Note the orientation of the small circuit board containing the RH sensor.** Pull it out and discard it in compliance with local disposal guidelines for circuit boards.



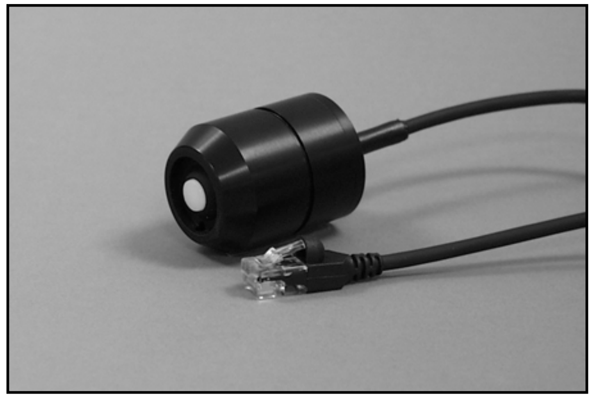
4. Push gently but firmly to install the new sensor (Onset part # HUM-RHPCB-2) **in the same orientation.**

5. Put the new sensor cap and membrane on. Do not force the cap. If it does not go on easily, the sensor may be installed backwards. Reverse the sensor and try again.

Maintenance

The Temperature/RH smart sensor is sensitive to dust, salts and other airborne contamination. Periodically inspect the RH sensor. If contamination is present on the protective cap, gently rinse it with cool fresh water. If the sensor itself is contaminated, you can rinse it with distilled water. Do not use hot water, organic solvents, or detergents. Dry before use.

Silicon Pyranometer Smart Sensor (Part # S-LIB-M003)



The Silicon Pyranometer smart sensor is designed to work with the HOBO® Weather Station logger. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Weather Station. All calibration parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming, calibration, or extensive setup.

Inside this Package

- Silicon Pyranometer smart sensor

Specifications	Silicon Pyranometer Smart Sensor
Measurement Range	0 to 1280 W/m^2
Spectral Range	300 to 1100 nm (see Figure 4)
Accuracy	Typically within ± 10 W/m^2 or ± 5%, whichever is greater in sunlight; Additional temperature induced error ± 0.38 W/m^2/°C from +25°C (0.21 W/m^2/°F from +77°F)
Angular Accuracy	Cosine corrected 0 to 80 degrees from vertical (see Figure 5); Azimuth Error < ±2% error at 45 degrees from vertical, 360 degree rotation
Resolution	1.25 W/m^2
Drift	< ±2% per year
Calibration	Factory recalibration available
Operating Temperature Range	-40° to +75°C (-40° to +167°F)
Environmental Rating	Weatherproof
Housing	Anodized aluminum housing with acrylic diffuser and O-ring seal
Dimensions	4.1 cm height x 3.2 cm diameter (1 5/8 in. x 1 1/4 in.)
Weight	120 g (4 oz)
Bits per Sample	10
Number of Data Channels *	1
Measurement Averaging Option	Yes
Cable Length Available	3.0 m (9.8 ft)
Length of Smart Sensor Network Cable *	3.0 m (9.8 ft)
Part Number	S-LIB-M003
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Weather Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Part #: MAN-S-LIB
Doc #: 6708-D

Mounting

Accessories

- Light Sensor Mounting Bracket (Part # M-LBB)
- Light Sensor Level (Part # M-LLA)

Bracket Mounting

It is recommended that you mount the Silicon Pyranometer smart sensor with the light sensor bracket on a pole or tripod (see Figure 1). To mount the sensor using the bracket:

1. Attach the light sensor bracket to a 1¼ inch to $1^5/_8$ inch pole with the provided U-bolts.

   Note: The bracket can also be mounted on a flat, vertical surface using four screws.
2. Position the Silicon Pyranometer sensor on top of the bracket with its cable running through the slot in the bracket.
3. Using the two screws supplied, attach the sensor to the bracket through the two holes on either side of the slot.

   Note: Do not completely tighten the screws until you level the sensor.
4. Position the bracket so it faces toward the equator, minimizing the chance of shading.
5. Mount the bracket on the mast with the two U-bolt assemblies, mounting it high enough on the mast to avoid the possibility of shading the sensor.

   Note: If you mount the sensor above eye level, use a step ladder or other secure platform when leveling the sensor so that you can clearly view the Light Sensor Level (Part # M-LLA).

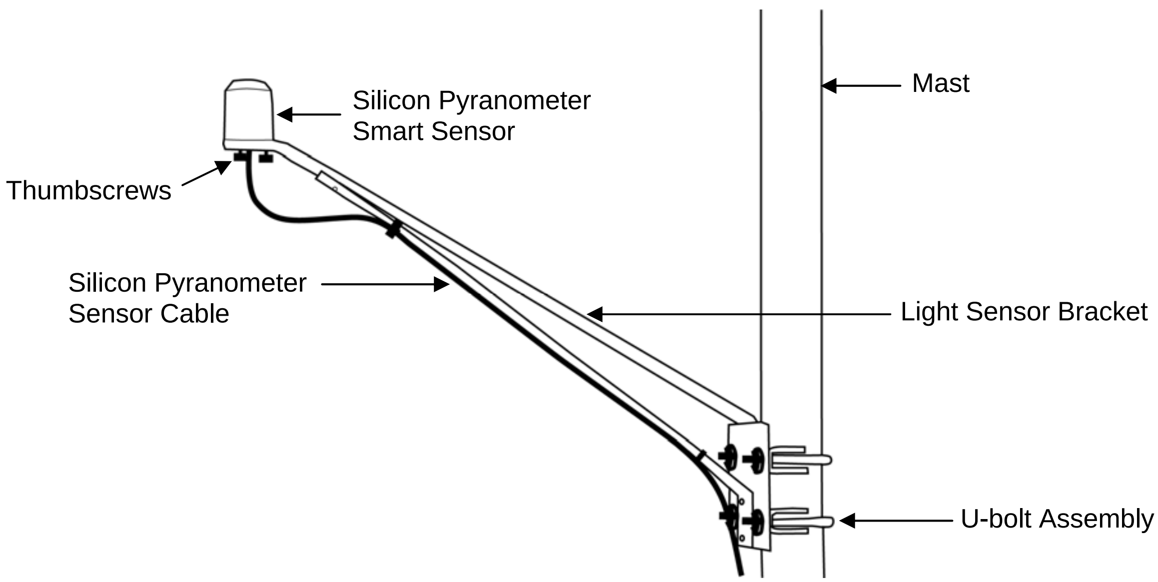


Figure 1: Silicon Pyranometer Sensor Bracket Mounting

6. Make sure the screws holding the sensor to the mounting bracket are loose.

7. Place the Light Sensor Level on the Silicon Pyranometer smart sensor.
8. Adjust the height of the thumbscrews to level the sensor (start with the thumbscrews protruding about 1/16 inch from the bracket).
9. Once the sensor is near level, tighten the Phillips head screws.
10. Check the level and repeat above steps if necessary (see Figure 2).
11. **IMPORTANT**: Don't forget to remove the level when you are done with it.

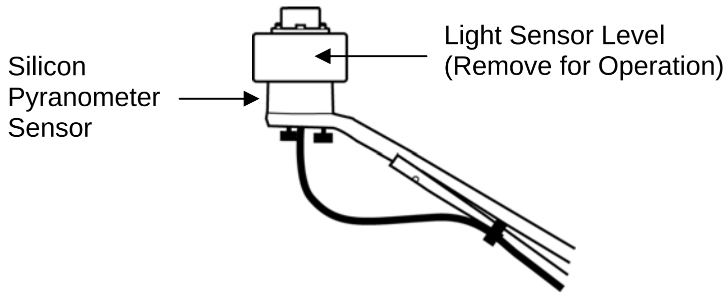


Figure 2: Leveling the Sensor on the Light Sensor Bracket

Specialized Application Mounting

To mount the Silicon Pyranometer sensor using a mounting plate of your own design:

1. Drill a 0.56 (9/16) inch hole in the middle of the plate, then drill two #25 holes 1.063 (1-1/16) inches apart on either side of the center hole. Cut a 0.31 (5/16) inch-wide slot in the mounting plate. See Figure 3. The plate should be a thickness of 1/8 inch or less.
2. Slide the sensor through the 0.31 (5/16) inch-wide slot.
3. Attach the sensor using two 6-32 x 3/8 inch screws and lock washers (not included).
4. Shim the sensor as necessary to level it.

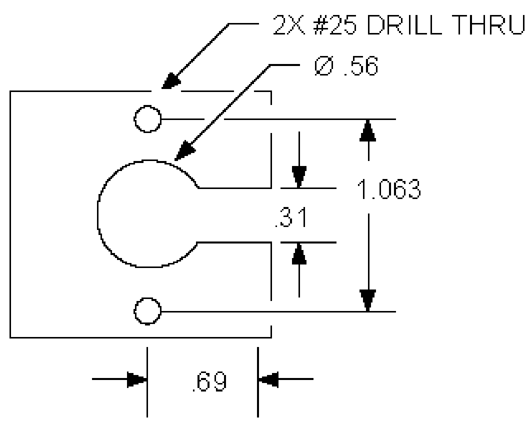


Figure 3: Recommended Mounting Plate Dimensions

Mounting Considerations

- Small errors in alignment can produce significant errors. Be certain the sensor is mounted level.
- Mount the sensor where it will not be in a shadow. Any obstruction should be below the plane of the sensor head. If that is not possible, try to limit obstructions to below 5 degrees, where the effect will be minimal.
- If possible, avoid placing the sensors in dusty locations. Dust, pollen, and salt residue that collect on the top of the sensor can significantly degrade accuracy.
- Refer to the *HOBO Weather Station User's Guide* for more information about setting up complete HOBO Weather Stations.

Connecting the Sensor to the Logger

To start using the Silicon Pyranometer smart sensor, stop the HOBO Weather Station logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adaptor, which allows you to plug two sensors into one port (Part # S-ADAPT). The next time you use the HOBO Weather Station, it will automatically detect the new smart sensor.

The HOBO Weather Station supports a maximum of 15 data channels; this sensor uses one channel. Launch the logger and verify the sensor is functioning correctly. See the *HOBO Weather Station User's Guide* for more details about connecting smart sensors to the HOBO Weather Station.

Operation

The Silicon Pyranometer smart sensor supports measurement averaging. When measurement averaging is enabled, data is sampled more frequently than it is logged. The multiple samples are then averaged together and the average value is stored as the data for the interval. For example, if the logging interval is set at 10 minutes and the sampling interval is set at 1 minute, each recorded data point will be the average of 10 measurements.

Measurement averaging is useful for reducing noise in the data. It is recommended that you use measurement averaging whenever the Silicon Pyranometer smart sensor is placed in an area where the light level can vary quickly with respect to the logging interval (for example, during partly cloudy conditions). Note that fast sampling intervals (less than 1 minute) may significantly reduce battery life. See the *HOBO Weather Station User's Guide* for more details about sensor operation and battery life.

Spectral Characteristics

This sensor uses a silicon photodiode to measure solar power per unit area (watts per square meter). Silicon photodiodes are not ideal for use as solar radiation sensors and the photodiode in this Silicon Pyranometer is no exception (see Figure 4). An ideal pyranometer has equal spectral response from 280 to 2800 nm. However, when calibrated properly and used correctly, the Silicon Pyranometer smart sensor should perform well in most situations.

The sensor is calibrated for use in sunlight (an Eppley Precision Spectral Pyranometer is used as reference standard). Accordingly, if the sensor is used under natural sunlight, the measurement errors will be small. Note that significant errors may result from using the sensor under artificial light, within plant canopies, in greenhouses, or any other conditions where the spectral content differs from sunlight.

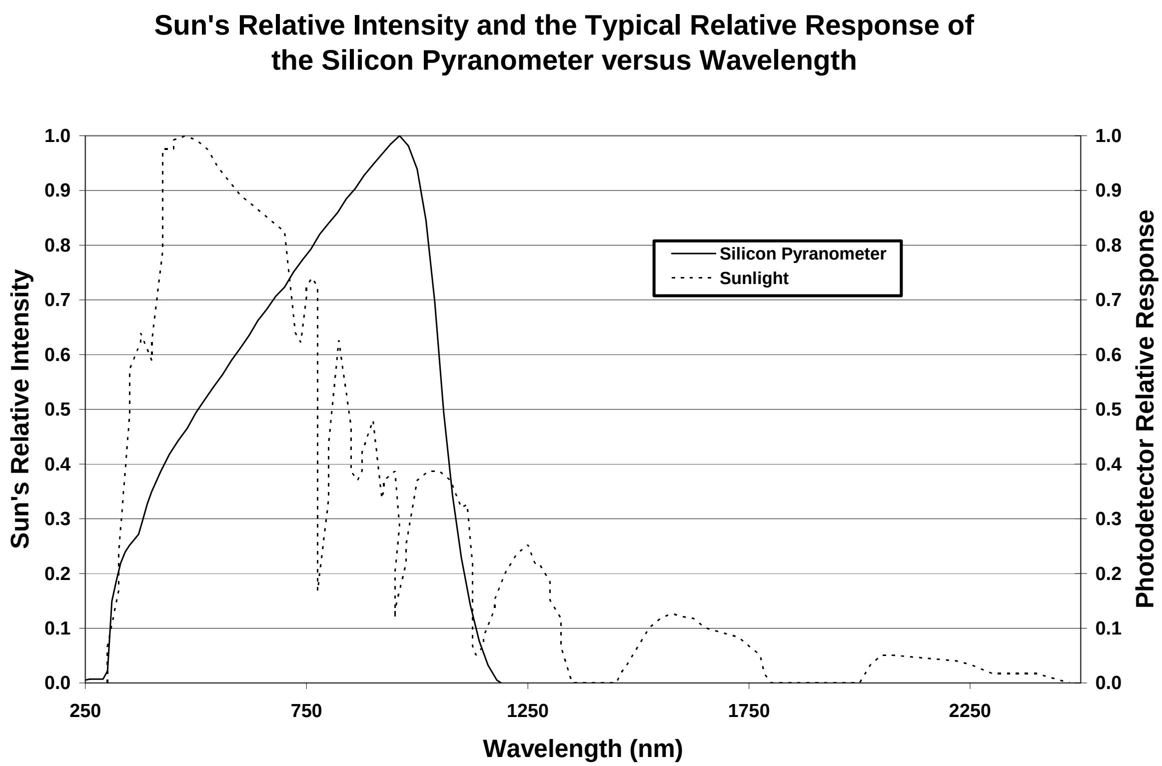


Figure 4: S-LIB-M003 Silicon Pyranometer Response Curve

Cosine Correction

The Silicon Pyranometer smart sensor housing is designed to give an accurate cosine response. Figure 5 shows a plot of relative intensity versus angle of incidence for a typical sensor and for the theoretical ideal response. Deviation from ideal response is less than 5% from 0 to 70 degrees and less than 10% from 70 to 80 degrees.

Note that as the angle approaches 90 degrees, the ideal cosine response approaches zero. As a result, small errors in measured intensity will result in very large percentage errors compared to the ideal response from 80 to 90 degrees.

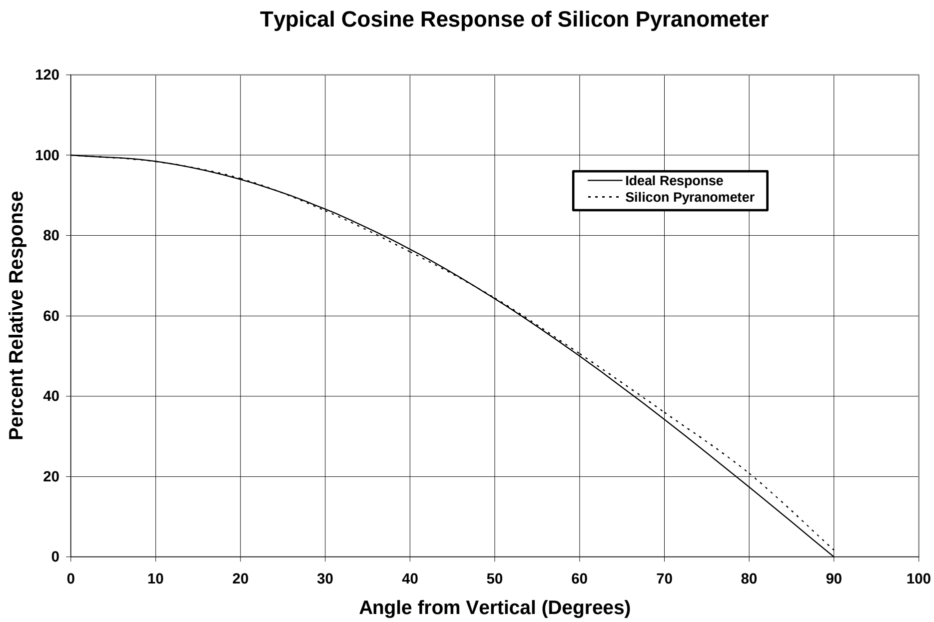


Figure 5: S-LIB-M003 Typical Cosine Response Curve

Maintenance

Dust on the sensor will degrade sensor accuracy. Periodically inspect the sensor and if necessary, gently clean the diffuser with a damp sponge. Do not open the sensor as there are no user serviceable parts inside.

Warning: DO NOT use alcohol, organic solvents, abrasives, or strong detergents to clean the diffuser element on the Silicon Pyranometer smart sensor. The acrylic material used in the sensor can be crazed by exposure to alcohol or organic solvents. Clean the sensor only with water and/or a mild detergent such as dishwashing soap if necessary. It is recommended that you use vinegar to remove hard water deposits from the diffuser element. Under no circumstances should the sensor be immersed in any liquid.

Verifying Sensor Accuracy

It is recommended that you test the Silicon Pyranometer smart sensor annually for accuracy. If the sensor is not providing accurate data, it may be damaged or out of calibration. If you are unsure of accuracy, send the smart sensor back to Onset for testing and possible re-calibration. Only Onset can complete calibration. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

Rain Gauge Smart Sensor (Part # S-RGA-M002, S-RGB-M002)

The Rain Gauge smart sensor is designed to work with HOBO Station loggers. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO® Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive user setup.

Inside this Package:

- Rain Gauge Smart Sensor
- Mounting Accessories: 2 hose clamps, 3 screws

Specifications	Rain Gauge Smart Sensor
Measurement Range	0 to 12.7 cm (0 to 5 in.) per hour, maximum 4000 tips per logging interval
Calibration Accuracy	±1.0% at up to 20 mm/hour (1 in./hour)
Resolution	0.01 in. (S-RGA-M002) or 0.2 mm (S-RGB-M002)
Calibration	Requires annual calibration: can be field calibrated or returned to the factory for re-calibration
Operating Temperature Range	0° to +50°C (+32° to +122°F), survival -40° to +75°C (-40° to +167°F)
Environmental Rating	Weatherproof
Housing	15.24 cm (6 in.) aluminum bucket
Mechanism	Tipping bucket; stainless steel shaft with brass bearings
Dimensions	22.8 cm height x 15.4 cm diameter (9 x 6 in.), 15.4 cm (6.06 in.) receiving orifice
Weight	1 Kg (2 lbs)
Bits per Sample	12
Number of Data Channels*****	1
Data Format	Number of tips per recorded measurement, reported in inches or millimeters
Measurement Averaging	No
Length of Smart Sensor Network Cable*****	2 m (6.5 ft)
Part Numbers	S-RGA-M002 (0.01 in. per tip with 2 m cable) S-RGB-M002 (0.2 mm per tip with 2 m cable)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

***** A single HOBO Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Part #: MAN-SRGX
Doc #: 14091-A

Mounting

NOTICE: During shipment the tipping assembly has been secured to avoid possible damage to the pivot assembly. Lift off the collector ring assembly (ring, screen, and funnel), and remove the rubber band from inside to release the tipping-bucket mechanism before installation.

Mounting Considerations

- For the most accurate rainfall measurements, it is recommended that you mount the Rainfall sensor upslope, about 3 meters (10 feet) away from the tripod, on a 1.5 meter high mounting pole (Part # M-MPB). Alternatively, you can mount the Rainfall sensor on the tripod mast. This section includes steps for both configurations.
- Tall objects can interfere with accurate rain measurements. It is recommended that you place the rain bucket away from the obstruction by a distance greater than three times the height of the obstruction. If that is not possible, raise the rain bucket as high as possible to avoid shedding.
- Avoid splashing and puddles. Be sure the gauge is high enough above any surface that rain will not splash into the top of the collector.
- Vibration can significantly degrade accuracy of the tipping bucket mechanism. In windy locations make sure that the bucket will be vibration-free. Consider using guy wires to secure a pole or tower-mounted bucket.
- Refer to the *HOBO Station Tripod Setup Guide* for more information.

Mounting the Sensor on a HOBO Station Tripod

Accessories:

- One Meter Mast (Part # M-MPA)
- Guy Wire Kit (Part # M-GWA)
- Mast Level (Part # M-MLA)

Secure the Rain Gauge sensor near the top of the mast on the side opposite the cross arm, using the two hose clamps provided.

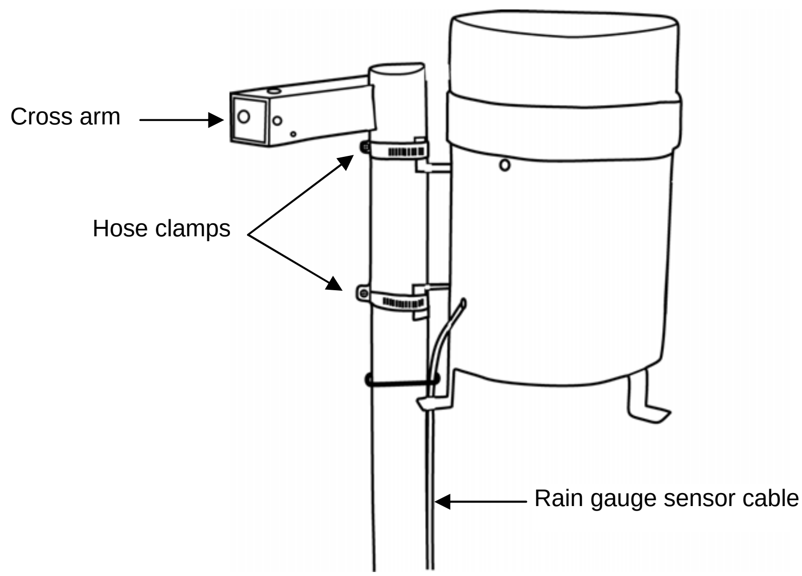


Figure 1: Rain Gauge sensor on the tripod mast

1. Open each hose clamp and place it around the mast.
2. Close the hose clamps until the rain gauge side bracket easily slides into the clamp.
3. Hold the Rain Gauge sensor bracket against the mast with the top of the Rain Gauge sensor above the top of the mast.
4. Slip the upper clamp over the side bracket and tighten the clamp until the rain gauge is secure. **Note:** Be sure the collector is above the top of the mast so you don't get any splashing, wind, shedding, or shadow effects.
5. Install the lower clamp and check that the top of the bucket is level. **Note:** For windy locations, it is recommended that you use the Guy Wire Kit (Part # M-GWA) to reduce vibration and ensure data collection accuracy (installed later).

Mounting the Sensor on a Pole

Secure the Rain Gauge sensor to the separate mounting pole, using the two hose clamps provided (see the instructions on the next page). This separate mounting pole can either be pounded in the ground or mounted in concrete, depending on how firm the ground is.

In either case, be sure the pole is vertical when you install it. The top of the pole should be slightly less than the height desired for the top of the Rain Gauge sensor (1 meter or 3 feet is typical).

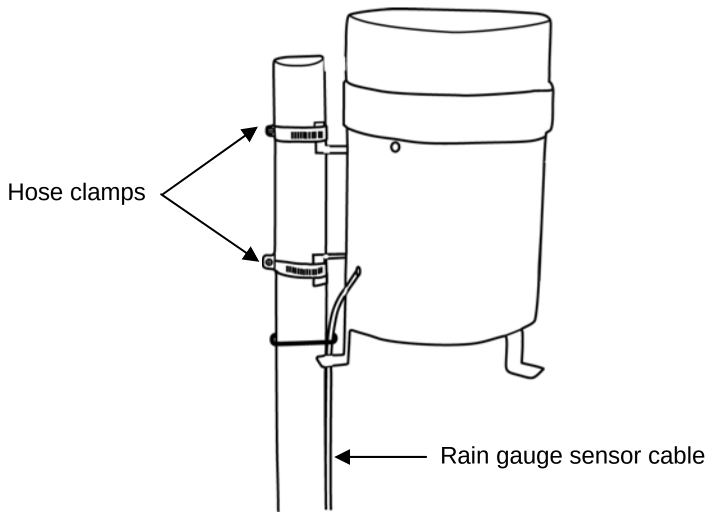


Figure 2: Rain Gauge sensor on separate mounting pole

Horizontal Surface Mounting

If mounting the Rain Gauge on a horizontal surface:

- The Rain Gauge housing MUST be mounted in a LEVEL position, clear of overhead structures, and in a location free from vibration
- Place the bucket on the mounting surface and mark the holes for the three mounting screws
- For wood surfaces, drill three 1/16th inch holes
- For concrete, drill three appropriately sized holes with a masonry bit, and install screw plug inserts
- Use shims as required to level the bucket
- Fasten the bucket with the screws shipped with the Rain Gauge

Connecting the Sensor to a Logger

To start using the Rain Gauge smart sensor, stop the logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adapter (Part # S-ADAPT), which allows you to plug two sensors into one port. The next time you use the HOBO Station, it will automatically detect the new sensor. Note that a HOBO Station supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly.

Operation

The Rain Gauge smart sensor measures rainfall by counting the number of tips per recorded measurement, up to 4000 tips per logging interval (40 inches or 80 cm of rain).

Maintenance

Clean the filter screen, funnel, and tipping-bucket mechanism with mild soap and water and a cotton swab. An accumulation of dirt, bugs, etc. on the tipping bucket will adversely affect the calibration. Oil the needle bearings with light oil on an annual basis. In harsh environments, it is recommended that you lubricate the needle bearings more frequently.

Field Calibration

The tipping-bucket mechanism is a simple and highly reliable device. Absolutely accurate Rain Gauge smart sensor calibration can be obtained only with laboratory equipment, but an approximate field check can be easily done. The Rain Gauge smart sensor must be calibrated with a controlled rate of flow of water through the tipping-bucket mechanism.

The maximum rainfall rate that the Rain Gauge smart sensor can accurately measure is one inch of rain per hour (36 seconds between bucket tips). Therefore, the Rain Gauge smart sensor should be field calibrated using a water flow rate equivalent to, or less than, one inch of rain per hour (more than 36 seconds between bucket tips).

To Check Calibration

1. Obtain a plastic or metal container of at least one liter capacity. Make a very small hole (a pinhole) in the bottom of the container.
2. Place the container in the top funnel of the Rain Gauge Smart Sensor. The pinhole should be positioned so that the water does not drip directly down the funnel orifice.
3. Follow the instructions for the Rain Gauge model you have.

   S-RGA-M002: Pour exactly 473 ml of water into the container. Each tip of the bucket represents 0.01 inch of rainfall.

   S-RGB-M002: Pour exactly 373 ml of water into the container. Each tip of the bucket represents 0.2 mm of rainfall.

- If the test takes less than one hour for this water to run out, the hole (step 1) is too large. Repeat the test with a smaller hole.
- Successful field calibration of this sort should result in one hundred tips plus or minus two.
- Adjusting screws are located on the outside bottom of the Rain Gauge housing. These two socket head set screws require a 5/64 inch Allen wrench. Turning the screws clockwise increases the number of tips per measured amount of water. Turning the screws counterclockwise decreases the number of tips per measured amount of water. A ¼ turn on both screws either clockwise or counterclockwise increases or decreases the number of tips by approximately one tip. Adjust both screws equally; if you turn one a half turn, then turn the other a half turn.
- Repeat these steps as necessary until the sensor has been successfully calibrated.

Wind Speed Smart Sensor (Part # S-WSA-M003)

The Wind Speed smart sensor is designed to work with HOBO® Station loggers. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive user setup.

Inside this Package

- Wind Speed smart sensor

Specifications	Wind Speed Smart Sensor
Measurement Range	0 to 45 m/sec (0 to 100 mph)
Accuracy	±1.1 m/sec (2.4 mph) or ±4% of reading, whichever is greater
Resolution	0.38 m/sec (0.8 mph)
Service Life	> 5 year life typical, factory replaceable mechanism
Distance Constant	3 m (9.8 ft)
Starting Threshold	≤ 1 m/sec (2.2 mph)
Maximum Wind Speed Survival	54 m/sec (120 mph)
Measurement Definition	Wind speed: Average wind speed over logging interval Gust: Fastest 2 second gust during the logging interval See *Measurement Operation* for more information.
Operating Temperature Range	-40° to +75°C (-40° to +167°F)
Environmental Rating	Sensor and Cable Jacket: Weatherproof
Housing	Three cup polycarbonate anemometer: Modified Teflon® bearings and hardened beryllium shaft with ice shedding design
Dimensions	19.0 x 8.1 cm (7.5 x 3.2 in)
Weight	300 g (10 oz)
Bits per Sample	Wind Speed: 8 Gust Speed: 8
Number of Data Channels *	2
Measurement Averaging Option	No
Cable Length Available	3.0 m (9.8 ft)
Length of Smart Sensor Network Cable *	0.5 m (1.6 ft)
Part Number	S-WSA-M003
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Weather Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Doc #: 13287-B, Part #: MAN-SWSA

Mounting the Sensor to a Tri-pod

You can mount the Wind Speed sensor to a tri-pod using a cross arm, as shown below.

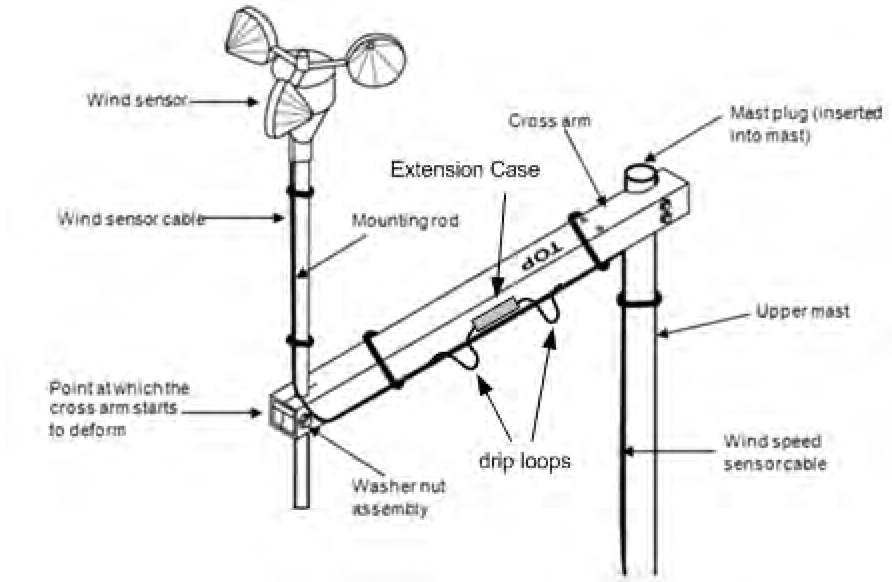


Figure 1: Mounting Wind Speed Sensor to Tri-pod Cross Arm

Placement and Mounting Considerations

- The Wind Speed smart sensor should be mounted vertically in a location free of wind shadows.
- For accurate wind speed measurements, mount the sensor at a distance of at least five times the height of the nearest tree, building, or other obstruction.
- Be sure to secure the sensor cable with cable ties to protect the cable from damage.
- Ground wire must be used. Attach it to the mounting pole or tripod.
- Although the wind sensor is designed to operate in 100+ mph winds, it can be damaged with improper handling. Store the sensor in its shipping box until you are ready to install it.
- Mount the Weatherproof Extension Case horizontally on the cross arm and put a drip loop on either side of the connector housing to prevent water from entering.
- Refer to the *HOBO Station Tri-pod Setup Guide* for more information.

Accessories

- Full Cross Arm (Part # M-CAA)
- Half Cross Arm (Part # M-CAB)

Steps

Refer to Figure 1 while mounting the Wind Speed sensor.

1. Mount Sensor to Mounting Pole. Insert the sensor onto the mounting, as shown at right.
2. Insert Mounting Pole into Cross Arm. Secure the ground wire to the lug nut on the cross arm.
3. Insert a 1/4-20 x 1 3/4 inch hex head bolt with a flat washer on it through the 1/4 inch hole on the end of the cross arm. Tighten with a 7/16 inch wrench until snug.
4. Install another flat washer and nylock nut on the bolt, allowing the black mounting rod to protrude 1/2 inch (1.3 cm) from the bottom of the cross arm.
5. Tighten the nut and bolt until the rod is clamped in place and the cross arm just starts to deform.

Figure 2: Attach Wind Speed Sensor to Mounting Pole

6. Adjust the height of the sensor in the cross arm as necessary. You can adjust the sensor height by raising and lowering the entire mast, the wind sensor on the cross arm, or a combination of both.
   a. Loosen the tri-clamp bolts and raise or lower the entire mast so that the wind sensor is close to the desired height. Make sure there is at least 5 cm (2 inches) of mast extending below the lower tri-clamp.
   b. Make sure the upper mast dimple is still facing north (if in northern hemisphere) and then re-tighten the tri-clamps. Once the tri-clamp bolts are tight, tighten the lock nuts to lock the bolts in place. This requires two wrenches: one to hold the bolt and one to tighten the lock nut against the tri-clamp.
   c. Loosen the bolt on the wind sensor mounting rod and raise or lower it as necessary so the center of the wind sensor anemometer cups is at the desired height. Re-tighten the bolt.
7. Secure Cables.

   Use cable ties to secure the sensor cables to the cross arm, bracket, and mast as shown in Figure 1. The sensor cables should run below the cross arm and brackets to minimize the chance of birds pecking and damaging the cables. Cable ties should be spaced no more than .3 m (1 foot) apart.

   Mount the Weatherproof Extension Case horizontally on the cross arm and put a drip loop on either side of the connector housing to prevent water from entering.

Mounting the Wind Speed Sensor to a Pole

1. Mount Sensor to Mounting Pole.

   Insert the sensor onto the mounting, as shown below.

Figure 3: Attach Wind Speed Sensor to Mounting Pole

2. Loosely secure the sensor mounting pole with two hose clamps (not included), as shown in Figure 3.
3. Adjust the height of the sensor as necessary.
4. Tighten the hose clamps making sure that the pole remains vertical.
5. Mount the Extension Case horizontally on the pole using zip ties.

6. Put a drip loop in the cable where it enters the Extension Case from the sensor to prevent water from entering. The cable from the Extension Case to the ground should hang straight down.

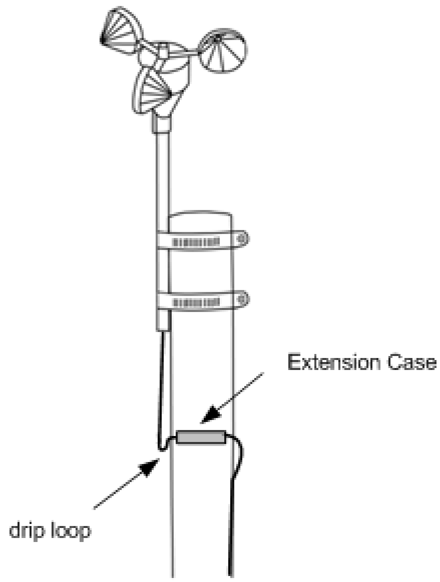


Figure 4: Wind Speed Smart Sensor Mounted on Pole

Connecting the Sensor to a Logger

To start using the Wind Speed smart sensor, stop the logger and insert the modular jack into an available port. If a port is not available, use a 1-to-2 adapter (Part # S-ADAPT), which allows you to plug in two sensors into one port. The next time the HOBO Station is used, it will automatically detect the new smart sensor. Note that the HOBO Station supports a maximum of 15 data channels; this smart sensor requires two data channels for wind speed and gust. Launch the logger and verify that the sensor is functioning correctly.

Measurement Operation

The Wind Speed smart sensor measures both average wind speed and gust wind speed. Average speed is the average wind speed over the logging interval. Gust speed is the maximum wind speed for the logging interval based on two second sub-intervals. If the logging interval is set at 2 seconds (or less), the gust speed and average speed will be the same. If the logging interval is set to 1 second, the same sensor reading will be recorded until a new 2-second average is calculated. This means the sensor will report the same wind speed (its calculated average) for two samples before calculating and reporting a new value for another two samples.

Maintenance

The Wind Speed smart sensor does not require any maintenance other than an occasional cleaning. If dust, cobwebs, salt or other contaminants collect in the cups of the anemometer, rinse the sensor with mild soap and fresh water.

Verifying Sensor Accuracy

Onset recommends that you check the accuracy of the Wind Speed smart sensor annually. The Wind Speed smart sensor cannot be calibrated. Onset uses precision components to obtain accurate measurements. If the smart sensor is not providing accurate data, then it may be damaged or possibly worn out if it has been in use for several years. If you are unsure of the smart sensor’s accuracy, you can send the smart sensor back to Onset for re-certification and replacement of the mechanism if needed. Contact Onset or your dealer for a Return Merchandise Authorization (RMA) number before sending the sensor.

AquiStar® PT12 / SDI-12 SUBMERSIBLE PRESSURE/TEMPERATURE SMART SENSOR

FEATURES

- SDI-12 v1.3 interface and Modbus® RTU interface
- Small diameter
- Optional body lengths
- Twist open case
- Pressure and temperature
- 316 stainless steel, Viton® and Teflon® construction *(Titanium optional)*
- Polyethylene, polyurethane and FEP Teflon® cable options

DESCRIPTION

INW's patented AquiStar® PT12/SDI-12 submersible pressure sensor represents the latest in state-of-the-art level measurement technology. Building on years of successful experience, this industry standard SDI-12 v1.3 interface device offers great noise immunity, thermal performance and transient protection. In addition, this device returns temperature and time data and operates with low power.

The sensor's end cone is interchangeable with a 1/4" NPT inlet which allows for increased application use and easy hookup. The modular-designed AquiStar® PT12/SDI-12 sensor can be factory serviced and repaired saving on future upgrade and repair costs.

OPERATION

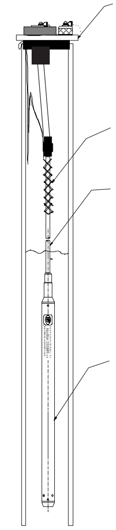
INW's PT12/SDI-12 submersible level sensor features an SDI-12 interface that makes the product easy to interface to SDI-12 recorders, can be daisy-chained on one cable up to 200 feet (30 meters), and operates on low power. This makes it a preferred choice for many environmental professionals with existing SDI-12 systems. For further flexibility, this sensor features a Modbus® RTU communication interface.

The U.S.G.S. OSW accuracy enhanced calibration is an option on the 15 psig (10.5 H_2O) unit.

APPLICATIONS

Due to its rugged construction, the AquiStar® PT12 / SDI-12 Sensor can be used to replace analog sensors. Units can be used to monitor groundwater, well, tank and tidal levels, as well as for pump testing and flow monitoring.

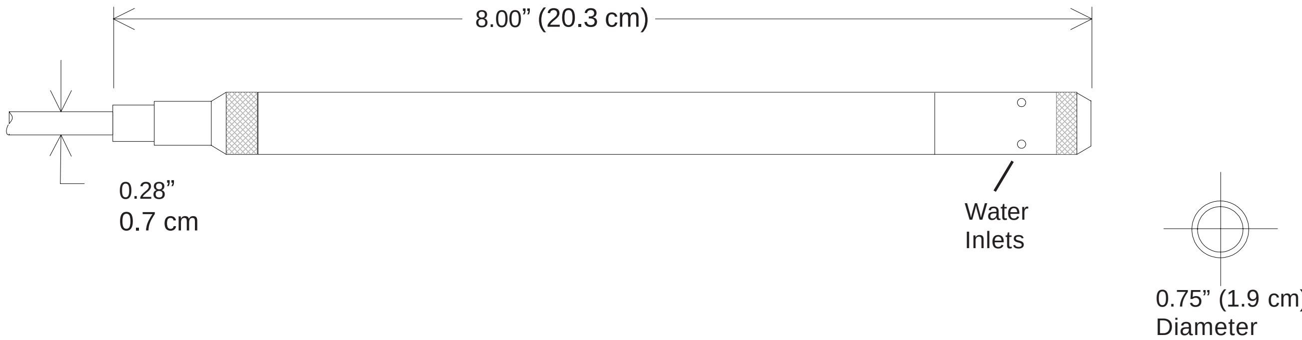
2" (5.1 cm) Monitoring Well Dedicated Assembly



Instrumentation Northwest, Inc.
1-800-776-9355
http://www.inwusa.com

PT12 / SDI-12 SUBMERSIBLE PRESSURE/TEMPERATURE SMART SENSOR

DIMENSIONS, SPECIFICATIONS, and ORDERING INFORMATION



MECHANICAL

SENSOR

Body Material	316 stainless *(Titanium option)*
Wire Seal Materials	Viton® and Teflon®
Desiccant	High- & Standard-capacity packs
Terminating Connector	Available
Weight	.80 lbs. (0.4 kg)
Diameter	0.75 inches (1.9 cm)
Length	8 inches (20.3 cm)

CABLE

OD	0.28" (0.7 cm) maximum
Break Strength	138 lbs (62.7 kg)
Maximum Length	200 feet (61 m) for SDI-12 2000 feet (610 m) for Modbus®
Weight	4 lbs. per 100 feet (1.8 kg per 30 m)

ELECTRICAL

PRESSURE

Pressure Ranges	
PSIG (gauge)	5, 15, 30, 50, 100, 300
PSIA (absolute)	20, 30, 50, 100, 300
mH_2O (gauge)	3.5, 10.5, 21, 35, 70, 210
mH_2O (absolute)	14, 21, 35, 70, 210
Static Accuracy *(B.F.S.L. 25° C)*	± 0.1% FSO (maximum) ± 0.06% FSO (typical) *± 0.05% available on request*
Maximum Zero Offset *at 25° C*	± 0.25% FSO
Resolution	16 bit
Over Range Protection	2x [except 300 PSI (210 H_2O) and higher]
Compensated Temp. Range	0° C to 40° C
Extended Temp. Version	-10° C to 50° C
Operating Temp. Range	-5° C to 70° C
Extended Temp. Version	-20° C to 70° C
Storage Temp. Range	-20° C to 80° C
Extended Temp. Version	-60° C to 80° C
Operating Voltage:	9 to 16 VDC
Over Voltage Protection:	24 VDC
Power Supply Current:	Active 3mA Avg./10mA Peak
Power Supply Current:	Sleep 150 µA
Electromagnetic & Transient Protection:	IEC-61000 - 4-3, 4-4, 4-5, 4-6

Contact factory for extended temperature ranges.

Information in this document is subject to change without notice.

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