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Environmental Impacts on the Performance of Pavement Foundation Layers-Phase I

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July 8, 2021

PROBLEM STATEMENT





PROBLEM STATEMENT

Freezing

Thaw Weakening



https://myferndalenews.com/frost-boils-reason-emergency-road-restrictions_55759/

https://porthawkesburyreporter.com/spring-weight-restrictions-partially-lift

SEASONAL LOAD RESTRICTION (SLR)

Avoid additional loads



Keep the damage minimum



Organize heavy vehicles/ keep the adverse effect minimum

Determining SLR:

□Subsurface Instrumentation

- In-situ Stiffness Testing



(Image: patch.com)

INSTRUMENTATION

Instrumented with an array of:

- □ Soil Moisture
- **Temperature**
- Weather Station to measure climate data
 - On site
 - □ Road Weather Information Systems (RWIS)
 - Environmental Sensing Stations
 - Modern Era Retrospective Analysis for Research and Applications (MERRA)

Overview of Research Plan

□ Task 1 – Initial Memorandum on Expected Research Benefits and Potential Implementation Steps

Task 2 – Field Data Collection

Task 3 – Modelling Analyses

Task 4 – Final Report

Objective of this Study:

(1) Clean and pre-process the soil & weather data

(2) Develop a data-driven model that uses weather data as input to:

- Predict the soil temperature and certain depths
- Predict the <u>number of freeze thaw cycles</u> at certain depths and <u>start/end time</u>, and duration of cycles over time

(3) Create a <u>tool</u> to provide soil temperature and number/duration of freeze-thaw cycles that implements the model

Literature review:

Few studies are done on the prediction of the soil temperatures :

Different methods implemented:

Inear regression model, non-linear regression model, neural networks

Majority of studies predict the soil temperatures at lower frequency, (e.g. monthly average)

Few on the daily soil temperature

Different sets of climate variables are used (not consistent across literature)

Literature review:

Other studies that predicted soil temperatures:

1. Predict daily average temperature using superposition of two models: predict monthly average temperature and daily average temperature amplitude using <u>air temperature, solar radiation, wind speed, relative humidity</u> <u>and day of year</u> [Xing et al., 2018]

2. Estimate daily soil surface temperature using <u>mean, maximum and minimum</u> <u>air temperature, relative humidity, sunshine hours and solar radiation</u> [Talaee et al., 2013]

3. Predict daily soil surface temperature using parameters like <u>average air</u> <u>temperature, total solar radiation, average relative humidity, average dew</u> <u>point temperature, average wind speed and total potential evapotranspiration</u> [Kim et al., 2014]

Objective of this Study:

(1) Clean and pre-process the soil & weather data

(2) Develop a data-driven model that uses weather data as input to:

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- Predict the <u>number of freeze thaw cycles</u> at certain depths and <u>start/end time</u>, and duration of cycles over time

(3) Create a <u>tool</u> to provide soil temperature and number/duration of freeze-thaw cycles that implements the model

(1) Input Data:

Dataset 1 (of 2):

<u>Temperature and moisture data</u> of 6 different locations are available within 2-mile span of roadway at Monticello, Minnesota

• Cell 185; Cell 186; Cell 188; Cell 189; Cell 127; Cell 728

Frequency: 15-minute time intervals Time period: August 2017 to December 2019

<u>Climate data</u>: air temperature, relative humidity, wind speed, net radiation, precipitation

(1) Input Data (Dataset 1):

Temperature data collected at 12 different depths for all stations

| Cell no. | Cell 185 | Cell 186 | Cell 188 | Cell 189 | Cell 127 | Cell 728 |
|----------|----------|----------|----------|----------|----------|----------|
| | T 1/2 | | Dep | oth (in) | | |
| TC_1 | 2.8 | 3 | 3 | 3 | 3 | 3 |
| TC_2 | 3.8 | 4 | 4 | 4 | 4 | 4 |
| TC_3 | 9.3 | 9.5 | 9.5 | 9.5 | 6.5 | 6.5 |
| TC_4 | 14.8 | 15 | 15 | 15 | 9 | 9 |
| TC_5 | 15.8 | 16 | 16 | 16 | 10 | 10 |
| TC_6 | 18.3 | 18.5 | 18.5 | 18.5 | 12 | 14 |
| TC_7 | 19.3 | 19.5 | 19.5 | 19.5 | 18 | 18.5 |
| TC_8 | 23.8 | 24 | 24 | 24 | 24 | 24 |
| TC_9 | 35.8 | 36 | 36 | 36 | 36 | 36 |
| TC_10 | 47.8 | 48 | 48 | 48 | 48 | 48 |
| TC_11 | 59.8 60 | | 60 | 60 | 60 | 60 |
| TC_12 | 71.8 | 72 | 72 | 72 | 72 | 72 |

Moisture data collected at 4 depths for all locations

| Cell no. | Cell 185 | Cell 186 | Cell 188 | Cell 189 | Cell 127 | Cell 728 |
|----------|----------|----------|----------|----------|----------|----------|
| | | | Dep | oth (in) | | |
| EC_1 | 5 | 5 | 5 | 5 | 6.5 | 8.5 |
| EC_2 | 14 | 14 | 14 | 14 | 29 | 19.5 |
| EC_3 | 17 | 17 | 17 | 17 | 36 | 24 |
| EC_4 | 20.5 | 20.5 | 20.5 | 20.5 | | 36 |

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(1) Input Data:

Dataset 2 (of 2):

<u>Temperature and moisture data</u> for 2 different counties in are Minnesota: Olmsted and Koochiching

Frequency: 1-hour time intervals Time period: 2005-2012, 2012-2019 (Koochiching); 2000-2007, 2010-2017 (Olmsted)

<u>Climate data (same as other dataset)</u>: air temperature, relative humidity, wind speed, net radiation, precipitation

(1) Input Data (Dataset 2):

Temperature/moisture sensor locations for the two-time spans

| Dataset location | Time span | Depth of temperature sensors |
|------------------|--------------|---|
| | 2005 to 2010 | 10; 40; 70; 90; 120; 180; 240; 300; 360; 420; 480; 540; 600; 720; 840; 960 |
| Koochiching | 2012 to 2019 | 10; 30; 50; 80; 120; 150; 180; 210; 240; 300; 360; 420; 480; 540; 600; 640; 780; 910 |
| | 2000 to 2007 | 25; 60; 90; 120; 180; 240; 300; 360; 420; 480; 600; 720; 840; 960; 1080 |
| Olmsted | 2010 to 2017 | 10; 25; 50; 70; 130; 190; 250; 310; 370; 430; 490; 550; 610; 730; 850; 970 |

| Dataset location | Time span | Depth of moisture sensors |
|------------------|--------------|---|
| Kaaabiahing | 2005 to 2010 | N/A |
| Koochiching | 2012 to 2019 | 80, 120, 150, 180, 210, 240, 300, 360, 420, 480, 540, 600, 780, 910 |
| Olmstad | 2000 to 2007 | 60, 90, 120, 180, 240, 300, 360, 420, 480, 600, 720, 840, 960, 1080 |
| Omisted | 2010 to 2017 | 70, 130, 190, 250, 310, 370, 430, 490, 550, 610, 730, 850, 970 |

(1) Input Data: preprocessing

Dataset 1: Percent (%) missing temperature data

| | TC1 | TC2 | TC3 | TC4 | TC5 | TC6 | TC7 | TC8 | TC9 | TC10 | TC11 | TC12 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| Cell 185 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 12 | 2 | 87 | 2 |
| Cell 186 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | 11 | < 1 | < 1 | < 1 |
| Cell 188 | < 1 | < 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cell 189 | < 1 | < 1 | 0 | 0 | 0 | 0 | 0 | 0 | NA | 0 | 0 | 0 |
| Cell 127 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 |
| Cell 728 | < 1 | < 1 | < 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Outliers: identified and removed from the dataset Missing Data:

- Number of missing elements were very small (other than TC9 and TC11 in Dataset 1)
- Data imputation was used to fill in missing elements as appropriate
- Dataset 2 had very little missing data

(1) Input data: Freeze-thaw cycle calculations

Justification: Number of freeze-thaw cycles significantly impacts the soil properties

Number of freeze thaw cycles depends on:

- Freezing temperature
- <u>Thaw temperature (can be different from freezing temperature)</u>
- <u>Time</u> the soil temperature is lower than the freezing and higher than the thaw temperature

(1) Input data: Freeze-thaw cycle calculation

To undergo a complete freeze-thaw cycle, soil temperature needs to be higher than <u>thaw temperature</u> and then it needs to be lower than <u>freezing temperature</u>.



Thaw temperature is 0°C

9 different <u>freezing temperatures</u> are considered: Ranging from -0.001 °C, to -1 °C

(1) Input data: Freeze-thaw cycle calculation

The variation in number of cycles at different depth are shown below (Cell 185, Dataset 1, for 2018 (1 year, Jan-Dec), similar data in other locations)



- increase freezing temperature, number of cycles reduces significantly
- If assume larger freezing temperatures, # of cycles reduces with depth (makes sense); if assume smaller at deeper depths it increases significantly (doesn't make sense)

(1) Input data: Freeze-thaw cycle calculations

"Time delay" is defined as a minimum period of time required for a half of a freeze-thaw cycle to be completed in order for it to count as a F-T cycle



more than time delay span (1 hour here); considered as complete freezing

(1) Input Data: Freeze-thaw cycle calculations

4 different <u>time delays</u> considered: 1-hour, 4-hour, 12-hour and 24-hour

The variation in number of cycles at different depth are shown below (Cell 185, **Dataset 1**, for 2018 (1 year, Jan-Dec))



Increasing the time delay reduces the number of cycles calculated at shallower depths

(1) Input Data: Freeze-thaw cycle calculations

Final Method chosen:

Based on the updated MnDot method, the following is used to evaluate the number of freeze-thaw cycles

- Freezing temperature is -1°C
- Thaw temperature is 0°C
- Time delay to ensure freezing is 24 hours
- Time delay to ensure thaw is 5 hours

(1) Input Data: Summary

2 input datasets of weather/soil data used as input

Quality controlled and pre-processed

Freeze-thaw calculation method chosen

- Based on the updated MnDot method:
 - Freezing temperature is -1°C
 - Thaw temperature is 0°C
 - Time delay to ensure freezing is 24 hours
 - Time delay to ensure thaw is 5 hours

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(2) Model Development

1. Stepwise regression is used to choose variables

- Independent (low correlation)
- Most influential
- 2. Data is divided in training and testing datasets
- 3. Different models considered to predict soil temperatures
- 4. Performance of models are compared with measured data

(2) Data Processing: Model input variables

The variables are analyzed, and 2 types of variables are created:

- 1. Time variables (this slide)
- 2. Climate variables (next slide)

Four time variables were considered

- 1. Month number (1 to 12)
- 2. Week number (1 to 52)
- 3. Day of year (1 to 365)
- 4. Timestep (1 to 4*24 for 15-minute timestep data)

(2) Data Processing: Model input variables

Air temperature (AirTemp) Relative humidity (RH) Rain or precipitation (Rain) Windspeed (Wind) Radiation (rad) Daily average:

air temperature (avgTemp) relative humidity (avgRH) precipitation (avgRain) wind speed (avgWind) solar radiation (avgrad) Variation in WRT daily average: air temperature (varTemp) relative humidity (varRH) precipitation (varRain) windspeed (varWind) solar radiation (varRad)

(2) Model Development: Stepwise regression

model (influential & independent variables)

| | Week | Month | Danaf | d | ure | | | | | | | | | | | | | | |
|-----------|-------|-------|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|------|-------|-------|-------|-------|-----|
| Week | 1 | wonth | Day of Vear | ste | rat | | | | | ure | | | | | | | | | |
| Month | 1 | 1 | Teur | ime | ədu | in | | | | rat | 1 | | | | | | | | |
| DayofYear | 1 | 1 | 1 | 7 | Ten | Ro | RH | pu | ion | ədu | 2. | | | | 0 | | | | |
| Timestep | 0 | 0 | 0 | 1 | Air | | | Ň | liat | Ter | Ra | RH | pu | ion | tur | | | | |
| AirTemp | 0.22 | 0.21 | 0.22 | 0.11 | 1 | | | | Rac | Air | tion | ion | Ň | liat | era | | | | |
| Rain | 0.02 | 0.02 | 0.02 | 0.01 | 0.04 | 1 | - | | | ion | aria | riat | tion | Rac | du | ain | - | | 5 |
| RH | 0.22 | 0.22 | 0.22 | -0.25 | -0.24 | 0.09 | 1 | | | iati | S S | Vai | riat | uo | r Te | e R | R | 'ind | tio |
| Wind | -0.09 | -0.09 | -0.09 | 0.04 | -0.11 | 0.01 | -0.23 | 1 | | Var | | | Va | iati | Ai | rag | age | N a | dia |
| rad | 0 | 0 | 0 | 0.04 | 0.46 | -0.03 | -0.5 | 0.18 | 1 | | | | | Var | age | Ave | ver | ag | Ra |
| varTemp | 0 | 0 | 0 | 0.4 | 0.27 | -0.01 | -0.55 | 0.26 | 0.5 | 1 | | | | | ver | | 4 | lvei | age |
| varRain | 0 | 0 | 0 | 0.01 | 0 | 0.96 | 0.03 | 0.02 | -0.02 | -0.01 | 1 | | | | 4 | | | 4 | ver |
| varRH | 0 | 0 | 0 | -0.36 | -0.21 | 0.04 | 0.71 | -0.27 | -0.51 | -0.78 | 0.04 | 1 | | | | | | | A |
| varWind | 0 | 0 | 0 | 0.05 | 0.1 | 0.02 | -0.27 | 0.71 | 0.35 | 0.37 | 0.02 | -0.38 | 1 | | | | | | |
| varRad | 0 | 0 | 0 | 0.04 | 0.15 | -0.02 | -0.4 | 0.28 | 0.91 | 0.55 | -0.02 | -0.56 | 0.39 | 1 | | | | | |
| avgTemp | 0.22 | 0.22 | 0.22 | 0 | 0.96 | 0.04 | -0.09 | -0.18 | 0.34 | 0 | 0 | 0 | 0 | 0 | 1 | | | | |
| avgRain | 0.09 | 0.09 | 0.09 | 0 | 0.15 | 0.26 | 0.24 | 0 | -0.04 | 0 | 0 | 0 | 0 | 0 | 0.16 | 1 | | | |
| avgRH | 0.31 | 0.31 | 0.31 | 0 | -0.13 | 0.09 | 0.71 | -0.06 | -0.2 | 0 | 0 | 0 | 0 | 0 | -0.13 | 0.34 | 1 | | |
| avgWind | -0.12 | -0.12 | -0.12 | 0 | -0.25 | 0 | -0.06 | 0.71 | -0.11 | 0 | 0 | 0 | 0 | 0 | -0.26 | 0 | -0.08 | 1 | |
| avgrad | -0.01 | -0.01 | -0.01 | 0 | 0.77 | -0.02 | -0.33 | -0.18 | 0.42 | 0 | 0 | 0 | 0 | 0 | 0.8 | -0.09 | -0.46 | -0.25 | 1 |

<u>No color:</u>

- | correlation coefficient | < 0.3
- <u>Green</u>:

Yellow:

- 0.3 < |correlation coefficient| < 0.7;
- correlation coefficient | > 0.7 (High correlations)

(2) Model Development: Stepwise regression model (influential & independent variables)

High correlation (> 0.7)

Time variables:

(Week - Month); (Week - Day of Year);

Climate variables:

(Rain – variation Rain); (RH – variation RH); (Wind – variation Wind);
(Radiation – variation Radiation); (variation RH – variation Temp);
(Air Temperature – Average Air Temperature);
(Air Temperature – average Radiation);
(average Air Temperature – average Radiation)

Remaining variables used for this study:

1. Day of Year; 2. Time step;

3. Air temperature, 4. Radiation, 5. Variation in air temperature,

6. Variation in rain, 7. Variation in RH, 8. Variation in wind

(2) Model Development: Data Division

Dataset 1:

Dates available: January 2018 to April 2019

Data division:

Training data: all of 2018, which (~75% of data) Testing data: 2019, January to April

Dataset 2:

Dates available: January 2000 to February 2007

Data division:

Training data: 2005 to Feb 2005, which (~79% of data) Testing data: Sept 2005 to Feb 2007

(2) Model Selection

Various models were considered to predict soil temperature (time series data)

- Vector Auto Regression
- Vector Auto Regression Moving Average
- Vector Error Correction Models



However, these models were unable to predict the soil temperature trends at this data frequency

(2) Model Selection

- Thus, non-linear regression model is used in this study
- 4th order polynomial model is utilized
- Two different methods were considered:

Model 1: Individual depths

Predict the soil temperatures at each depth using climate parameters

Model 2: Individual depths: Daily average + variation WRT daily predict daily average soil temperature at each dept + timestep-based variation with respect to the daily average temperature

(2) Model Selection: Temperature prediction



- Both the models can generally predict the temperature
- Models have a few spikes in predictions

(2) Model Selection: Improvements

To reduce the spikes in temperature prediction, two different filters are developed.

Filter 1: Limit the variation in each timestep to a reasonable value

Filter 2: Remove the predicted temperatures which were significantly higher or lower than the temperature bound

(2) Model Selection : Filter 1

Based on the values obtained from all locations, following ranges are selected considering 99% of data selection:

| Depth | Acceptable Variation Range |
|------------------------|----------------------------|
| 3 inch to 9 inch | From -1 to 1 |
| 9-inch | From -0.5 to 0.5 |
| More than 9-inch depth | From -0.25 to 0.25 |

If the change is out bound, then maximum effective range is selected as the change in temperature from the previous



(2) Model Selection : Filter 2

Remove the outliers in predicted value if the temperature is outside the bounds of the max/min soil temperatures at each depth

If the predicted value is out of bounds, then previous predicted value is used

| Temperature (°C) | 9 inch | 15 inch | 16 inch | 19.5 inch | 24 inch | 48 inch | 72 inch |
|------------------|--------|---------|---------|-----------|---------|---------|---------|
| Maximum value | 42 | 40 | 38 | 34 | 32 | 28 | 26 |
| Minimum value | -24 | -22 | -22 | -14 | -10 | -4 | 0 |

(2) Model Selection : Model comparison



RMSE values for testing dataset at 18.5-inch depth



Model 2 has slightly better performance in predicting <u>temperature</u>; filters help improve model performance

RMSE values for testing dataset at 24-inch depth

(2) Model Results : Freeze-thaw cycle count



<u>Model 1 (with filters) has better accuracy</u> in prediction of # of freeze-thaw cycles compared to Model 2

(2) Model Results: Freeze-thaw duration

| | | | Cell 185 | | 7 7 | |
|------------|--------------|-----------|--------------|---------------|----------|--------------|
| Dopths | Mathad | Number of | Frozen start | Frozen end | Frozen | Total Frozen |
| Deptils | Wiethou | cycles | day | day | duration | duration |
| | Actual value | 1 | Jan-02 | Mar-08 | 65 | 65 |
| 0 E inch | | | Jan-02 | Jan-07 | 5 | |
| 9.5 1101 | Method 1 | 3 | Jan-09 | Feb-23 | 45 | 60 |
| | | | Feb-26 | Mar-08 | 10 | |
| 14 Qinch | Actual value | 1 | Jan-02 | Mar-15 | 72 | 72 |
| 14.8 Inch | Method 1 | 1 | Jan-02 | Mar-09 | 66 | 66 |
| 15 Qinch | Actual value | 1 | Jan-03 | Mar-16 | 72 | 72 |
| 15.8 Inch | Method 1 | 1 | Jan-02 | Mar-09 | 66 | 66 |
| 10.2 inch | Actual value | 1 | Jan-19 | Mar-18 | 58 | 58 |
| 18.3 Inch | Method 1 | 1 | Jan-02 | Mar-03 | 60 | 60 |
| | Actual value | 1 | Jan-20 | Mar-18 | 57 | 57 |
| 19.3 inch | Mathad 1 | 2 | Jan-02 | Jan-07 | 5 | F.7 |
| | Method 1 | Z | Jan-10 | Jan-10 Mar-03 | | 57 |
| | Actual value | 1 | Jan-22 | Mar-20 | 57 | 57 |
| 23.8 inch | Mathad 1 | 2 | Jan-02 | Jan-07 | 5 | F.7 |
| | Method 1 | Z | Jan-10 | Mar-03 | 52 | 57 |
| 17.0 in ch | Actual value | 0 | - | - | - | - |
| 47.8 mch | Method 1 | 0 | - | - | - | - |
| 71.0 : | Actual value | 0 | _ | _ | _ | - |
| 71.8 Inch | Method 1 | 0 | - | - | - | - |

Method 1 best predicts the freezing start/end day and duration

(2) Model Results: Freeze-thaw duration

| Cell | Freezin | g period | Thawing period | | | | | |
|----------|----------------|----------------|-----------------|----------------|--|--|--|--|
| location | Actual value | Predicted | Actual value | Predicted | | | | |
| Cell 185 | Jan 2 – Mar 8 | Jan 2 – Mar 3 | Mar 8 – Mar 20 | Mar 3- Mar 9 | | | | |
| Cell 186 | Jan 2 – Mar 9 | Jan 2 – Mar 8 | Mar 9 – Mar 25 | Mar 8- Mar 9 | | | | |
| Cell 188 | Jan 2 – Mar 8 | Jan 2 – Mar 2 | Mar 8 – Mar 29 | Mar 2- Mar 9 | | | | |
| Cell 189 | Jan 2 – Mar 9 | Jan 2 – Feb 14 | Mar 9 – Apr 1 | Feb 14- Mar 9 | | | | |
| Cell 127 | Jan 2 – Mar 8 | Jan 2 – Mar 10 | Mar 8 – Mar 23 | Mar 8- Mar 15 | | | | |
| Cell 728 | Jan 2 – Mar 15 | Jan 2 – Mar 10 | Mar 15 – Mar 23 | Mar 10- Mar 15 | | | | |

(2) Model Development: Summary

2 different models using non-linear regression models
 Model 1: Individual depth
 Model 2: Individual depth: Daily average + variation WRT daily
 2 filters used to improve model performance

Choose best model to predict :

- Soil temperatures: Model 1 w/ filters
- Number of freeze-thaw cycles: Model 2 w/filters
- Start/end and duration of freezing & thawing period: both but Model 1 w/filters is better

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(3) Create a <u>tool</u> to provide soil temperature and number/duration of freeze-thaw cycles that implements the model

(3) Tool Development : Description (Directions/Cover Page)

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(3) Tool Development: Description (Calculations)

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| 1 | DateTim | e 4 | Air Temperature (degree C |) Rain (mm) | Relative humidity (%) | Wind speed (m/s) | olar Radiation (W/n | 12 Depth (mm) | | | | | | | |
| 2 | 01/01/18 00 | :00 | -15.43 | 0.00 | 63.64 | 4.03 | -49.14 | 75.00 | | | | | | | |
| 3 | 01/01/18 00 | :15 | -15.66 | 0.00 | 63.37 | 4.39 | -50.10 | | | | | | | | |
| 4 | 01/01/18 00 | :30 | -15.83 | 0.00 | 63.71 | 4.08 | -44.86 | | | | | | | | |
| 5 | 01/01/18 00 | :45 | -15.99 | 0.00 | 64.50 | 3.04 | -40.91 | | | | | | | | |
| 6 | 01/01/18 01 | :00 | -16.13 | 0.00 | 63.99 | 3.33 | -40.27 | | | | | | | | |
| 7 | 01/01/18 01 | :15 | -16.3 | 0.00 | 64.93 | 2.59 | -40.96 | | | Tompon | .tuno | | | | |
| 8 | 01/01/18 01 | :30 | -16.49 | 0.00 | 65.29 | 2.58 | -43.22 | | | rempera | ature | Numbe | er of Freeze-Th | aw cycles | |
| 9 | 01/01/18 01 | :45 | -16.75 | 0.00 | 65.78 | 2.26 | -47.49 | | | predict | tion | | | | |
| 10 | 01/01/18 02 | :00 | -16.99 | 0.00 | 65.66 | 2.43 | -42.77 | | | | | | | | |
| 11 | 01/01/18 02 | :15 | -17.12 | 0.00 | 66.07 | 2.02 | -41.24 | | | | | | | | |
| 12 | 01/01/18 02 | :30 | -17.31 | 0.00 | 66.97 | 1.68 | -37.47 | | | | | | | | |
| 13 | 01/01/18 02 | :45 | -17.65 | 0.00 | 68.51 | 2.76 | -38.50 | | | Pr | edict s | oil temperatu | re and | | |
| 14 | 01/01/18 03 | :00 | -17.95 | 0.00 | 68.79 | 2.78 | -43.44 | | | | Nu | mbor of evelo | | | |
| 15 | 01/01/18 03 | :15 | -18.21 | 0.00 | 69.25 | 2.72 | -48.97 | | | | INU | mber of cycles | • | | |
| 16 | 01/01/18 03 | :30 | -18.47 | 0.00 | 69.58 | 3.07 | -50.93 | | | | | | | | |
| 17 | 01/01/18 03 | :45 | -18.72 | 0.00 | 70.31 | 2.42 | -49.94 | | | | | | | | |
| 18 | 01/01/18 04 | :00 | -19 | 0.00 | 70.37 | 2.24 | -48.10 | | | | | | | | |
| 19 | 01/01/18 04 | :15 | -19.26 | 0.00 | /0.// | 1.99 | -47.90 | | | | | | | | |
| 20 | 01/01/18 04 | :30 | -19.54 | 0.00 | 70.84 | 2.28 | -47.29 | | | | | | | | |
| | 01/01/18 04 | :45 | -19.85 | 0.00 | /1.1/ | 2.13 | -47.15 | | | | | | | | |
| -22 | 01/01/18 05 | :00 | -20.08 | 0.00 | 72.02 | 2.36 | -46.11 | | | | | | | | |
| 23 | 01/01/18 05 | :15 | -20.31 | 0.00 | /2.15 | 2.23 | -45.46 | | | | | | | | |
| 24 | 01/01/18 05 | :30 | -20.57 | 0.00 | 72.38 | 1.88 | -44.38 | | | | | | | | |
| 25 | 01/01/18 05 | :45 | -20.89 | 0.00 | 73.29 | 1.72 | -42.72 | | | | | | | | |
| 26 | 01/01/18 06 | :00 | -21.06 | 0.00 | 73.13 | 1.49 | -42.32 | | | | | | | | |
| 27 | 01/01/18 06 | :15 | -21.24 | 0.00 | 73.23 | 2.05 | -42.01 | | | | | | | | |
| 28 | 01/01/18 06 | :30 | -21.46 | 0.00 | 73.50 | 2.01 | -41.92 | | | | | | | | |
| 29 | 01/01/18 06 | :45 | -21.8 | 0.00 | 73.85 | 2.24 | -42.91 | | | | | | | | |
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(3) Tool Development: Description (Inputs)

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| 1 | DateTime | | Air Temperature (d | legree C) | Rain (| mm) | Relative l | numidity (%) | Wi | nd speed (m/s) | Sola | r Radiation (| W/m2) |
| 2 | 01/01/18 00:00 |) | -15.43 | | 0.0 | 0 | 6 | 3.64 | | 4.03 | | -49.14 | |
| 3 | 01/01/18 00:15 | 5 | -15.66 | | 0.0 | 0 | 6 | 3.37 | | 4.39 | | -50.10 | |
| 4 | 01/01/18 00:30 | D I | -15.83 | | 0.0 | 0 | 6 | 3.71 | | 4.08 | | -44.86 | |
| 5 | 01/01/18 00:45 | 5 | -15.99 | | 0.0 | 0 | 6 | 4.50 | | 3.04 | | -40.91 | |
| 6 | 01/01/18 01:00 | D | -16.13 | | 0.0 | 0 | 6 | 3.99 | | 3.33 | | -40.27 | |
| 7 | 01/01/18 01:15 | 5 | -16.3 | | 0.0 | 0 | 6 | 4.93 | | 2.59 | | -40.96 | |
| 8 | 01/01/18 01:30 |) / | -16.49 | | 0.0 | 0 | 6 | 5.29 | | 2.58 | | -43.22 | |
| | | | | | | | | | | | | | |

Column A: <u>date and time of day</u> in "mm/dd/yy hh:mm" with a timestep of <u>15 minutes</u>

(3) Tool Development: Description (Inputs)

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| | А | | В | | с | D | | E | F | |
| 1 | DateTime | Air | Temperature (de | gree C) | Rain (mm) | Relative humidity (%) | Wi | nd speed (m/s) | Solar Radiation (W/m2) | |
| 2 | 01/01/18 00:00 | | -15.43 | | 0.00 | 63.64 | | 4.03 | -49.14 | |
| 3 | 01/01/18 00:15 | | -15.66 | | 0.00 | 63.37 | | 4.39 | -50.10 | |
| 4 | 01/01/18 00:30 | | -15.83 | | 0.00 | 63.71 | | 4.08 | -44.86 | |
| 5 | 01/01/18 00:45 | | -15.99 | | 0.00 | 64.50 | | 3.04 | -40.91 | |
| 6 | 01/01/18 01:00 | | -16.13 | | 0.00 | 63.99 | | 3.33 | -40.27 | |
| 7 | 01/01/18 01:15 | | -16.3 | | 0.00 | 64.93 | | 2.59 | -40.96 | |
| 8 | 01/01/18 01:30 | | -16.49 | | 0.00 | 65.29 | | 2.58 | -43.22 | |
| | | | | | | | | | | |

Column B: *Outside air temperature* in ^oC

(3) Tool Development: Description (Inputs)

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| L1 | 1 \bullet : \times \checkmark f_{\star} Number of cycles | | | | | | | | | | |
| | А | В | } | С | | D | | E | | F | |
| 1 | DateTime | Air Temperatu | ıre (degree C) | Rain (mr | m) Relative | humidity (%) | Win | nd speed (m/s) | Solar | Radiation (V | V/m2) |
| 2 | 01/01/18 00:00 | -15 | .43 | 0.00 | | 63.64 | | 4.03 | | -49.14 | |
| 3 | 01/01/18 00:15 | -15 | .66 | 0.00 | | 63.37 | | 4.39 | | -50.10 | |
| 4 | 01/01/18 00:30 | -15 | .83 | 0.00 | | 63.71 | | 4.08 | | -44.86 | |
| 5 | 01/01/18 00:45 | -15 | .99 | 0.00 | | 64.50 | | 3.04 | | -40.91 | |
| 6 | 01/01/18 01:00 | -16 | .13 | 0.00 | | 63.99 | | 3.33 | | -40.27 | |
| 7 01/01/18 01:15 | | -16.3 | | 0.00 | | 64.93 | 2.59 | | -40.96 | | |
| 8 | 01/01/18 01:30 | -16 | .49 | 0.00 | | 65.29 | | 2.58 | | -43.22 | |
| | | | | | | | | | | | |

Column C: Total *rainfall* in mm

(3) Tool Development: Description (Inputs)

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| L1 | 1 • : $\times \checkmark f_{*}$ Number of cycles | | | | | | | | | | | |
| | А | В | | С | | D | | E | | | F | |
| 1 | DateTime | Air Temperatu | re (degree C) | Rain (m | m) Relative | humidity (%) | Wi | nd speed (m/ | /s) | Solar | Radiation (V | V/m2) |
| 2 | 01/01/18 00:00 | -15. | 43 | 0.00 | | 63.64 | | 4.03 | | | -49.14 | |
| 3 | 01/01/18 00:15 | -15. | 66 | 0.00 | | 63.37 | | 4.39 | | | -50.10 | |
| 4 | 01/01/18 00:30 | -15. | 83 | 0.00 | | 63.71 | | 4.08 | | | -44.86 | |
| 5 | 01/01/18 00:45 | -15. | 99 | 0.00 | | 64.50 | | 3.04 | | | -40.91 | |
| 6 | 01/01/18 01:00 | -16. | 13 | 0.00 | | 63.99 | | 3.33 | | | -40.27 | |
| 7 | 01/01/18 01:15 | -16 | .3 | 0.00 | | 64.93 | | 2.59 | | | -40.96 | |
| 8 | 01/01/18 01:30 | -16. | 49 | 0.00 | | 65.29 | | 2.58 | | | -43.22 | |
| | | | | | | | | | | | | |

Column D: Relative humidity values in %

(3) Tool Development: Description (Inputs)

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| L1 | 1 • : $\times \checkmark f_{*}$ Number of cycles | | | | | | | | | |
| | А | В | | С | D | | E | F | | |
| 1 | DateTime | Air Temperatu | re (degree C) | Rain (mm) | Relative humidity (% |) Wi | nd speed (m/s) | Solar Radiation (W/m2) | | |
| 2 | 01/01/18 00:00 | -15. | 43 | 0.00 | 63.64 | | 4.03 | -49.14 | | |
| 3 | 01/01/18 00:15 | -15. | 66 | 0.00 | 63.37 | | 4.39 | -50.10 | | |
| 4 | 01/01/18 00:30 | -15. | 83 | 0.00 | 63.71 | | 4.08 | -44.86 | | |
| 5 | 01/01/18 00:45 | -15. | 99 | 0.00 | 64.50 | | 3.04 | -40.91 | | |
| 6 | 01/01/18 01:00 | -16. | 13 | 0.00 | 63.99 | | 3.33 | -40.27 | | |
| 7 | 01/01/18 01:15 | -16 | .3 | 0.00 | 64.93 | | 2.59 | -40.96 | | |
| 8 | 01/01/18 01:30 | -16. | .49 | 0.00 | 65.29 | | 2.58 | -43.22 | | |
| | | | | | | | | | | |



(3) Tool Development: Description (Inputs)

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| | Α | В | | С | D | E | | F |
| | | | | | | | | |
| 1 | DateTime | Air Temperature | e (degree C) | Rain (mm) | Relative humidity (%) | Wind spe | ed (m/s) Sol | ar Radiation (W/m2) |
| 1 2 | DateTime 01/01/18 00:00 | Air Temperature -15.43 | e (degree C) 3 | Rain (mm) 0.00 | Relative humidity (%) 63.64 | Wind spe 4.0 | ed (m/s) Sol | ar Radiation (W/m2) -49.14 |
| 1 2 3 | DateTime 01/01/18 00:00 01/01/18 00:15 | Air Temperature -15.4 -15.6 | e (degree C) 3 6 | Rain (mm) 0.00 0.00 | Relative humidity (%) 63.64 63.37 | Wind spe 4.0 4.3 | ed (m/s) Sol 33 59 | ar Radiation (W/m2) -49.14 -50.10 |
| 1 2 3 4 | DateTime 01/01/18 00:00 01/01/18 00:15 01/01/18 00:30 | Air Temperatur -15.43 -15.60 -15.83 | e (degree C) 3 6 3 | Rain (mm) 0.00 0.00 0.00 | Relative humidity (%) 63.64 63.37 63.71 | Wind spe 4.0 4.3 4.0 | ed (m/s) Sol 13 19 18 | ar Radiation (W/m2) -49.14 -50.10 -44.86 |
| 1 2 3 4 5 | DateTime 01/01/18 00:00 01/01/18 00:15 01/01/18 00:30 01/01/18 00:45 | Air Temperatur -15.4 -15.6 -15.8 -15.9 | e (degree C) 3 6 3 9 | Rain (mm) 0.00 0.00 0.00 0.00 | Relative humidity (%) 63.64 63.37 63.71 64.50 | Wind spe 4.0 4.3 4.0 3.0 | ed (m/s) Sol 33 39 08 04 | ar Radiation (W/m2) -49.14 -50.10 -44.86 -40.91 |
| 1 2 3 4 5 6 | DateTime 01/01/18 00:00 01/01/18 00:15 01/01/18 00:30 01/01/18 00:45 01/01/18 01:00 | Air Temperatury -15.4 -15.6 -15.8 -15.9 -15.9 -16.1 | e (degree C) 3 6 3 9 3 | Rain (mm) 0.00 0.00 0.00 0.00 0.00 0.00 | Relative humidity (%) 63.64 63.37 63.71 64.50 63.99 | Wind spe 4.0 4.3 4.0 3.0 3.3 | ed (m/s) Sol 33 39 38 38 34 33 | ar Radiation (W/m2) -49.14 -50.10 -44.86 -40.91 -40.27 |
| 1 2 3 4 5 6 7 | DateTime 01/01/18 00:00 01/01/18 00:15 01/01/18 00:30 01/01/18 00:45 01/01/18 01:00 01/01/18 01:15 | Air Temperatury -15.43 -15.60 -15.83 -15.99 -16.13 -16.3 | e (degree C) 3 6 3 9 3 | Rain (mm) 0.00 0.00 0.00 0.00 0.00 0.00 | Relative humidity (%) 63.64 63.37 63.71 64.50 63.99 64.93 | Wind spe 4.0 4.3 4.0 3.0 3.3 2.5 | ed (m/s) Sol 33 39 08 04 33 39 | ar Radiation (W/m2) -49.14 -50.10 -44.86 -40.91 -40.27 -40.96 |
| 1 2 3 4 5 6 7 8 | DateTime 01/01/18 00:00 01/01/18 00:15 01/01/18 00:30 01/01/18 00:45 01/01/18 01:00 01/01/18 01:15 01/01/18 01:30 | Air Temperatury -15.43 -15.60 -15.83 -15.99 -16.13 -16.33 -16.49 | e (degree C) 3 6 3 9 3 3 9 9 | Rain (mm) 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 | Relative humidity (%) 63.64 63.37 63.71 64.50 63.99 64.93 65.29 | Wind spe 4.0 4.3 4.0 3.0 3.3 2.5 2.5 | ed (m/s) Sol 33 39 38 34 33 39 38 | ar Radiation (W/m2) -49.14 -50.10 -44.86 -40.91 -40.27 -40.96 -43.22 |



(3) Tool Development: Description (Inputs)

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| | D | | E | | F | | G | |
| Relativ | e humidity (%) | Wi | ind speed (m/s) | Sola | ar Radiation (W/m2 |) Dep | oth (mm) | |
| | 63.64 | | 4.03 | | -49.14 | | 75.00 | - |
| | 63.37 | | 4.39 | | -50.10 | | | |
| | 63.71 | | 4.08 | | -44.86 | | | |
| | | | | | | - | | |

Column G: <u>soil depth</u> in **mm** for which temperature needs to be estimated.

There is a drop down button for the user can select specific depths.

(3) Tool Development : Description (Running the Calculations)

The tool has three buttons :

1. Temperature prediction

Temperature prediction

- Number of freeze thaw cycles (and start time/duration)
- Predict soil temperature and number of cycles (Note this does the calculations of both (1) and (2) together

Number of Freeze-Thaw cycles

Predict soil temperature and Number of cycles

(3) Tool Development : Description (Running the Calculations)

Temperature prediction

Number of Freeze-Thaw cycles Predict soil temperature and Number of cycles

1. Temperature prediction

Based on the given climate input and soil depth, predicts <u>soil</u> <u>temperature</u> at each timestep.

| | | | [| | | |
|------------------------|------------|----|---|----------|---------------|----|
| F | G | AF | | AG | AH | AI |
| Solar Radiation (W/m2) | Depth (mm) | | | Temperat | ure predictio | n |
| -49.14 | 75.00 | | | -11.2023 | | |
| -50.10 | | | | -11.0578 | | |
| -44.86 | | | | -11.0963 | | |
| -40.91 | | | | -11.4808 | | |
| -40.27 | | | | -11.4674 | | |
| | | | | | | |
| -40.27 | | | | -11.4674 | | |

(3) Tool Development: Description (Running the Calculations)

Temperature prediction

Number of Freeze-Thaw cycles Predict soil temperature and Number of cycles

2. Number of freeze thaw cycles

Based on the predicted temperature (and climate data) it calculates the following at the specified depth:

- 1. number of freeze-thaw cycles
- 2. Starting time of freeze and thaw
- 3. duration of freeze-thaw cycles

| ∜ L | М | N | 0 |
|------------------|---------------------|-----------------|-------------------|
| Number of cycles | Freezing start time | Thaw start time | Duration of cycle |
| 5 | 1/2/2018 | 1/7/2018 | 6 |
| | 1/8/2018 | 2/22/2018 | 45 |
| | 2/25/2018 | 2/28/2018 | 3 |
| | 3/3/2018 | 3/6/2018 | 3 |
| | 5/5/2010 | 5/0/2010 | |

(3) Tool Development: Description (Running the Calculations)

Temperature prediction

Number of Freeze-Thaw cycles Predict soil temperature and Number of cycles

3. Predict soil temperature and number of cycles

Completes calculation of both (1) and (2) together, i.e. <u>soil</u> <u>temperatures</u> and <u>number and duration of freeze-thaw cycles</u>

| G | н | 1 | J | К | L | М | N | 0 |
|------------|---|----------|----------|---|------------------|---------------------|-----------------|-------------------|
| Depth (mm) | | Temperat | Duration | | Number of cycles | Freezing start time | Thaw start time | Duration of cycle |
| 75.00 | | -11.2023 | | | 1 | 1/2/2018 | 1/7/2018 | 6 |
| | | -11.0578 | | | | | | |

(3) Tool Development: Checks before running

Once user presses any of the buttons, the tool will first check whether all the inputs are valid, i.e.

- Are all input values numerical (non-text)
- Are all values for each column a reasonable value

If <u>not</u>, the tool will generate a message showing that some of the variables/data are not valid and the result generated may not be correct.



(3) Tool Development: Checks before running

After that, the tool checks with the user to ask if it is ok to run the program.

Depending on the during of the data input, the tool requires some time to calculate and provide results to the user. The tool will then ask if this is ok with the user.

The user can select 'Yes', which results in the code running; or 'No' in which case the program will terminate.



(3) Tool Development: Summary

The tool has been developed in Excel to predict for a user-specified depth:

- 1. Soil temperature
- 2. Number of freeze-thaw cycles
- 3. Starting time of freezing and thawing
- 4. Duration of the cycles

Debugging checks have also been implemented in the tool to provide the user some information about the input data and possible errors.

Questions?

Principal Investigator: Bora Cetin, Ph.D.
Co-Principal Investigator: Kristen Cetin, Ph.D., Tuncer Edil, Ph.D.,
Research Team: Debrudra Mitra

Department of Civil and Environmental Engineering Michigan State University