CALCULATION OF FREEZE-THAW CYCLES: Follow up from TAP discussion

The occurrence of freeze-thaw cycles significantly impacts the performance of pavement systems over time. However, there is no widely accepted method to calculate the number of freeze-thaw cycles from soil temperature data. Freeze-thaw cycles consist of two components, including a freezing component and a thawing component. To ensure complete freezing, the soil temperature needs to be lower than the *freezing point temperature*, and after it must be higher than *thaw temperature* to ensure the soil is completely thawed. Thus, the number of freeze-thaw cycles depends on several factors, including the freezing point and thaw temperature and the *time duration* of each portion of the cycle, to ensure complete freezing/thawing.

As discussed in previous reports, three different methods were considered to calculate the number of freeze-thaw cycles, including a method using a *fixed freezing temperature*, *modified reference temperature* and a *time delay*. In addition to these methods, based on feedback by MnDOT during our recent TAP meeting, one additional method was also considered. In this methods, similar the *time delay* method, a minimum time was required to occur for both the freezing and thawing period, in order for a freeze-thaw cycle to be considered to have occurred. These time requirements include 24 hours below the *freezing point temperature,* 5 hours above the *thaw temperature*. This is consistent with what MnDOT uses for their calculation of freeze-thaw cycles. For this method, 0 °C is used as both the freezing point temperature and thaw temperature. However, as discussed in previous reports and during the recent TAP meeting, we are aware that the temperature sensor used in the data collection has an error of +/- 1°C. As such, we proposed to use a slightly modified version of MnDOT's method, where, instead of 0 °C, -1°C is used as the freezing point temperature. The variation between these two methods is shown schematically in Figure 1.
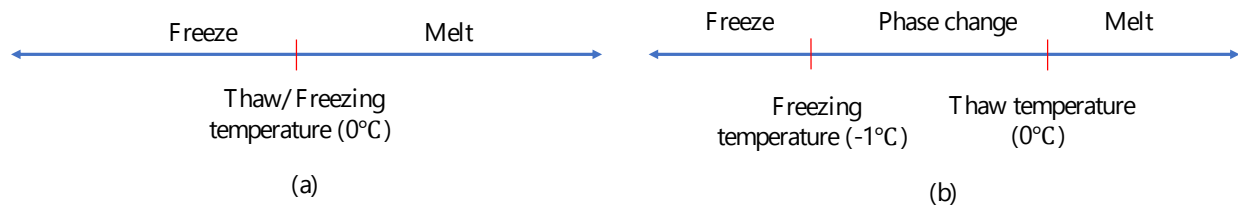
Figure 1: Schematic representation of (a) the freeze-thaw calculation method suggested by MnDOT and (b) a slightly modified version of MnDOT's method that includes the use of a -1°C freezing point temperature, due to the known +/- 1°C error in the sensor systems used to collection temperature data. *Note: Both methods include a 24-hour minimum freeze period and 5-hour minimum thaw period*

The variation in the number of freeze-thaw cycles for these two methods along with the two previously mentioned temperature-based methods (i.e. *fixed freezing temperature* and *modified reference temperature*) are shown in Figure 2. As seen in the figure, as compared to MnDOT's method, the *fixed freezing temperature* method predicts a significantly higher number of freeze-thaw cycles. Similarly, the *modified reference temperature method* generally predicts a

smaller number of cycles for all the depths. When comparing the number of freeze-thaw cycles calculated using MnDOT's method (i.e. Figure 1a) and the modified version of this (i.e. Figure 1b), these methods have similar results (Figure 2). The modified version generally predicts a slightly smaller number of freeze-thaw cycles. Based on this comparison, and since we feel it is important to consider the temperature sensor error, we proposed to use MnDOT's method with the modified freezing point temperature (-1°C).
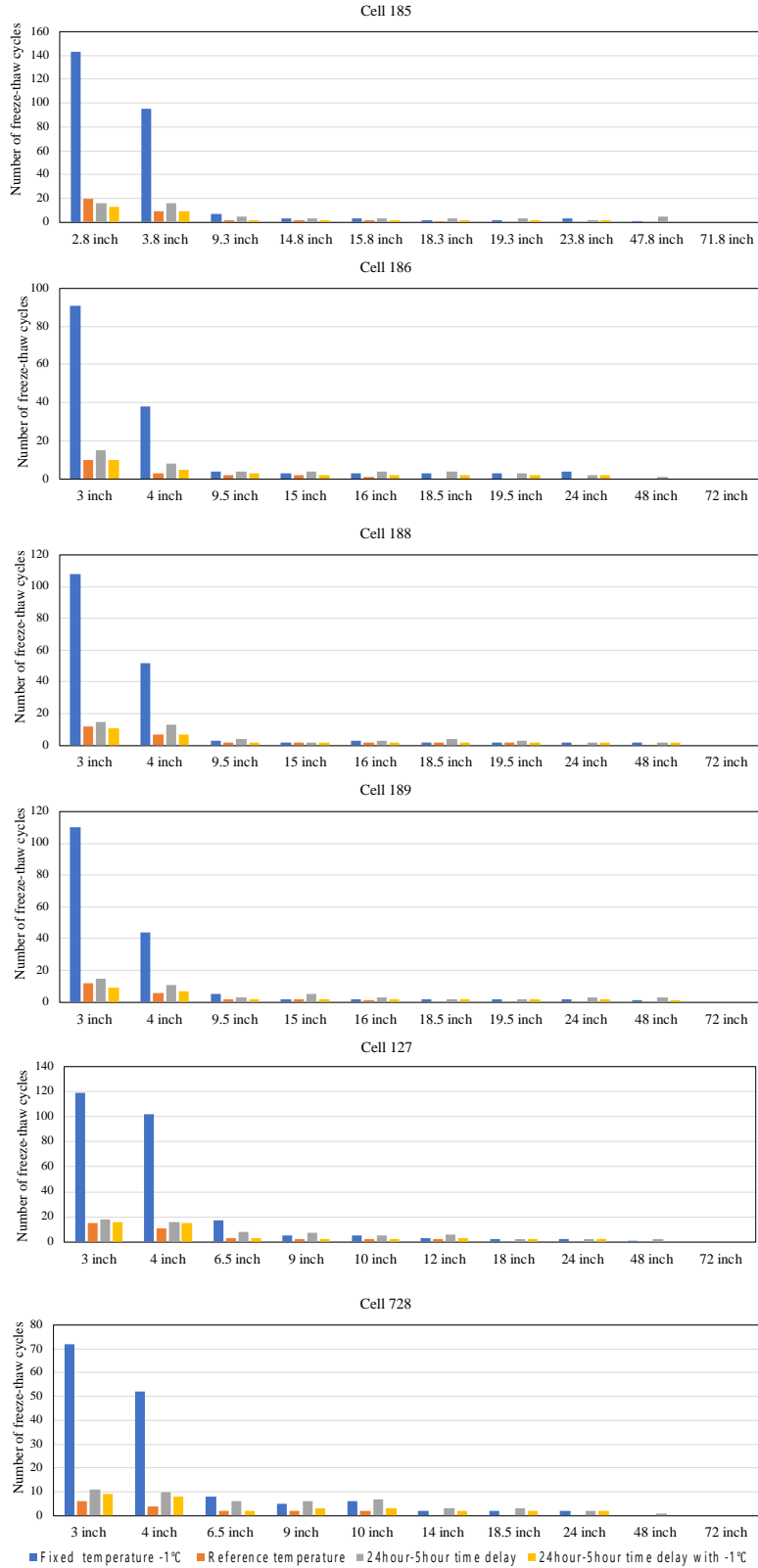
Figure 2: Number of freeze-thaw cycles for different method, including the *fixed freezing temperature (blue), modified reference temperature (orange), MnDOTs method (24hour-5hour time delay), and MnDOTs method with a freezing point temperature of -1°C*

The impact of different time durations of the freezing and thawing periods were also considered. In this comparison, -1°C was used as the *freezing point temperature*, to account for error in the temperature sensors used in data collection. Six different time delay periods (i.e. minimum period of time that must occur during a freezing period of a freeze-thaw cycle in order for it to be counted as a freeze-thaw cycle) were evaluated, from 4 hours to 24 hours at a timestep of 4 hours. Similarly, for the thawing period 7 different time periods were considered, from 0 hours to 24 hours with a timestep. This resulted in a total of 42 different combinations. All combinations were considered for all available datasets. The results for different depths are compared in Figure 3 to the MnDOT method (24hour-5hour). In Figure 3, the results of the number of cycles are shown for two sample cells. The values for all locations are provided in the Appendix.
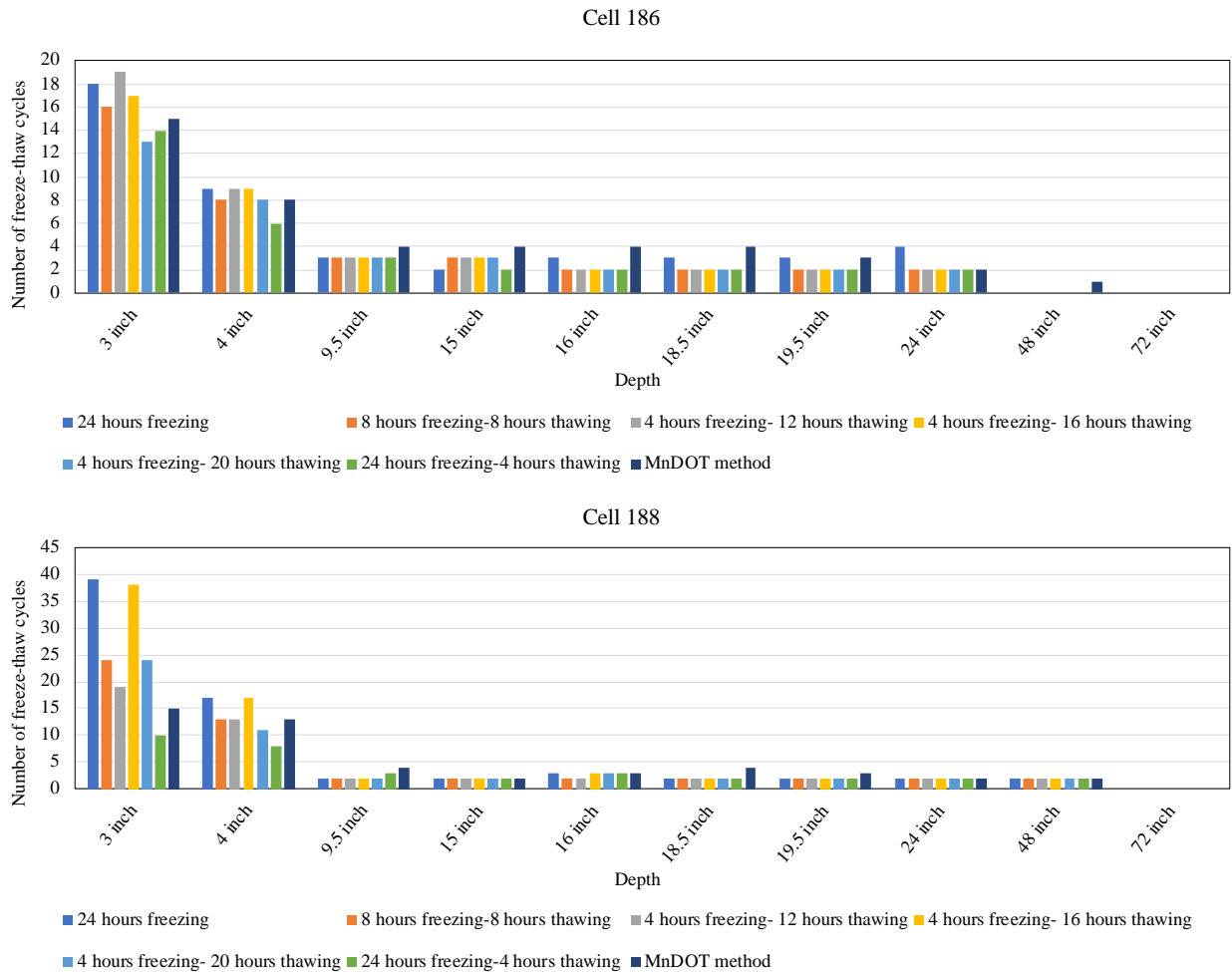
Figure 3: Number of freeze-thaw cycles for different time delay combinations *(Note: the MnDOT method (dark blue) considers 24-hours for freezing and 5-hours for thawing; all results shown use a freezing point temperature of -1°C, and thaw temperature of 0°C)*

As seen in Figure 3 and in the Appendix, the resulting freeze-thaw cycle counts from the methods with a -1°C freezing temperature and varying freezing or thawing time period are

impacted by the assumed minimum time duration required for either freezing or thawing. However, there is not one of these methods that is more similar to the MnDOT method as compared to the others. Based on all these results, we suggest the use of the MnDOT method, with the addition of using a -1°C as the freezing point temperature and 0°C as the thawing temperature to calculate the number of freeze thaw cycles.

Appendix

	Thaw time delay (hours)	Freeze time delay (hours)	TC_1 2.8 inch	TC_2 3.8 inch	TC_3 9.3 inch	TC_4 14.8 inch	TC_5 15.8 inch	TC_6 18.3 inch	TC_7 19.3 inch	TC_8 23.8 inch	TC_10 47.8 inch	TC_12 71.8 inch
	0	4	97	55	5	3	3	2	2	3	0	0
	0	8	83	43	5	3	2	2	2	3	0	0
	0	12	64	33	4	3	2	2	2	3	0	0
	0	16	48	21	4	2	2	2	2	3	0	0
	0	20	25	14	3	2	2	2	2	3	0	0
	0	24	19	14	3	2	2	2	2	3	0	0
	4	4	75	41	4	3	3	2	2	2	0	0
	4	8	62	32	4	3	2	2	2	2	0	0
	4	12	45	22	3	3	2	2	2	2	0	0
	4	16	30	13	3	2	2	2	2	2	0	0
	4	20	17	10	2	2	2	2	2	2	0	0
	4	24	16	10	2	2	2	2	2	2	0	0
Freezing temperature = -1°C	8	4	42	25	4	3	3	2	2	2	0	0
	8	8	31	19	4	3	2	2	2	2	0	0
	8	12	21	13	3	3	2	2	2	2	0	0
	8	16	14	10	3	2	2	2	2	2	0	0
	8	20	10	7	2	2	2	2	2	2	0	0
	8	24	9	7	2	2	2	2	2	2	0	0
	12	4	31	17	4	3	3	2	2	2	0	0
	12	8	21	12	4	3	2	2	2	2	0	0
	12	12	15	8	3	3	2	2	2	2	0	0
	12	16	10	5	3	2	2	2	2	2	0	0
	12	20	7	3	2	2	2	2	2	2	0	0
	12	24	6	3	2	2	2	2	2	2	0	0
	16	4	21	14	4	3	3	2	2	2	0	0
	16	8	15	11	4	3	2	2	2	2	0	0
	16	12	11	8	3	3	2	2	2	2	0	0
	16	16	7	5	3	2	2	2	2	2	0	0
	16	20	4	3	2	2	2	2	2	2	0	0
	16	24	3	3	2	2	2	2	2	2	0	0
	20	4	12	11	4	3	3	2	2	2	0	0
	20	8	10	9	4	3	2	2	2	2	0	0
	20	12	8	7	3	3	2	2	2	2	0	0
	20	16	6	5	3	2	2	2	2	2	0	0
	20	20	4	3	2	2	2	2	2	2	0	0
	20	24	3	3	2	2	2	2	2	2	0	0
	24	4	11	10	4	3	3	2	2	2	0	0
	24	8	10	8	4	3	2	2	2	2	0	0
	24	12	8	6	3	3	2	2	2	2	0	0
	24	16	6	5	3	2	2	2	2	2	0	0
	24	20	4	3	2	2	2	2	2	2	0	0
	24	24	3	3	2	2	2	2	2	2	0	0
0°C	5	24	16	16	5	3	3	3	3	2	5	0

	Cell no: 186		August 2017 to April 2019									
	Thaw time delay (hours)	Freeze time delay (hours)	TC_1 3 inch	TC_2 4 inch	TC_3 9.5 inch	TC_4 15 inch	TC_5 16 inch	TC_6 18.5 inch	TC_7 19.5 inch	TC_8 24 inch	TC_10 48 inch	TC_12 72 inch
Freezing temperature = -1°C	0	4	66	26	4	3	3	3	3	4	0	0
	0	8	51	22	3	3	3	3	3	4	0	0
	0	12	40	16	3	2	3	3	3	4	0	0
	0	16	26	11	3	2	3	3	3	4	0	0
	0	20	20	11	3	2	3	3	3	4	0	0
	0	24	18	9	3	2	3	3	3	4	0	0
	4	4	54	17	4	3	2	2	2	2	0	0
	4	8	40	13	3	3	2	2	2	2	0	0
	4	12	31	11	3	2	2	2	2	2	0	0
	4	16	18	7	3	2	2	2	2	2	0	0
	4	20	15	7	3	2	2	2	2	2	0	0
	4	24	14	6	3	2	2	2	2	2	0	0
	8	4	28	11	4	3	2	2	2	2	0	0
	8	8	16	8	3	3	2	2	2	2	0	0
	8	12	10	6	3	2	2	2	2	2	0	0
	8	16	8	4	3	2	2	2	2	2	0	0
	8	20	7	4	3	2	2	2	2	2	0	0
	8	24	7	4	3	2	2	2	2	2	0	0
	12	4	19	9	3	3	2	2	2	2	0	0
	12	8	11	7	2	3	2	2	2	2	0	0
	12	12	6	5	2	2	2	2	2	2	0	0
	12	16	4	3	2	2	2	2	2	2	0	0
	12	20	3	3	2	2	2	2	2	2	0	0
	12	24	3	3	2	2	2	2	2	2	0	0
	16	4	17	9	3	3	2	2	2	2	0	0
	16	8	10	7	2	3	2	2	2	2	0	0
	16	12	6	5	2	2	2	2	2	2	0	0
	16	16	4	3	2	2	2	2	2	2	0	0
	16	20	3	3	2	2	2	2	2	2	0	0
	16	24	3	3	2	2	2	2	2	2	0	0
	20	4	13	8	3	3	2	2	2	2	0	0
	20	8	8	6	2	3	2	2	2	2	0	0
	20	12	5	5	2	2	2	2	2	2	0	0
	20	16	4	3	2	2	2	2	2	2	0	0
	20	20	3	3	2	2	2	2	2	2	0	0
	20	24	3	3	2	2	2	2	2	2	0	0
	24	4	13	8	3	3	2	2	2	2	0	0
	24	8	8	6	2	3	2	2	2	2	0	0
	24	12	5	5	2	2	2	2	2	2	0	0
	24	16	4	3	2	2	2	2	2	2	0	0
	24	20	3	3	2	2	2	2	2	2	0	0
	24	24	3	3	2	2	2	2	2	2	0	0
0°C	5	24	15	8	4	4	4	4	3	2	1	0

	Cell no: 188		August 2017 to April 2019									
	Thaw time delay (hours)	Freeze time delay (hours)	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_10	TC_12
			3 inch	4 inch	9.5 inch	15 inch	16 inch	18.5 inch	19.5 inch	24 inch	48 inch	72 inch
Freezing temperature = -1°C	0	4	76	44	3	2	3	2	2	2	2	0
	0	8	63	33	3	2	3	2	2	2	2	0
	0	12	56	28	2	2	3	2	2	2	2	0
	0	16	39	17	2	2	3	2	2	2	2	0
	0	20	24	13	2	2	2	2	2	2	2	0
	0	24	19	13	2	2	2	2	2	2	2	0
	4	4	56	31	3	2	3	2	2	2	2	0
	4	8	43	22	3	2	3	2	2	2	2	0
	4	12	38	17	2	2	3	2	2	2	2	0
	4	16	24	11	2	2	3	2	2	2	2	0
	4	20	13	9	2	2	2	2	2	2	2	0
	4	24	13	9	2	2	2	2	2	2	2	0
	8	4	28	13	3	2	3	2	2	2	2	0
	8	8	20	9	3	2	3	2	2	2	2	0
	8	12	15	6	2	2	3	2	2	2	2	0
	8	16	10	4	2	2	3	2	2	2	2	0
	8	20	8	4	2	2	2	2	2	2	2	0
	8	24	8	4	2	2	2	2	2	2	2	0
	12	4	20	9	3	2	3	2	2	2	2	0
	12	8	14	6	3	2	3	2	2	2	2	0
	12	12	10	4	2	2	3	2	2	2	2	0
	12	16	6	2	2	2	3	2	2	2	2	0
	12	20	4	2	2	2	2	2	2	2	2	0
	12	24	4	2	2	2	2	2	2	2	2	0
	16	4	14	9	3	2	3	2	2	2	2	0
	16	8	11	6	3	2	3	2	2	2	2	0
	16	12	8	4	2	2	3	2	2	2	2	0
	16	16	4	2	2	2	3	2	2	2	2	0
	16	20	2	2	2	2	2	2	2	2	2	0
	16	24	2	2	2	2	2	2	2	2	2	0
	20	4	11	9	3	2	3	2	2	2	2	0
	20	8	10	6	3	2	3	2	2	2	2	0
	20	12	8	4	2	2	3	2	2	2	2	0
	20	16	4	2	2	2	3	2	2	2	2	0
	20	20	2	2	2	2	2	2	2	2	2	0
	20	24	2	2	2	2	2	2	2	2	2	0
	24	4	10	8	3	2	3	2	2	2	2	0
	24	8	9	5	3	2	3	2	2	2	2	0
	24	12	7	3	2	2	3	2	2	2	2	0
	24	16	3	2	2	2	3	2	2	2	2	0
	24	20	2	2	2	2	2	2	2	2	2	0
	24	24	2	2	2	2	2	2	2	2	2	0
0°C	5	24	15	13	4	2	3	4	3	2	2	0

	Cell no: 189		August 2017 to April 2019									
	Thaw time delay (hours)	Freeze time delay (hours)	TC_1 3 inch	TC_2 4 inch	TC_3 9.5 inch	TC_4 15 inch	TC_5 16 inch	TC_6 18.5 inch	TC_7 19.5 inch	TC_8 24 inch	TC_10 48 inch	TC_12 72 inch
Freezing temperature = -1°C	0	4	78	37	4	2	2	2	2	2	1	0
	0	8	62	27	3	2	2	2	2	2	1	0
	0	12	51	21	3	2	2	2	2	2	1	0
	0	16	36	13	3	2	2	2	2	2	1	0
	0	20	22	11	3	2	2	2	2	2	1	0
	0	24	17	11	3	2	2	2	2	2	1	0
	4	4	55	25	2	2	2	2	2	2	1	0
	4	8	41	16	2	2	2	2	2	2	1	0
	4	12	32	13	2	2	2	2	2	2	1	0
	4	16	20	10	2	2	2	2	2	2	1	0
	4	20	14	8	2	2	2	2	2	2	1	0
	4	24	12	8	2	2	2	2	2	2	1	0
	8	4	30	13	2	2	2	2	2	2	1	0
	8	8	21	7	2	2	2	2	2	2	1	0
	8	12	14	6	2	2	2	2	2	2	1	0
	8	16	11	4	2	2	2	2	2	2	1	0
	8	20	9	3	2	2	2	2	2	2	1	0
	8	24	7	3	2	2	2	2	2	2	1	0
	12	4	19	10	2	2	2	2	2	2	1	0
	12	8	12	6	2	2	2	2	2	2	1	0
	12	12	9	5	2	2	2	2	2	2	1	0
	12	16	6	3	2	2	2	2	2	2	1	0
	12	20	4	2	2	2	2	2	2	2	1	0
	12	24	3	2	2	2	2	2	2	2	1	0
	16	4	14	10	2	2	2	2	2	2	1	0
	16	8	10	6	2	2	2	2	2	2	1	0
	16	12	8	5	2	2	2	2	2	2	1	0
	16	16	5	3	2	2	2	2	2	2	1	0
	16	20	3	2	2	2	2	2	2	2	1	0
	16	24	2	2	2	2	2	2	2	2	1	0
	20	4	12	10	2	2	2	2	2	2	1	0
	20	8	9	6	2	2	2	2	2	2	1	0
	20	12	8	5	2	2	2	2	2	2	1	0
	20	16	5	3	2	2	2	2	2	2	1	0
	20	20	3	2	2	2	2	2	2	2	1	0
	20	24	2	2	2	2	2	2	2	2	1	0
	24	4	12	9	2	2	2	2	2	2	1	0
	24	8	9	6	2	2	2	2	2	2	1	0
	24	12	8	5	2	2	2	2	2	2	1	0
	24	16	5	3	2	2	2	2	2	2	1	0
	24	20	3	2	2	2	2	2	2	2	1	0
	24	24	2	2	2	2	2	2	2	2	1	0
0°C	5	24	15	11	3	5	3	2	2	3	3	0

	Cell no: 127		August 2017 to April 2019									
	Thaw time delay (hours)	Freeze time delay (hours)	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_10	TC_12
			3 inch	4 inch	6.5 inch	9 inch	10 inch	12 inch	18 inch	24 inch	48 inch	72 inch
Freezing temperature = -1°C	0	4	103	80	13	4	5	3	2	2	1	0
	0	8	78	62	10	4	5	3	2	2	1	0
	0	12	52	45	7	4	4	3	2	2	0	0
	0	16	35	29	7	3	4	3	2	2	0	0
	0	20	20	18	7	2	3	3	2	2	0	0
	0	24	19	18	5	2	3	3	2	2	0	0
	4	4	93	69	9	4	4	3	2	2	1	0
	4	8	69	54	7	4	4	3	2	2	1	0
	4	12	45	39	5	4	3	3	2	2	0	0
	4	16	29	24	5	3	3	3	2	2	0	0
	4	20	17	17	5	2	2	3	2	2	0	0
	4	24	16	17	3	2	2	3	2	2	0	0
	8	4	55	39	8	4	4	3	2	2	1	0
	8	8	35	26	7	4	4	3	2	2	1	0
	8	12	20	17	5	4	3	3	2	2	0	0
	8	16	11	9	5	3	3	3	2	2	0	0
	8	20	10	8	5	2	2	3	2	2	0	0
	8	24	9	8	3	2	2	3	2	2	0	0
	12	4	45	32	8	4	4	3	2	2	1	0
	12	8	27	20	7	4	4	3	2	2	1	0
	12	12	13	12	5	4	3	3	2	2	0	0
	12	16	9	8	5	3	3	3	2	2	0	0
	12	20	8	7	5	2	2	3	2	2	0	0
	12	24	7	7	3	2	2	3	2	2	0	0
	16	4	26	20	8	4	4	3	2	2	1	0
	16	8	16	15	7	4	4	3	2	2	1	0
	16	12	9	9	5	4	3	3	2	2	0	0
	16	16	6	5	5	3	3	3	2	2	0	0
	16	20	5	4	5	2	2	3	2	2	0	0
	16	24	5	4	3	2	2	3	2	2	0	0
	20	4	21	16	6	4	4	3	2	2	1	0
	20	8	13	12	6	4	4	3	2	2	1	0
	20	12	8	8	4	4	3	3	2	2	0	0
	20	16	5	5	4	3	3	3	2	2	0	0
	20	20	4	4	4	2	2	3	2	2	0	0
	20	24	4	4	3	2	2	3	2	2	0	0
	24	4	19	16	6	4	4	3	2	2	1	0
	24	8	12	12	6	4	4	3	2	2	1	0
	24	12	8	8	4	4	3	3	2	2	0	0
	24	16	5	5	4	3	3	3	2	2	0	0
	24	20	4	4	4	2	2	3	2	2	0	0
	24	24	4	4	3	2	2	3	2	2	0	0
0°C	5	24	18	16	8	7	5	6	2	2	2	0

	Cell no: 728		August 2017 to April 2019									
	Thaw time delay (hours)	Freeze time delay (hours)	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_10	TC_12
			3 inch	4 inch	6.5 inch	9 inch	10 inch	14 inch	18.5 inch	24 inch	48 inch	72 inch
Freezing temperature = -1°C	0	4	54	40	6	5	6	2	2	2	0	0
	0	8	40	26	6	5	5	2	2	2	0	0
	0	12	23	18	5	5	5	2	2	2	0	0
	0	16	16	13	4	4	5	2	2	2	0	0
	0	20	12	11	4	4	4	2	2	2	0	0
	0	24	11	10	3	4	4	2	2	2	0	0
	4	4	44	33	5	4	5	2	2	2	0	0
	4	8	33	20	5	4	4	2	2	2	0	0
	4	12	18	14	4	4	4	2	2	2	0	0
	4	16	12	10	3	3	4	2	2	2	0	0
	4	20	10	10	3	3	3	2	2	2	0	0
	4	24	9	9	2	3	3	2	2	2	0	0
	8	4	32	24	5	4	5	2	2	2	0	0
	8	8	22	13	5	4	4	2	2	2	0	0
	8	12	12	11	4	4	4	2	2	2	0	0
	8	16	9	8	3	3	4	2	2	2	0	0
	8	20	9	8	3	3	3	2	2	2	0	0
	8	24	8	7	2	3	3	2	2	2	0	0
	12	4	24	20	5	4	5	2	2	2	0	0
	12	8	17	10	5	4	4	2	2	2	0	0
	12	12	11	9	4	4	4	2	2	2	0	0
	12	16	8	6	3	3	4	2	2	2	0	0
	12	20	8	6	3	3	3	2	2	2	0	0
	12	24	7	5	2	3	3	2	2	2	0	0
	16	4	16	14	5	4	5	2	2	2	0	0
	16	8	12	9	5	4	4	2	2	2	0	0
	16	12	7	8	4	4	4	2	2	2	0	0
	16	16	5	5	3	3	4	2	2	2	0	0
	16	20	5	5	3	3	3	2	2	2	0	0
	16	24	4	4	2	3	3	2	2	2	0	0
	20	4	12	9	5	4	5	2	2	2	0	0
	20	8	9	7	5	4	4	2	2	2	0	0
	20	12	7	7	4	4	4	2	2	2	0	0
	20	16	5	5	3	3	4	2	2	2	0	0
	20	20	5	5	3	3	3	2	2	2	0	0
	20	24	4	4	2	3	3	2	2	2	0	0
	24	4	12	9	5	4	5	2	2	2	0	0
	24	8	9	7	5	4	4	2	2	2	0	0
	24	12	7	7	4	4	4	2	2	2	0	0
	24	16	5	5	3	3	4	2	2	2	0	0
	24	20	5	5	3	3	3	2	2	2	0	0
	24	24	4	4	2	3	3	2	2	2	0	0
0°C	5	24	11	10	6	6	7	3	3	2	1	0

Koochiching		2005 to 2011											
Thaw time delay (hours)	Freeze time delay (hours)	TC_040	TC_070	TC_090	TC_180	TC_240	TC_300	TC_360	TC_420	TC_480	TC_540	TC_600	TC_720
		4	7	9	18	24	30	36	42	48	54	60	72
0	4	65	29	7	6	6	6	6	6	6	5	7	1
0	8	41	16	7	6	6	6	6	6	6	5	7	1
0	12	23	12	7	6	6	6	6	6	6	5	5	1
0	16	17	11	7	6	6	6	6	6	6	5	4	0
0	20	13	9	7	6	6	6	6	6	6	5	4	0
0	24	12	9	7	6	6	6	6	6	6	5	3	0
4	4	61	27	7	6	6	6	6	6	6	5	5	1
4	8	37	14	7	6	6	6	6	6	6	5	5	1
4	12	21	12	7	6	6	6	6	6	6	5	5	1
4	16	16	11	7	6	6	6	6	6	6	5	4	0
4	20	13	9	7	6	6	6	6	6	6	5	4	0
4	24	12	9	7	6	6	6	6	6	6	5	3	0
8	4	44	19	7	6	6	6	6	6	6	5	5	1
8	8	25	12	7	6	6	6	6	6	6	5	5	1
8	12	16	10	7	6	6	6	6	6	6	5	5	1
8	16	13	9	7	6	6	6	6	6	6	5	4	0
8	20	12	8	7	6	6	6	6	6	6	5	4	0
8	24	11	8	7	6	6	6	6	6	6	5	3	0
12	4	25	14	7	6	6	6	6	6	6	5	5	1
12	8	14	10	7	6	6	6	6	6	6	5	5	1
12	12	9	9	7	6	6	6	6	6	6	5	5	1
12	16	8	8	7	6	6	6	6	6	6	5	4	0
12	20	8	7	7	6	6	6	6	6	6	5	4	0
12	24	8	7	7	6	6	6	6	6	6	5	3	0
16	4	17	13	7	6	6	6	6	6	6	5	5	1
16	8	12	10	7	6	6	6	6	6	6	5	5	1
16	12	8	9	7	6	6	6	6	6	6	5	5	1
16	16	7	8	7	6	6	6	6	6	6	5	4	0
16	20	7	7	7	6	6	6	6	6	6	5	4	0
16	24	7	7	7	6	6	6	6	6	6	5	3	0
20	4	17	13	7	6	6	6	6	6	6	5	5	1
20	8	12	10	7	6	6	6	6	6	6	5	5	1
20	12	8	9	7	6	6	6	6	6	6	5	5	1
20	16	7	8	7	6	6	6	6	6	6	5	4	0
20	20	7	7	7	6	6	6	6	6	6	5	4	0
20	24	7	7	7	6	6	6	6	6	6	5	3	0
24	4	17	12	6	6	6	6	6	6	6	5	5	1
24	8	12	9	6	6	6	6	6	6	6	5	5	1
24	12	8	8	6	6	6	6	6	6	6	5	5	1
24	16	7	7	6	6	6	6	6	6	6	5	4	0
24	20	7	7	6	6	6	6	6	6	6	5	4	0
24	24	7	7	6	6	6	6	6	6	6	5	3	0
0°C	5	24	22	21	12	7	6	7	11	11	6	7	19	14

(Left axis label: Freezing temperature = -1°C)

	Koochiching		2012 to 2019											
	Thaw time delay (hours)	Freeze time delay (hours)	TEMP_080	TEMP_120	TEMP_150	TEMP_180	TEMP_210	TEMP_240	TEMP_360	TEMP_420	TEMP_480	TEMP_540	TEMP_600	TEMP_640
			8	12	15	18	21	24	36	42	48	54	60	64
Freezing temperature = -1°C	0	4	24	11	11	8	8	8	8	7	6	5	4	2
	0	8	19	11	11	8	8	8	8	7	6	5	4	2
	0	12	16	11	11	8	8	8	8	7	6	5	4	2
	0	16	16	11	10	8	8	8	8	7	6	5	4	2
	0	20	16	11	10	8	8	8	8	7	6	5	4	2
	0	24	16	11	10	8	8	8	8	7	6	5	4	2
	4	4	24	11	11	8	8	8	8	7	6	5	4	2
	4	8	19	11	11	8	8	8	8	7	6	5	4	2
	4	12	16	11	11	8	8	8	8	7	6	5	4	2
	4	16	16	11	10	8	8	8	8	7	6	5	4	2
	4	20	16	11	10	8	8	8	8	7	6	5	4	2
	4	24	16	11	10	8	8	8	8	7	6	5	4	2
	8	4	22	10	11	8	8	8	8	7	6	5	4	2
	8	8	18	10	11	8	8	8	8	7	6	5	4	2
	8	12	16	10	11	8	8	8	8	7	6	5	4	2
	8	16	16	10	10	8	8	8	8	7	6	5	4	2
	8	20	16	10	10	8	8	8	8	7	6	5	4	2
	8	24	16	10	10	8	8	8	8	7	6	5	4	2
	12	4	17	10	11	8	8	8	8	7	6	5	4	2
	12	8	15	10	11	8	8	8	8	7	6	5	4	2
	12	12	14	10	11	8	8	8	8	7	6	5	4	2
	12	16	14	10	10	8	8	8	8	7	6	5	4	2
	12	20	14	10	10	8	8	8	8	7	6	5	4	2
	12	24	14	10	10	8	8	8	8	7	6	5	4	2
	16	4	12	9	10	8	8	8	8	7	6	5	4	2
	16	8	12	9	10	8	8	8	8	7	6	5	4	2
	16	12	12	9	10	8	8	8	8	7	6	5	4	2
	16	16	12	9	9	8	8	8	8	7	6	5	4	2
	16	20	12	9	9	8	8	8	8	7	6	5	4	2
	16	24	12	9	9	8	8	8	8	7	6	5	4	2
	20	4	11	8	10	8	8	8	8	7	6	5	4	2
	20	8	11	8	10	8	8	8	8	7	6	5	4	2
	20	12	11	8	10	8	8	8	8	7	6	5	4	2
	20	16	11	8	9	8	8	8	8	7	6	5	4	2
	20	20	11	8	9	8	8	8	8	7	6	5	4	2
	20	24	11	8	9	8	8	8	8	7	6	5	4	2
	24	4	10	8	10	8	8	8	8	7	6	5	4	2
	24	8	10	8	10	8	8	8	8	7	6	5	4	2
	24	12	10	8	10	8	8	8	8	7	6	5	4	2
	24	16	10	8	9	8	8	8	8	7	6	5	4	2
	24	20	10	8	9	8	8	8	8	7	6	5	4	2
	24	24	10	8	9	8	8	8	8	7	6	5	4	2
0°C	5	24	22	13	14	12	14	12	11	8	8	7	5	5

Olmsted			2000 to 2007											
Thaw time delay (hours)	Freeze time delay (hours)	TC_060	TC_090	TC_120	TC_180	TC_300	TC_360	TC_420	TC_480	TC_600	TC_720	TC_840	TC_960
		6	9	12	18	30	36	42	48	60	72	84	96
0	4	39	19	14	10	9	7	5	4	1	1	0	1
0	8	36	17	13	10	9	7	5	4	1	1	0	1
0	12	31	15	13	10	9	7	5	4	1	1	0	1
0	16	24	13	12	10	9	7	5	4	1	1	0	1
0	20	22	12	10	9	8	6	4	3	0	0	0	0
0	24	22	12	10	9	8	6	4	3	0	0	0	0
4	4	38	19	12	10	9	7	5	4	1	1	0	1
4	8	35	17	12	10	9	7	5	4	1	1	0	1
4	12	31	15	12	10	9	7	5	4	1	1	0	1
4	16	24	13	12	10	9	7	5	4	1	1	0	1
4	20	22	12	10	9	8	6	4	3	0	0	0	0
4	24	22	12	10	9	8	6	4	3	0	0	0	0
8	4	34	18	12	10	8	7	5	4	1	1	0	1
8	8	32	16	12	10	8	7	5	4	1	1	0	1
8	12	29	14	12	10	8	7	5	4	1	1	0	1
8	16	22	12	12	10	8	7	5	4	1	1	0	1
8	20	20	11	10	9	7	6	4	3	0	0	0	0
8	24	20	11	10	9	7	6	4	3	0	0	0	0
12	4	29	18	12	10	8	7	5	4	1	1	0	1
12	8	27	16	12	10	8	7	5	4	1	1	0	1
12	12	24	14	12	10	8	7	5	4	1	1	0	1
12	16	18	12	12	10	8	7	5	4	1	1	0	1
12	20	16	11	10	9	7	6	4	3	0	0	0	0
12	24	16	11	10	9	7	6	4	3	0	0	0	0
16	4	25	17	12	10	8	7	5	4	1	1	0	1
16	8	23	15	12	10	8	7	5	4	1	1	0	1
16	12	21	14	12	10	8	7	5	4	1	1	0	1
16	16	15	12	12	10	8	7	5	4	1	1	0	1
16	20	13	11	10	9	7	6	4	3	0	0	0	0
16	24	13	11	10	9	7	6	4	3	0	0	0	0
20	4	23	16	11	10	8	7	5	4	1	1	0	1
20	8	21	14	11	10	8	7	5	4	1	1	0	1
20	12	19	13	11	10	8	7	5	4	1	1	0	1
20	16	14	12	11	10	8	7	5	4	1	1	0	1
20	20	13	11	10	9	7	6	4	3	0	0	0	0
20	24	13	11	10	9	7	6	4	3	0	0	0	0
24	4	21	16	11	10	8	7	5	4	1	1	0	1
24	8	19	14	11	10	8	7	5	4	1	1	0	1
24	12	17	13	11	10	8	7	5	4	1	1	0	1
24	16	14	12	11	10	8	7	5	4	1	1	0	1
24	20	13	11	10	9	7	6	4	3	0	0	0	0
24	24	13	11	10	9	7	6	4	3	0	0	0	0
0°C	5	24	40	25	22	13	10	15	6	5	0	0	0	0

Freezing temperature = -1°C

Olmsted		2010 to 2017											
Thaw time delay (hours)	Freeze time delay (hours)	TC_050	TC_070	TC_130	TC_190	TC_250	TC_310	TC_370	TC_430	TC_490	TC_550	TC_610	TC_730
		5	7	13	19	25	31	37	43	49	55	61	73
0	4	80	27	16	9	8	7	6	4	2	1	0	0
0	8	63	21	15	9	8	7	5	3	1	1	0	0
0	12	41	20	15	9	8	7	5	3	1	1	0	0
0	16	32	19	14	9	8	7	5	3	1	1	0	0
0	20	29	16	14	9	8	7	5	3	1	1	0	0
0	24	27	16	14	9	8	7	5	3	1	1	0	0
4	4	68	26	15	9	8	7	6	4	2	1	0	0
4	8	54	21	14	9	8	7	5	3	1	1	0	0
4	12	35	20	14	9	8	7	5	3	1	1	0	0
4	16	29	19	13	9	8	7	5	3	1	1	0	0
4	20	27	16	13	9	8	7	5	3	1	1	0	0
4	24	25	16	13	9	8	7	5	3	1	1	0	0
8	4	45	24	14	9	8	7	6	4	2	1	0	0
8	8	39	20	13	9	8	7	5	3	1	1	0	0
8	12	27	19	13	9	8	7	5	3	1	1	0	0
8	16	23	18	12	9	8	7	5	3	1	1	0	0
8	20	22	15	12	9	8	7	5	3	1	1	0	0
8	24	20	15	12	9	8	7	5	3	1	1	0	0
12	4	35	22	14	9	8	7	6	4	2	1	0	0
12	8	33	18	13	9	8	7	5	3	1	1	0	0
12	12	24	17	13	9	8	7	5	3	1	1	0	0
12	16	21	16	12	9	8	7	5	3	1	1	0	0
12	20	20	13	12	9	8	7	5	3	1	1	0	0
12	24	18	13	12	9	8	7	5	3	1	1	0	0
16	4	32	20	13	9	8	7	6	4	2	1	0	0
16	8	31	17	12	9	8	7	5	3	1	1	0	0
16	12	23	16	12	9	8	7	5	3	1	1	0	0
16	16	21	15	11	9	8	7	5	3	1	1	0	0
16	20	20	12	11	9	8	7	5	3	1	1	0	0
16	24	18	12	11	9	8	7	5	3	1	1	0	0
20	4	30	18	13	9	8	7	6	4	2	1	0	0
20	8	29	15	12	9	8	7	5	3	1	1	0	0
20	12	21	14	12	9	8	7	5	3	1	1	0	0
20	16	19	13	11	9	8	7	5	3	1	1	0	0
20	20	18	11	11	9	8	7	5	3	1	1	0	0
20	24	16	11	11	9	8	7	5	3	1	1	0	0
24	4	27	17	12	9	8	7	6	4	2	1	0	0
24	8	26	14	11	9	8	7	5	3	1	1	0	0
24	12	18	13	11	9	8	7	5	3	1	1	0	0
24	16	16	12	10	9	8	7	5	3	1	1	0	0
24	20	15	10	10	9	8	7	5	3	1	1	0	0
24	24	14	10	10	9	8	7	5	3	1	1	0	0
0°C 5	24	37	32	27	15	9	9	7	8	5	2	1	0

Freezing temperature = -1°C