A DISTRIBUTED TEMPERATURE SENSOR NETWORK TO MEASURE AND INFER FROST PENETRATION

R.D. McLeod[1], B.W. Podaima[2], M.R. Friesen[1] and J.A. Blatz[3]
1 Electrical & Computer Engineering,University of Manitoba, Canada
2 Internet Innovation Centre, University of Manitoba, Canada
3 Civil Engineering, University of Manitoba, Canada

Abstract: Municipal water supply line freezing is a seasonal problem in cold-climate areas. During a record cold winter in 2014, Winnipeg, Canada had over 2600 homes' municipal water supply lines freeze, generally at depths of 8ft below grade and often beneath roadways or other areas not insulated by snow cover. Upon having supply lines thawed, residents were required to run their taps into late June to prevent refreezing, as frost continued to penetrate downward well after ambient temperatures had turned moderate in the springtime. A system of distributed sensors was installed to monitor ground and water temperature. The objective is to demonstrate a means to pre-emptively predict potential service interruptions due to supply line freeze-up. Temperature sensors were installed at grade, at 8 feet below grade, and at the ingress of the water meter to the residence to monitor water supply line temperatures in the City of Winnipeg. The prototype employs Arduino microcontrollers equipped with LM35 temperature sensors with data transmission over wireless (XBee) as well as commercial thermistor sensors (Lascar) with cloud data collection over Wi-Fi. Data integration includes weather data from Environment Canada, estimated frost penetration from the City of Winnipeg Water and Waste Department, as well as the sensor data collected directly. As of March 1, 2015, fitting the below grade temperature data with a second order polynomial predicts temperatures 8 feet below grade to reach approximately 3.2 degrees Celsius in mid-April. This prediction made on March 1 proved accurate as of April 13, 2015. Through most of the winter, water supply temperatures were consistently cooler than the surrounding ground temperatures. Water supply temperatures began to exceed ground temperatures in early April 2015.

1 INTRODUCTION

In 2014, Manitoba, Canada experienced the coldest winter since 1898. Mean temperature in January 2014 was -17.75 C with the mean during 1999-2013 being -14.1 C. Among the inconveniences of high home heating bills, difficulties in clearing frozen snow and ruts off of city roads, and stalled cars, some residents of Winnipeg also experienced frozen water supply lines. Typically, the freezing occurred between the water main and the home, either under the resident's property (e.g. driveway or front yard) or under the City of Winnipeg property (sidewalk or road). Approximately 2600 homes experienced frozen water supply lines in winter of 2014, whereas typically only a few dozen homes in Winnipeg carry this annual risk, and those homes are typically those built without basements and consequently water supply lines are not installed as deeply as homes with basements.

The first frozen water supply lines began to appear in November 2013, and the peak of frozen lines (up to 100 new freeze-ups reported daily) occurred in late February and early March 2014. However, new freeze-ups were being reported into early June of 2014, demonstrating the known delay in ground heating even when ambient temperatures have moderated to spring and summer values. While a small percentage of residents remained without water for the duration of their freeze-up, most residents were without water for a period ranging from days to weeks, while the City of Winnipeg installed temporary hoses from neighbouring properties and worked through the backlog with a variety of successful thawing strategies. Nevertheless, the accumulated cost to the City in thawing services, overtime hours for personnel, offering water and facilities to residents at firehalls, public pools, and community centres, and associated costs is estimated to be $8.4 million (http://www.winnipegfreepress.com/local/city-touts-plan-for-frozen-pipes-283320391.html).

More northern climates have long term solutions integrated with the design of the home to prevent water supply line freeze-up. For example, instead of a single supply line reaching to each home from the water main, homes may be built with two lines to the main. One line supplies water to the home. A recirculating pump in the basement of the home recirculates water back to the water main through the second line when no water is being used in the home. In this way, water is continuously moving through the lines and is less likely to freeze.

In Winnipeg, large-scale mitigation by either installing recirculating pumps and return lines for each home at 8 ft. below grade is not practically or financially feasible on a large scale, and neither is a full re-installation of all water supply lines in the city at lower depths (e.g. 10 ft. below grade) as some affected residents called for after the experiences of winter 2014. Rather, a more practical focus is to work on measures to predict potential freezing risk which the municipality and/or residents themselves can implement, monitor, and on which they can take preventive measures. The primary preventive measure would be for a homeowner to let their water trickle in the a faucet in the home, ensuring that water continues to move through the supply line rather than sitting stagnant and facilitating freeze-up.

The key parameters of interest in a pre-emptive approach are supply line water temperatures and frost penetration. Frost penetration has been of interest in both academia as well as in practice for a considerable period of time (Kersten 1952, Berggren 1943), often for the purpose of predicting and modeling frost heave. Soil composition, moisture content, and environmental conditions are inputs into models to estimate frost penetration. In addition, surface type is also an important consideration, in particular for highways and airfields (Aldrich 1956). Complicating factors in terms of building predictive models also include non-uniform soil (multilayer soil) (Aldrich and Paynter 1966). More recently, numerical modeling methods have become standard and are often augmented or supported by field measurement. In contrast to frost heave, the principal interest here is in simply knowing if the frost has penetrated sufficiently to cause the freezing of a below-grade water pipe.

An increasingly attractive alternative to sophisticated models and methods is to measure ground temperatures directly or indirectly. This is increasingly feasible due to the increasing availability of wireless sensors on the market for relatively low-cost, and the ability to monitor data remotely through existing wireless infrastructure.

To monitor both frost penetration and supply line water temperature, a small network of wireless sensors was installed in Winnipeg, Manitoba, gathering temperature data at the following locations:

- Soil temperature at 8 ft. below grade on a residential lot in an old neighbourhood of the City of Winnipeg; this is also the approximate depth of water supply lines in most neighbourhoods in the City of Winnipeg; (three sensors at 8 feet, two for redundancy)
- Temperatures on the outside surface of the water supply line to the home, inside the home and as close as possible to the foundation wall, in four residences in neighbourhoods ranging from 35 to 95 years old. This serves as a proxy for the water temperature inside the supply line. (four sensors at 4 different locations)

The typical soil stratigraphy in the Winnipeg region from the ground surface down includes a weathered brown lacustrine clay, intact grey lacustrine clay, glacial till and limestone bedrock. The thickness of the brown and grey clay varies from about 10 to 15 m depending on the location within the City. The clays layers are mineralogically similar with typically high Atterberg Limits of 90% for the liquid limit and 30% for the plastic limit. These values reflect a high Illite and Smectite clay content. The clays often contain horizontal layers of silt and are highly laminated. The underlying till has a water content generally in the 5% to 10% range and is compact and dense in most areas providing an acceptable bearing stratum for deep foundations.

1.1 Wireless Sensor Networks

The term wireless sensor network (WSN) has become a generic term for any network that incorporates some degree of wireless or radio communication, as well as some parameter(s) being sensed. In this case, temperature is the parameter of interest, although additional sensors capable of sensing humidity or moisture content may play an increased role in the future. In early WSNs, as well as very specific type of WSNs such as a body sensor networks, the emphasis was also the network itself as well as the protocols necessary to shunt packets of data between nodes. A node was often a sensor node as well as packet forwarding and/or routing node. In many sensing scenarios, the network and its function has been replaced by in-place wireless infrastructure. These include local area wireless networks such as Wi-Fi, Bluetooth and/or ZigBee, or non-local wireless such as cellular. Leveraging existing wireless infrastructure has considerably benefitted the more pragmatic deployments of wireless sensor networks.

In this work, two alternative wireless sensor networks were considered with two somewhat complementary objectives. The first approach built a temperature collection platform based on the Arduino development platform. The second approach used an off-the-shelf turnkey technology of a commercial temperature probes with built in wireless and backend support from Lascar Electronics.

1.2 The Arduino based temperature probe

The Arduino based platform is more appropriately considered a student or hobbyist platform, although it has been used for a very large number of different applications and has considerable development support available on the web. This work used the OSEPP Uno R3 Plus board. This and other boards within the Arduino family have modules to integrate a wireless interface. Wireless modules for XBee or WiFi or are typically supported through or integrated on a daughter board, denoted a shield.

In this work, the actual temperature sensors were based on discrete and surface mount versions of the LM35 temperature probe from Texas Instruments. A brief description of the actual probe and configurations are discussed in a later section of this paper. The Arduino language is based on C/C++ and comes with a free and easy-to-use IDE. In this work, the initial system consisted of two Arduino boards with shields and XBee wireless modules. One Arduino was tasked with data collection and conversion from the LM35 temperature sensor. The other connected to a host computer via a mini USB cable. As this was built from the ground up, probe calibration was also required. Calibration was accomplished with a mini fridge and calibrated against a Lascar USB temperature sensor (EL-USB-1). In total, four probes were calibrated: three discrete and one surface mounted to a small PCB. All of these elements make for a very inexpensive system, very well suited to student projects. In this work, the Arduino platform became a back-up and confirmation system to augment data received from the commercial system discussed in Section 1.3. As a final note, there are also other wireless modules that may be more suitable in terms of range. For example, an Arduino prototype was also built using the APC220-43 semi-duplex low power transceiver module from APPCON Technologies, allowing the range to be extended to approximately 1000m. These devices also support cellular connectivity such as GSM and were used in a similar wireless sensor network project using Bluetooth scanning (Friesen et al. 2014). In addition, another alternative for the temperature probe is the DS18B20 from maxim integrated. These devices have a unique 64 bit code facilitating distributed temperature sensing applications.

1.3 The Lascar OTS Wi-Fi temperature probe.

The second device considered in this work was an off-the-shelf (OTS) solution from Lascar, specifically the EL-WiFi-TP probe (Fig. 1). It is highly configurable in terms of sample and data transmission rates.

Figure 1: The Lascar EL-WiFi-TP

Unlike the LM35 sensor used with the Arduino platform, the Lascar EL-WiFi-TP uses a thermistor. In addition to the configuration of Figure 1, the temperature sensor also supports an extension cable probe extender. In the initial configuration, the probe was located approximately 30m from the Wi-Fi router and it experienced very unreliable connectivity. As such, a significantly longer probe extender cable was required and incorporated.

A significant advantage of the OTS probe was the associated monitoring software. Once networked, data can be conveniently sent and stored on a cloud service, making it accessible from anywhere. The cloud service used is EasyLog Cloud powered by Files Thru The Air (EasyLog). An example of data collected from one of the probes is illustrated in Figure 2.

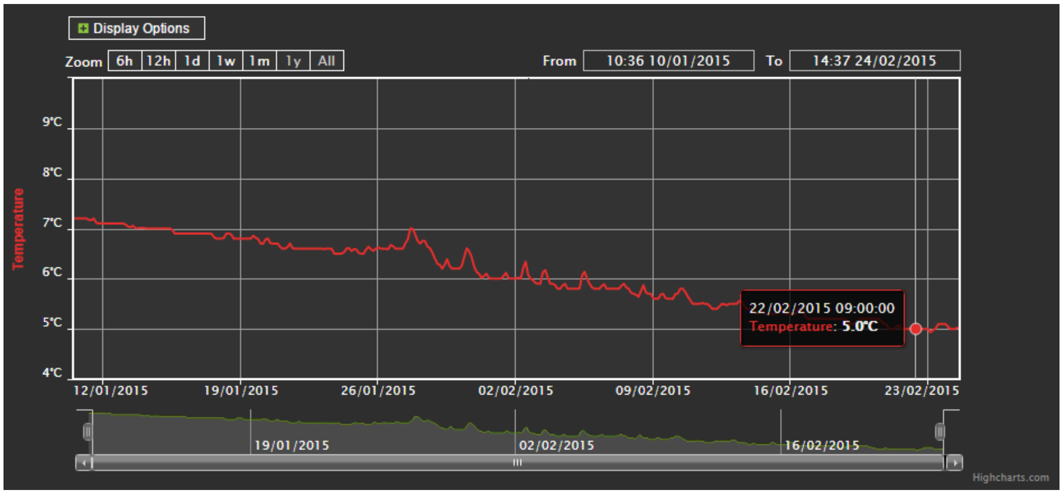


Figure 2: Illustration of data from a temperature probe from the EasyLog Cloud service (Screenshot)

2 THE TEMPERATURE PROBES AND NETWORK.

2.1 Temperature Probe Construction

In this work, the probes consisted of the OTS thermistors used with the Lascar probes, as well as LM35 temperature probes used with the Arduino boards. Three probes were installed at depths of 8 ft below grade in fall 2014 prior to freeze-up. Two probes used the Arduino platform and one used the Lascar probe. One Arduino probe failed soon after installation. The second Arduino probe has been read periodically to confirm readings taken from the Lascar probe; the data was found to be consistent and is not reported here. The Lascar probe is considered the primary temperature sensor for ground temperature data in this work.

The below-grade probes were constructed as follows. A 1 inch diameter PVC electrical conduit, 8 ft. long, served as the installation frame. The end of the PVC conduit was sealed to prevent moisture penetration. The physical probe was inserted into the PVC conduit (either the LM35 or the thermistor). The conduit was then filled with approximately 5 ft. of caulking inserted via holes drilled into the conduit at 1 foot intervals. The top 3 ft. of the conduit was filled with clean sand.

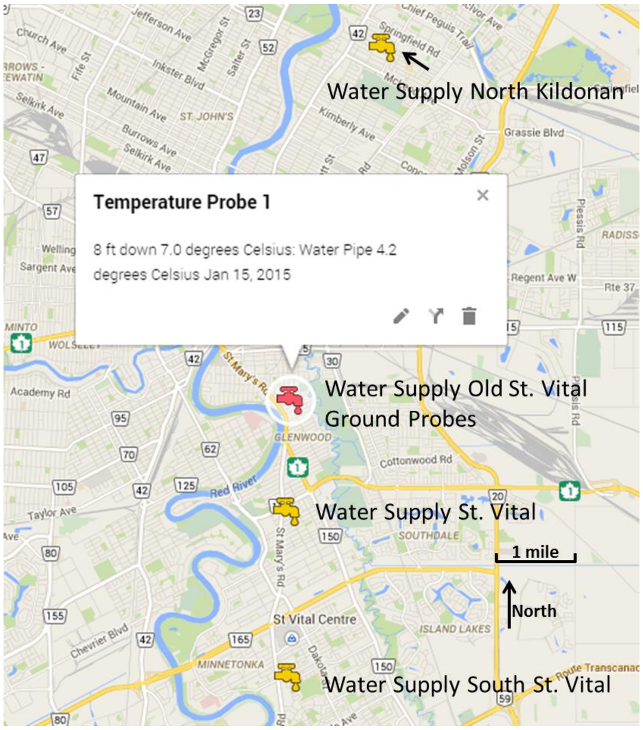
Three vertical boreholes were advanced into the ground adjacent to a roadway, but still under eventual snow cover. The borehole was advanced using a 1.75-inch diameter hand auger to 8.5 ft. below grade. The PVC conduit was placed in the borehole and the borehole was backfilled with clean sand and fine granular material. The extension cabling was trenched in small trench and run to a tree, somewhat camouflaged as this was installed along a residential street and not beyond being vandalized.

Although none of the above is difficult, it is also not the most convenient. Thus, a simpler data collection system was developed to provide similar information. Four thermistor probes (Lascar) were installed at the water supply line point of ingress into the residence (or as close as practical) (Fig. 3) in an attempt to infer the water supply temperature and consequently, when pipes may become at risk.

Figure 3: Illustration of a temperature probe on a water pipe.

2.2 Temperature Probe Network

Placing probes at depths of 8 ft. below grade is not overly difficult but lacks the convenience of installation and reading of probes located at water supply line point of ingress into the residence. The prototype system in this work has a total of five probes. Four of these are located at four distinct residences within Winnipeg, and one residence also includes the fifth probe monitoring ground temperature at 8 ft. below grade. Figure 4 illustrates the geographic locations of the temperature probes.



Temperature Probe 1

8 ft down 7.0 degrees Celsius: Water Pipe 4.2 degrees Celsius Jan 15, 2015

Figure 4: Temperature Probe Locations (Google Maps)

The location of the probe in the North Kildonan neighbourhood is also a location where the water supply line froze on April 2, 2014.

3 DATA COLLECTION AND DESCRIPTIVE ANALYSIS.

3.1 Data Collection

Data were collected from the end of November 2014 and are ongoing, although not all sensors came on-line at the same time.

Data collected from the probe installed 8 ft. below grade is the most easily processed as it displays very little variation, although not without some unexpected variation. The sampling rate on this type of probe can be set very coarsely and with the commercial OTS probe could reasonably be expected to last several months on one battery charge. Since the installation was fairly permanent, one battery charge would also be the lifespan of this probe in this prototype configuration. Issues associated with power management will be discussed subsequently.

Probes that were located on water supply lines are essentially sampling the temperature with a relatively small time constant (on the order of fractions of a minute). From the data, it is clear that the water in the supply line begins to warm immediately upon entering the portion of the water supply line in the home's basement. It was calculated that one flush volume of a standard toilet would draw the water from the water main across a typical residential street and into the home (approximately 100 ft. of 3/4 inch diameter supply line), and as such, the probe would momentarily record a temperature that proxies for the water temperature within the supply line. Thus, in order to make the inference as accurate as possible, probes have to sample aggressively, with only a small number of actual data points being reflective of the actual water temperature.

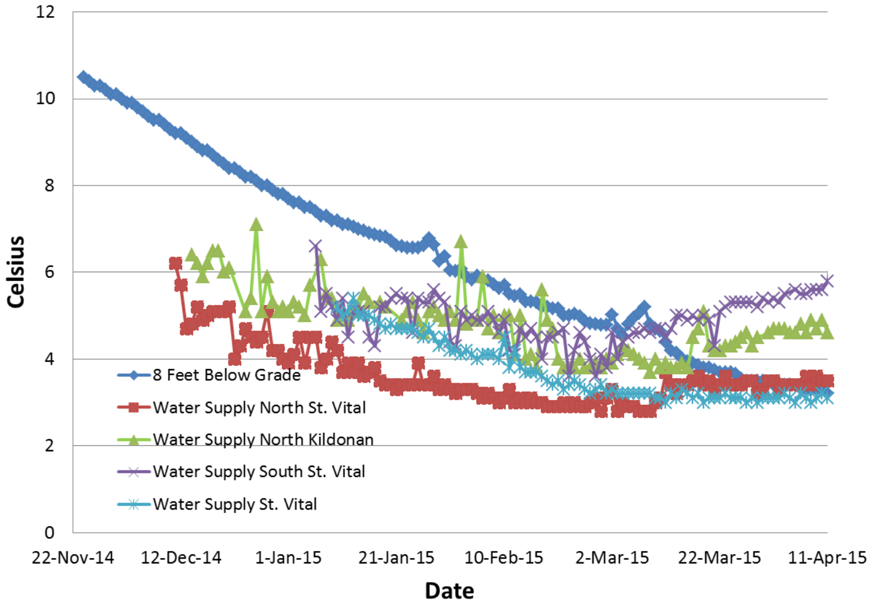


Figure 5: Temperature Sensor Data

Figure 5 presents the data to time of writing for the ground sensor and the four water supply line sensors.

Supply line temperatures: The temperatures at the collective water supply lines are shown on Figure 5 as the daily minimums. These are also uncorrected for the fact that the water within the line is expected to be somewhat cooler (1-2 degrees C) than the temperature recorded by the sensor on the supply line. Nonetheless, the temperatures at the water supply lines are below the recorded ground temperature at 8 ft. below grade (the approximate depth of the supply line itself). As more data is collected, it is anticipated that the ground will begin to be a contributing factor to water cooling, while at present the ground is in effect warming the incoming water. In Figure 5, one of the supply lines (St. Vital) has been fitted with a second degree polynomial which is slightly convex up. This curve projects an inferred water temperature of approximately 1.5 degree C in mid-April. Anecdotally, the supply line temperatures appear to be slightly responsive to ambient cold spells and warm spells. One hypothesis is that this is due to reservoirs in the city's water supply system being uncovered and exposed to the ambient temperature. While water certainly has a high heat capacity, even a large-volume uncovered reservoir may show slight temperature variations in response to ambient temperatures.

Ground temperature: In Figure 5, the data for the ground sensor at 8 ft. below grade represents a daily average of 144 data samples. There is very little variation associated with the data, with the data falling fairly linearly at approximately 0.5 degrees C per week. Figure 6 illustrates the ground sensor data more clearly fitted to both a linear and a polynomial model. As expected, the temperature is slightly convex up as seen in the data curve as well as the second order approximation. Using this second order fit, the temperature was predicted to be approximately 3.2 C in mid-April, and as of April 13, 2014, this has been realized.

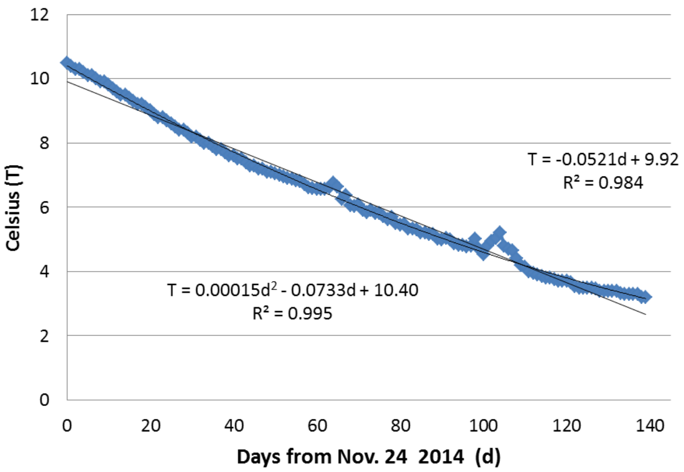


Figure 6: Curve fitted to data from sensor 8 feet below grade

Frost penetration: A model was developed to infer frost penetration, using cumulative freezing days or freezing index. Figure 7 illustrates the freezing index for 2015 (current year), 2014 (known cold year), and 2006 (a randomly-chosen year for reference). Data were extracted from http://climate.weather.gc.ca/ using the daily mean from a weather station in downtown Winnipeg (The Forks).

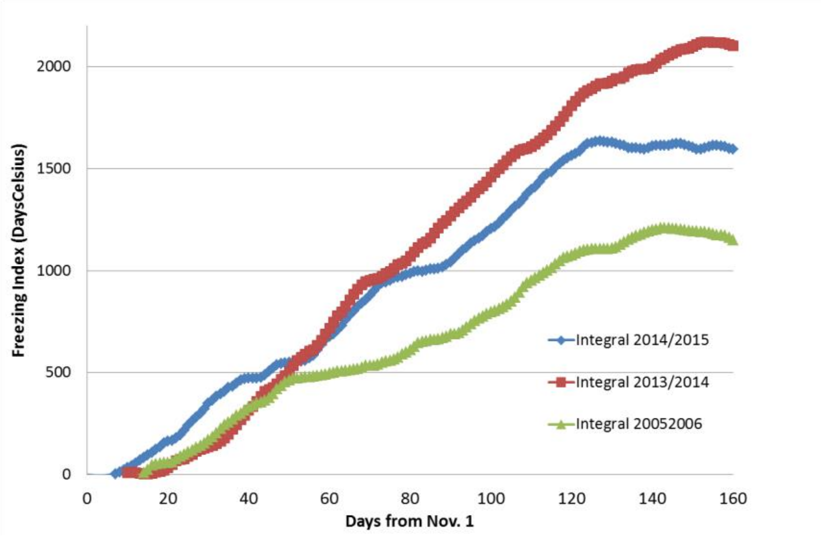


Figure 7: Cumulative Freezing Days (Freezing Index)

As per Figure 7, 2013/2014 and 2014/2105 were fairly close in terms of freezing index initially.

From the freezing index, a simplified model relating the freezing index to frost penetration was implemented. The model (Soliman 2008), as extracted from parametric and field experiments, is based upon the Stefan problem, more rigorously described by Frémond (1974). Fortuitously, this study was also done in Manitoba, Saskatchewan and Minnesota. The relationship between frost depth and cumulative freezing degree-days or freezing index (FI) can be represented by the following equation:

$$[1] \quad D_f = 4.8\sqrt{FI}$$

The coefficient of determination for this simplified model was estimated to be 0.89. Using this estimate of frost depth (D_f), Figure 8 illustrates the estimated frost penetration as calculated from the freezing index for 2013/2014 and 2014/2015.

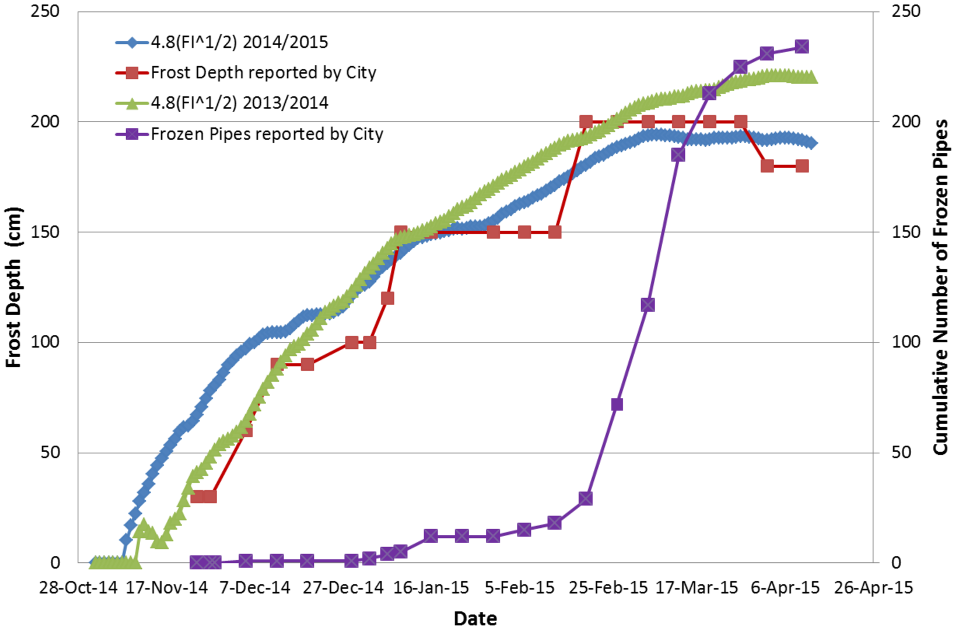


Figure 8: Frost Depth Estimation

Superimposed on Figure 8 are reported frost depth penetrations (Municipal “311” reporting) obtained from the city website (http://www.winnipeg.ca/waterandwaste/water/frozenPipes/default.stm) as well as the number of pipes that have been reported frozen in 2015.

For 2014/2015, it is somewhat reassuring that the estimated soil temperature at 8 ft. below grade is not expected to dip below zero C, based on relatively simple predictions. However, the means of knowing the temperature precisely at that depth is very valuable information and will be even more valuable when a true network of below grade probes is deployed. The frozen water supply lines in Winnipeg in 2013/2014 were not so much a function of geology and soil type as they were a function of geography, or more specifically, infrastructure installation practices at specific locations. This was demonstrated by the structured clustering of frozen pipes and properties at risk (Fig. 9), as estimated by the media outlet CBC (http://www.cbc.ca/news/canada/manitoba/map-shows-winnipeg-properties-at-risk-of-frozen-pipes-1.2594972). This information makes it even more reasonable to deploy a sensor network below grade at at-risk locations.

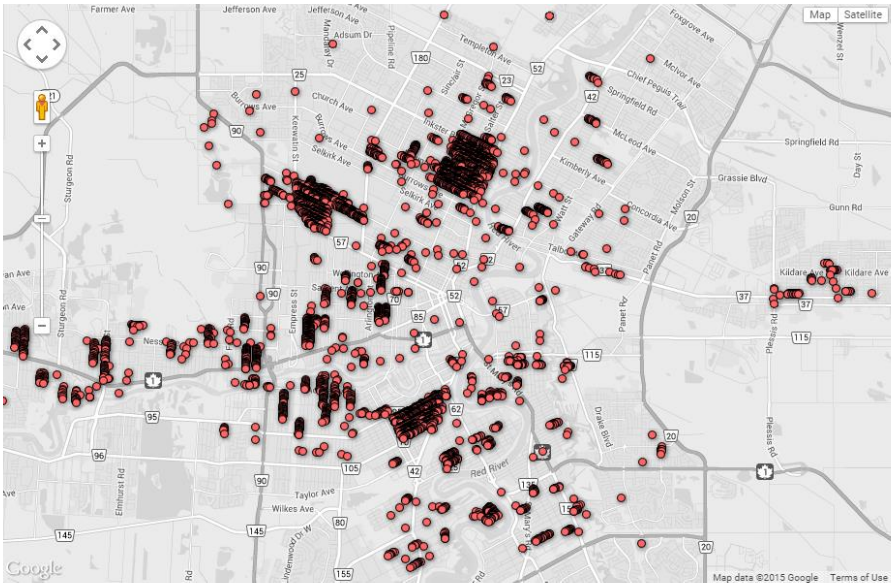


Figure 9: A distribution of Frozen Pipes in Winnipeg 2013/2014

Information being extracted from the water supply line ingress points to the home may prove to be even more useful, as this may allow for a site-specific indication of when a homeowner may be advised to trickle their water supply to prevent freezing. Similarly the same method may be used to help determine when running the water may be discontinued.

4 LIMITATIONS

This work was a prototype, intended to be expanded upon and scaled in the future. Through the prototype, a number of limitations are apparent. Although knowing the temperature at 8 ft. below grade is valuable, it would be even more useful to have an array of sensors at regular intervals at 2 ft. through 10 ft. below grade, and at multiple locations on that include bare surface (e.g. a street or sidewalk) as well as snow cover (e.g. a lawn). This would allow for a model to better fit the actual frost penetration progression as a function of the temperature at the ground/snow interface. In addition, a probe should be installed directly under the roadway as opposed to immediately adjacent. Frost penetration under the roadway is significantly greater than under a boulevard as illustrated in the schematic of Figure 10 (http://www.winnipeg.ca/waterandwaste/water/frozenPipes/thawingEquipment.stm).

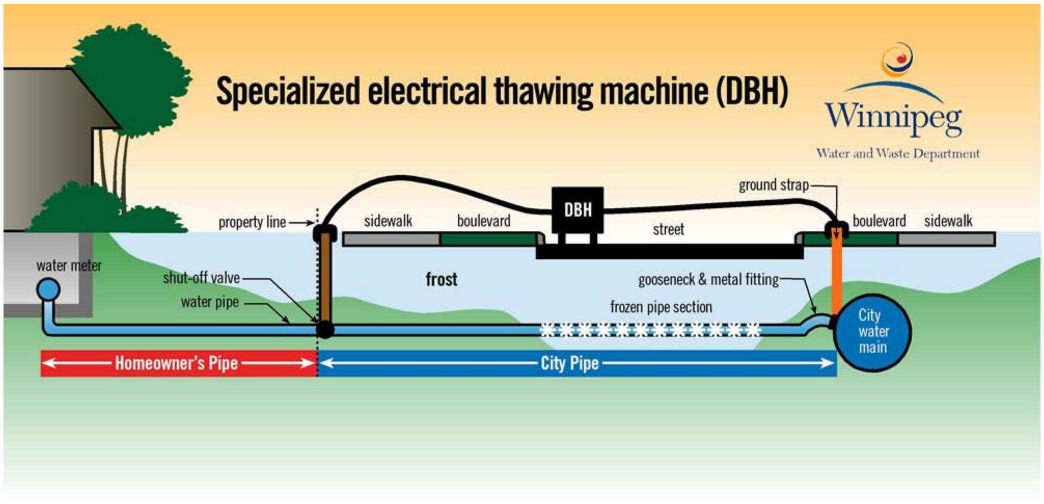


Figure 10 Schematic illustrating frost penetration under a roadway.

These considerations also bode well for water pipe temperature measurements to infer the potential of a pipe freezing.

Additional considerations when using this type of technology is related to battery life and the choice between "build or buy". The build option offers considerably greater flexibility, while the buy offers considerably greater convenience. The sensor monitoring the ground temperature has been running since Nov. 24, 2014 and reports approximately half the battery life remaining. It is however over sampled at a rate of 144 samples/day. This could realistically be reduced by an order of magnitude. The Wi-Fi signal strength is also a crucial determinant of battery life. The water supply line probe installed farthest from its associated WiFi access point (approximately 40 ft.) had a lifetime of just over a month while sampling at a rate of 1400 samples/day. This sampling rate is required as the time constants are considerably shorter for data collected at the water supply line.

5 SUMMARY

This project illustrates the relative ease with which a network of sensors can be inexpensively installed to provide either direct below-grade temperature data or an inference of water supply temperature through monitoring water supply line temperature at the point of ingress to a residence. Data collection is ongoing at the time of writing (March 2, 2015) and by the time of the conference in May 2015, additional insights should be available.

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