Considerations for Soil Moisture Monitoring

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1.0 Introduction

Soil is an important storage reservoir for water, holding it for future use, and buffering the plant-root environment against periods of water deficit (U.S. Department of Agriculture, 2008). Though soil moisture is estimated to account for only 0.001% (Shiklomanov, 1993) to 0.005% (Fetter, 2001) of the global water supply, it is an integral part of the hydrologic cycle at the land-atmosphere interface. The spatial and temporal variability of soil moisture both at the surface and in the root-zone is an important control in many hydrological and atmospheric fluxes. These fluxes play a critical role in water and energy balances, and have both a direct and indirect impact on water resources and local climate on global, regional and local scales. Regional water management can benefit from timely and reliable information about soil moisture content related to:

- Improved quantifications of flood risks by its effect on rainfall estimations on the soil profile and conversely negative anomalies to current plant water demands that are an indicator of (the onset of) droughts (Benninga, et al., 2018).

- The agricultural sector depends on sufficient root zone soil water availability for crop growth, while excess of soil water leads to severe losses. Many cultivation activities respond to the level of soil moisture in the fields. This dictates the timing of tilling, planting, harvesting, and the application of chemicals and fertilizers (Scott, et al., 2010).

Soil moisture is highly variable both spatially and temporally. It is widely recognized that improving the knowledge and understanding of soil moisture and the processes underpinning its spatial and temporal distribution is critical. Two main avenues are used for soil moisture monitoring: in situ, field based monitoring and earth observations via remote sensing. In situ instruments are the most accurate and can have a high temporal resolution when automated, but they lack spatial support (Benninga, et al., 2018). Conversely, earth observations and models provide areal estimates and enable the quantification of soil moisture across large spatial domains. Further, data generated from the insitu soil moisture provides a reference for validating earth observation models and land process models. The combination of in situ measurements at various depths, earth observation products, and land process models is essential to obtaining reliable soil moisture information at the temporal, horizontal and vertical resolutions required for the above-mentioned applications (Benninga, et al., 2018).

Presently, regional soil moisture monitoring at the provincial level is restricted to a limited distribution of in-situ soil moisture monitors tied to the Provincial Groundwater Monitoring Network (PGMN) originally deployed with reference to the Ontario Low Water Response (OLWR) Program. From a policy framework, the OLWR currently monitors precipitation and streamflow. Additional parameters for consideration within the OLWR framework consist of groundwater and soil moisture (Quinte Conservation, 2012). Ontario is lagging behind other jurisdictions that have well established soil moisture monitoring networks, particularly those in the Oklahoma, Illinois, Australia, etc. (Illinois State Water Survey, 2018; Monash University & Melbourne School of Engineering, 2015; University of Oklahoma, 2018).

Through the evaluation of other jurisdictional soil moisture monitoring networks (see Table 1), the objective of this report is to outline considerations for a NVCA-focused soil moisture

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monitoring network including examination of site location, data use in support of internal and external program, data management platform, equipment used, etc.

Funding for this project was provided by the Ontario Ministry of Environment, Conservation, and Parks (MECP).

2.0 Soil Moisture as a Drought Indicator

Soil moisture is the central variable by which agricultural drought is defined, and soil moisture mediates the relationship between meteorological and hydrological drought (Ochsner, 2018).

- Meteorological drought is defined as a lack of precipitation input over a specified region during a particular period of time (Hao & AghaKouchak, 2013). During meteorological drought, soil moisture quickly drops. Other water resources (e.g., streamflow and groundwater levels) follow at a slower pace. Likewise, during recovery from drought, increases in essential water sources within the state first requires recovery in soil moisture (Figure 1; Scott, et al., 2010).

- Agricultural / ecological drought corresponds to declining soil moisture negatively impacts agricultural production / the occurrence of reduced primary productivity in natural systems (Le Houérou, 1996). These two terms can be combined as agroecological drought, which is often preceded by meteorological drought, and may be followed by hydrological drought (Ochsner, et al., 2013).

- Hydrological drought is a period of inadequate surface and subsurface water resources to support established water uses (Hao & AghaKouchak, 2013).

Some of the more popular drought indexes that use soil moisture monitoring in the analysis and interpretation consists of: Palmer Drought Severity Index, Soil Moisture Deficit Index, Crop Moisture Index, and Soil Moisture Percentiles. There is no drought indicator in Ontario that presently uses soil moisture monitoring.

A regional-scale soil moisture monitoring network can provide an early indication of the spatial extent of developing adverse conditions. It also can assist in tracking impacts within other water resources of the area during developing and prolonged periods of precipitation extremes (Payero, et al., n.d.). As a part of the hydrologic cycle, soil moisture data can provide critical and timely information on where dry conditions may be developing across the region due to rainfall deficits.

Quinte Conservation (2014) undertook a review of the use of soil moisture data in drought condition assessment in jurisdictions outside Ontario with recommendations outlined below on the use of soil moisture data in the OLWR.

1. Soil moisture is a parameter that can change rapidly over relatively short distances owing to changes in soils, distribution of rainfall and hydrologic properties of the landscape. In situ networks in Ontario are sparse with a limited period of record. For these reasons it is recommended that the Province develop a model to calculate soil moisture levels based on soils mapping, climate, and radar data. The model would need to be used to review long term climate data to calculate soil moisture conditions.

2. The in situ network of soil moisture probes should be used to calibrate and verify the results of the model. Effort to expand and maintain the network of soil moisture probes
in the province is needed such that data is available for all of the different physiographic regions.

3. Review of the use of satellite imagery in this program would be required through consultation with organizations familiar with this process such as the University of Guelph (e.g., Aaron Berg).

4. The percentile method is recommended as being used to assess soil moisture data for drought conditions. A review of long term data would be required to calculate monthly percentiles with triggers for different low water conditions determined based on the historic data and review of historic levels declared throughout the Province.

Building on Quinte Conservation (2014) recommendations, it is presently considered premature to consider a soil moisture indicator for Ontario in support of the OLWR given the lack of in situ monitoring data in combination with the lack of a provincially accessible soil moisture model and QA/QC temporal data to satisfy statistical interpretations. Therefore, it is recommended to:

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Figure 1: Sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of drought and impacts cascade from this deficiency (University of Nebraska, 2018).
1. Evaluate all existing Ontario soil moisture monitoring networks including both government-led (e.g., MECP, MNRF, and Conservation Authorities) and private networks in terms of distribution and density to determine the location and spatial distribution and ownership (and availability) of the data.

2. From this, determine the time series length of the QA/QC data and identify the areas/sites of strengths and weakness to which to build a strong regional monitoring network from and also understand where the operational, spatial, and time series gaps are. This desktop information will be used to evaluate if a soil moisture indicator is at all feasible in the present state.

3. Complete a statistical analysis of a proposed soil moisture monitoring network that would satisfy regionally both low water and flood questions.

4. Solicit the development of regional to provincial scale remote sensed soil moisture models. Remote sensing using satellite imagery is also becoming more popular to assess soil moisture conditions over large spatial areas. This methodology has been shown to be good for detecting changes and extreme.

5. Use the identified golden spike, in-situ soil moisture monitors to calibrate the model with long term and continued soil moisture monitoring.

3.0 Examples of Existing Networks

A short desktop review of existing soil moisture monitoring networks in jurisdictions outside the NVCA watershed was undertaken to evaluate key program objectives, number of stations, installation depth and other parameters listed. The results, provided below in Table 1, are used to determine comparable opportunities at the NVCA.
<table>
<thead>
<tr>
<th>Network</th>
<th>Objective</th>
<th>Program Duration</th>
<th>Number of Stations</th>
<th>Telemetry Type</th>
<th>Probe Tech</th>
<th>Install Details</th>
<th>Other Parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Climate Analysis Network (SCAN), National Scale, USA <a href="https://www.wcc.nrcs.usda.gov/scan/">https://www.wcc.nrcs.usda.gov/scan/</a></td>
<td>to support natural resource assessments and conservation activities, including drought monitoring and mitigation, climate change trends, watershed health, agricultural needs (crop suitability and irrigation), runoff and flood changes</td>
<td>1991 - present</td>
<td>226 over 9,842,621 km²</td>
<td>cellular data in East; GOES in West</td>
<td>HydraProbe 5, 10*, 20, 50, and 100* cm *optional depth</td>
<td>air temperature, relative humidity, solar radiation, wind speed &amp; direction, liquid precipitation, barometric pressure</td>
<td>(including Puerto Rico)</td>
<td></td>
</tr>
<tr>
<td>U.S. Climate Reference Network (USCRN); NOAA, National Scale, USA <a href="https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/us-climate-reference-network-uscrn">https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/us-climate-reference-network-uscrn</a></td>
<td>to provide a continuous series of climate observations for monitoring trends in the nation's climate and supporting climate-impact research</td>
<td>late 1990's - present?</td>
<td>114 over 9,833,517 km²</td>
<td>Campbell Scientific TX320 GOES transmitter</td>
<td>Stevens HydraProbe II 5, 10, 20, 50, 100 cm x3 plots per station, 5-minute averaged data</td>
<td>air temperature, precipitation, surface temperature, solar radiation, wind speed, relative humidity, wetness</td>
<td>Soil moisture probes have been added to these stations following the SCAN network configuration (Ochnser, et al., 2013)</td>
<td></td>
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<tr>
<td>Automated Weather Data Network (AWDN), Regional Scale, USA Mid-West <a href="https://hprcc.unl.edu/awdn.php">https://hprcc.unl.edu/awdn.php</a></td>
<td>to gather observational data and provide it to stakeholders in agriculture and related fields.</td>
<td>1981 - present</td>
<td>110 over 2,052,481 km²</td>
<td>Theta probe (Delta-T DevicesML2x) (TDR)</td>
<td>10, 25, 50, 100 cm</td>
<td>air temperature, humidity, wind speed and direction, precipitation</td>
<td>measured every 60s and averaged hourly</td>
<td></td>
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<tr>
<td>Illinois Climate Network, State scale <a href="https://www.isws.illinois.edu/warm/weather/">https://www.isws.illinois.edu/warm/weather/</a></td>
<td>to obtain the necessary base of long-term information from which comparison assessments can be made between these data and other water resources in the state during periods of extremes in precipitation.</td>
<td>1981 - present</td>
<td>19 over 149,998 km² (as of 2010)</td>
<td>Stevens-Vitel Hydra-20</td>
<td>5, 10, 20, 50, 100, 150 cm</td>
<td></td>
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<tr>
<td>Network</td>
<td>Objective</td>
<td>Program Duration</td>
<td>Number of Stations</td>
<td>Telemetry Type</td>
<td>Probe Tech</td>
<td>Install Details</td>
<td>Other Parameters</td>
<td>Comments</td>
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<tr>
<td>Oklahoma Mesonet, State Scale <a href="http://mesonet.org/">http://mesonet.org/</a></td>
<td>soil moisture depth installations strategically placed to enhance agricultural and meteorological modeling, aid in drought monitoring and generate research quality datasets.</td>
<td>1991 - present</td>
<td>120 over 181,195 km²; at least one in each county</td>
<td>heat dissipation sensors (Campbell Scientific CS-229)</td>
<td>5, 25, 60, 75 cm</td>
<td>air temperature, relative humidity, wind speed &amp; direction, barometric pressure, solar radiation, rainfall, bare and vegetated soil temperature.</td>
<td></td>
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<tr>
<td>Murrumbidgee Soil Moisture Monitoring Network (MSMMN), Watershed Scale, Australia <a href="http://www.oznet.org.au/">http://www.oznet.org.au/</a></td>
<td>surface model validation &amp; development, and remote sensing applications</td>
<td>2001- present</td>
<td>38 over 84,917 km²</td>
<td>Campbell Scientific water content reflectometers, (CS615, CS616), TDR probes, and HydraProbes combined</td>
<td>0-30, 30-60, 60-90cm</td>
<td>many stations co-located with Bureau of Meteorology automatic weather stations</td>
<td>SM at 0-5 or 0-8 cm, sampled every 5 or 60 s, averaged over 20-30 min (second and first generation sites)</td>
<td></td>
</tr>
<tr>
<td>Integrated Watershed Management Program, Watershed Scale, CVC <a href="https://cvc.ca/watershed-science/watershed-monitoring/">https://cvc.ca/watershed-science/watershed-monitoring/</a></td>
<td>To track soil moisture and temperature in long-term forest monitoring sites as abiotic indicator of forest integrity</td>
<td>2008- present</td>
<td>6 active (26 historical) over 950 km²</td>
<td>None; downloaded 2x annually</td>
<td>Decagon 10HS installed vertically in top 20cm of soil profile; 2 installed in each of the 3 watershed zones</td>
<td>ground vegetation, regeneration, tree health, birds, downed wood, soil temperature</td>
<td>responses to questions</td>
<td></td>
</tr>
<tr>
<td>Wetland Ecohydrology Program, Watershed Scale, CVC <a href="https://cvc.ca/watershed-science/watershed-monitoring/">https://cvc.ca/watershed-science/watershed-monitoring/</a></td>
<td>To understand the occurrence of water through the unsaturated zone within rooting zone; to be used in conjunction with piezometers adjacent to wetlands.</td>
<td>2011- present</td>
<td>2 over 950 km²</td>
<td>None; downloaded 4x annually</td>
<td>Decagon ECH20 EC-5 10, 20, 30, 50, 100 cm</td>
<td>ground vegetation, regeneration, tree health, frogs, downed wood, groundwater levels, surface water levels, barometric pressure</td>
<td>responses to questions</td>
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</table>
4.0 In Situ Soil Moisture Monitoring Technology Considerations

Presently, the MECP is applying the following approach for soil moisture monitoring as part of the PGMN program: using Stevens HydraProbe II, connected to a telemetry system with three probes installed per station at depths of 5, 20, and 50 cm. Prior to the probe installation, soil samples were collected from these depths for particle size, density, and SM analyses, following the methods outlined in Appendix A. This section builds on the technology that is used for the MECP (PGMN) installed soil moisture monitoring.

4.1 Stevens HydraProbe Overview

The Stevens HydraProbe soil temperature and moisture sensor measures soil temperature, bulk electrical conductivity, and real dielectric permittivity based on the reflectance of an electrical signal transmitted through the soil between the center and three perimeter tines (Campbell Scientific (Canada) Corp., 2017). Dielectric permittivity describes a material’s ability to permit an electric field. The dielectric constant of dry soil is very small (1.5 to 4) relative to that of water (80 at room temperature), therefore soil moisture can be directly related to the dielectric constant (Atkins, et al., 1998). The key parameters of the probe are outlined below with unit specifications provided in Appendix B.

**Soil Temperature**: Soil temperature (Celsius or Fahrenheit) is the temperature of the sensor/soil water system. Daily temperature fluctuations between daytime highs and nighttime lows may be observed with the HydraProbe’s temperature data; becoming less pronounced with depth. Vegetation, tree canopy, and soil moisture are factors that affect daily soil temperature fluctuations (Cook, 2018).

**Soil Conductivity**: The soil electrical conductivity (Siemens (S)/m) is an indication of dissolved salts, dissolved solids, fertilizer, and pH in the soil. The HydraProbe will measure EC up to 1.5 S/m. The accuracy of EC parameters in soil are highly soil dependent; however, the HydraProbe’s EC measurements in slurry extracts, water samples, and aqueous solutions are accurate (Cook, 2018).

**Soil Moisture**: The HydraProbe provides accurate soil moisture measurements in units of water fraction by volume (wfv or m^3/m^3) (Campbell Scientific (Canada) Corp., 2017). That is, a percentage of water in the soil displayed in decimal form. Multiplying the water fraction by volume by 100 will equal the volumetric percent of water in soil (Stevens Water Monitoring Systems, Inc., 2006). For example, a water content of 0.20 wfv means that a 1 L soil sample contains 200 mL of water. Full saturation (all the soil pore spaces filled with water) is soil dependent, but typically occurs between 0.40 - 0.55 wfv for mineral soil. The unit of wfv was chosen for the HydraProbe for a number of important reasons (Stevens Water Monitoring Systems, Inc., 2006). First, the physics behind the soil moisture measurement dictates a response that is most closely tied with the wfv content of the soil. Second, without specific knowledge of the soil, one can not convert from wfv to the other unit systems (e.g., % capacity). Third, the unit wfv allows for direct comparison between readings in different soils: a 0.20 wfv clay contains the same amount of water as a 0.20 wfv sand.

Further, plant water availability, i.e., the equivalent depth of water in a soil section that is available for plant root use, can be determined from the soil moisture readings (whereas total plant water availability corresponds to the equivalent depth of water in the soil column that is available for plant root use.) These two extrapolated variables can be determined where the probes have been installed at increasing depth (e.g., 5, 10, 20, 50, 100 cm). The amount of water in each section depends on the soil moisture and the height of the section. These...
depths function to provide an idea of where the greatest and least amount of water is stored in the total soil water column (Cook, 2018).

**4.2 Soil Probe Depth**

The vertical distribution of the soil moisture monitor depths is related to vegetation rooting depth, soil type, and precipitation regime; capturing the change in soil moisture in the hydrologically dynamic layer in two main temporal zones: the near surface (0-5 cm) and the root zone (0—50 cm+, depending on the vegetation fabric). Typically the probes are installed at 5, 10, 20, 50, and 100 cm depths with the first four depths corresponding to the root zone and the last one installed below it. Further, the placement of multiple probe depths allows for the strategically enhancement of agricultural and meteorological modeling, aid in drought monitoring, and generate research quality datasets. Values measured by soil moisture probes can be used to calculate, hydrological variables such as soil water content, soil matric potential, and Fractional Water Index (FWI) (Illston, et al., 2004).

**4.3 Telemetry Restrictions**

At this time, incorporation of soil moisture monitoring in PGMN is restricted to stations with FTS Axiom datalogger telemetry. The Stevens Hydra Probe sensors do not have built-in memory therefore, installing them with FTS Hopper telemetry systems that simply transmit data with no internal memory, increases the risk of data gaps should there be transmission issues. The new FTS LT1 telemetry systems are not recommended at this time for this application as they can only connect to two sensors and soil moisture is monitored at three depths for each station.

The default soil moisture probes from FTS (Stevens Hydra Probe) have a 25-foot (7.6 m) cable with either a three-lead connection or bayonet connector which is directly compatible with FTS Inc. Axiom dataloggers. It is also possible to order these sensors with custom cable lengths up to 200 feet (~61 m). It is recommended that the appropriate custom length of cable is ordered for each site to avoid burying junctions that must be kept secure and dry within the conduit to the telemetry station.

**4.4 Data Quality Control**

At this time the MECP does not have established guidelines and/or protocols for: sensor calibration to site specific soil conditions, in situ validation, quality control, archiving, retrieval, etc. Factory default calibrations are being used as the interest is in relative change rather than absolute soil moisture values. It is also anticipated that data will be stored on and retrieved from the MNRF WISKI system.

Other soil moisture monitoring networks use the following protocols for quality control on their soil moisture data. After installations of soil moisture probes, the Oklahoma Mesonet considers the first 21 days of data to be erroneous, allowing time for the soil to heal around the sensor (Illston, et al., 2004). Both the Automated Weather Data Network in Nebraska (You, et al., 2010) and the Oklahoma Mesonet (Illston, et al., 2004) have automated algorithms to ensure quality control of their datasets, flagging occurrences that do not meet the following conditions for additional review: data should be within the appropriate range (-0 °C to 50 °C) and should not be erratic (Illston, et al., 2004). The degree of saturation cannot be greater than the soil’s porosity (Φ) and therefore must be between 0 and Φ (You, et al., 2010). When volumetric water content (VMC; θ) is less than field capacity, the changes
should not have a large decrease over time, and when the VMC is less than the permanent wilting point, VMC change should not be negative (You, et al., 2010). Day-to-day changes in soil moisture should not be excessive; Hubbard et al. (2005) and You et al. (2010) found applying a confidence interval factor of 3.0 was appropriate for Nebraska. Soil moisture measurements in spatial proximity to one another are likely to be statistically correlated. The relationship between stations can be used to flag erroneous measurements (Hubbard, et al., 2005). Finally, the HydraProbes have no calibration procedures; when data show periods of unreasonable wfv data (high atypical variability without coincident rainfall, apparent noise in temporal trends, values of zero in clay or loam soils, etc.), they are removed from service (Scott, et al., 2010).

5.0 Proposed NVCA Soil Moisture Monitoring Network

5.1 Vision/Mission of an NVCA Soil Moisture Monitoring Network

It is acknowledged that soil moisture is highly variable both spatially and temporally. Similar to the NVCA groundwater monitoring program objectives, the primary objective of the proposed NVCA soil moisture monitoring network is to provide baseline, regional soil moisture monitoring data in order to:

- Support water management activities such as: flood, drought response, planning decisions;
- Identify trends and correlations (e.g., related to changing climate), and support policy, standard, and guideline development/assessment;
- Better understanding of hydrologic correlations between precipitation, groundwater levels, and soil moisture;
- Share information with other water resource managers, public, consultants, academia, etc.

This regional framework can compliment more localized soil moisture monitoring activities. This network is not intended to replace nor provide the resolution required for precision agriculture or for field-based irrigation scheduling but to provide a background, emerging conditions approach. It is envisioned that the NVCA soil moisture monitoring network would be in alignment with provincial mandates (e.g., low water response and flood forecasting) with operational program alignment with the PGMN program led by the MECP given the existing monitoring infrastructure and hydrologic linkages.

It is encouraged that the soil moisture data will be collected in real time in order to maximize the potential beneficial use of the data. The data is envisioned to contribute to natural hazard warning, specifically low water and flood. Further, this information can be locally used to compliment and calibrate integrated hydrologic modelling, e.g., subwatershed scale modelling in support of subwatershed planning. If public facing, this data can also allow the NVCA stakeholders, especially the agricultural community/sector with regional baseline conditions to support business decision processes. Further, data generated from the in-situ soil moisture provides a reference for validating earth observation models and land process models as the combination of in situ measurements at various depths, earth observation products and land process models is essential to obtaining reliable soil moisture information at the temporal, horizontal and vertical resolutions.

Due to the temporal, seasonal, and annual variation in soil moisture monitoring (even more so then groundwater), a long-term, up front commitment is required before a statistically
A sound dataset is useable for analysis and interpretation. For example, this period could be ~5-7 years for theil-sen evaluation. Once a long-term dataset is available, past soil moisture conditions can be analyzed with known periods of drought and flooding to aid in forecasting models. The data logging for soil moisture should also be comparable to the PGMN program: hourly measurements, 365 days per year. This will allow one to one comparison of the datasets.

Sound database management is the foundation for credible decision making and effective long-term water management. Data generated from the soil moisture monitoring is required to be housed in an integrated hydrologic dataset. It is envisioned that data generated from the soil moisture monitoring network will be stored in the password protected MNRF WISKI platform. This integrated platform also contains snow survey, climate (precipitation and temperature), streamflow, and other data sources. For local data use, it is also envisioned that the data will be scraped from the MNRF WISKI system into the Oak Ridges Moraine Groundwater Program (ORMP) data management platform. The ORMP (YPDT-CAMC, n.d.) has developed a comprehensive database that is the foundation for long-term effective groundwater management. This integrated database incorporates geology (e.g., depth to bedrock, thickness of gravel, clay, etc.), ground water (e.g., water levels, pumping rates, and chemistry), surface water (e.g., streamflow rates) and climate (e.g., precipitation) related information across the watersheds that are situated within the Oak Ridges Moraine area, including the NVCA. The database was built recognizing effective water management requires access to data, spanning a range of agencies and disciplines.

### 5.2 Jurisdictional Considerations for Site Selection Criteria

Soil moisture monitoring sites should be representative of the region (both in climate and landscape position) without strong influence of local factors (including artificial irrigation, floodplains, orographically-induced severe winds, persistent extreme snow depths), unlikely to change over the next 50-100 years whether through land use encroachment, land ownership, or accessibility, etc., and should also be easily accessible year-round with preference to public over private land ownership (National Oceanic and Atmospheric Administration (NOAA), n.d.; USDA, 2004). The site would ideally also be in low-traffic areas away from public view (USDA, 2004). Sites should be located in areas with mapped soil types covering a large extent, preferably with medium texture soils in well drained areas and near or co-located with existing meteorological stations with historic daily precipitation and temperature data (NOAA, n.d.; USDA, 2004).

Tree canopy may affect precipitation input, upper slopes may be better drained than depressions, proximity to surface water may indicate high water table position, and hillslopes may have seeps/springs (Stevens Water Monitoring Systems Inc., 2018a, 2018b). The rooting zone varies in depth for forested sites compared to grasslands causing forests to have lower soil moisture at depth, while grasslands extract soil moisture from shallower depths (Zheng, et al., 2015). Sites that are prone to flooding or standing water should be avoided (Scott, et al., 2010).

Many established soil moisture monitoring networks have indicated that standard procedures are to install soil moisture probes in areas of grassy vegetation, avoiding forest cover (Ochsner, et al., 2013; USDA, 2004). For example, the Illinois Climate Network has all probes installed under sod cover (Scott, et al., 2010), and NASA recommends selecting sites that do not have tall grasses nor trees (Podest, 2017). While this may be beneficial for networks that aim to inform the agricultural community, data would not be representative at the regional scale. In contrast, Credit Valley Conservation (CVC, 2011) monitors soil moisture to inform forest health assessments. Also, overall network density and distribution should be considered...
in addition to using the physical attributes of a site to determine locations of soil moisture probe installations. When comparing data across the entire network, different vegetation types and thicknesses are likely to yield different soil moisture root uptake. Care must be taken when associating these data to adjacent areas where soil moisture observations are not made, especially those under a different surface cover (Scott et al. 2010).

5.3 Proposed NVCA Network Overview

The NVCA watershed was conceptually examined to delineate a proposed soil moisture monitoring network. This regional network would complement the existing climate, surface water, and groundwater monitoring networks in which the NVCA either leads or is an active partner in. Evaluation of potential sites is based principally on the soil hydrologic class, physiography, topography, and local land use; strategically distributed throughout the 3150 km² watershed. In support of the development of multi-parameter, golden spike monitoring sites, the soil moisture sites are limited to existing monitoring infrastructure. The potential sites were chiefly focused around PGMN sites and secondly the Water Survey of Canada stream gauges, the NVCA climate network, and the Simcoe Groundwater Monitoring Program sites. It is noted that sites with and without existing telemetry were considered.

Seven soil moisture monitoring sites are proposed; physiographically diversely located in the Oak Ridges Moraine, Niagara Escarpment, and Simcoe Lowlands areas, etc. and correspond to:

- 4 PGMN sites: W323 (Bradford; installed 2017; connected to telemetry 2018), W232-2 (Wasaga Beach), one of W244-2/W245-2 (Midhurst), W505-1 (Redickville).
- 2 SGMP sites: SS-11-09 (Glencairn) and SS-11-02 (west of Tottenham).
- 1 NVCA Climate station: the precipitation gauge at the Mono Township office (Table 2)

Each of the proposed PGMN and SGMP sites are comprised of a nest of at least two groundwater monitoring wells. Site W232-2 is a current FTS LT1 test station. Sites W244-2 and W245-2 have FTS Hopper telemetry, and would require telemetry upgrade to an FTS Axiom. Also, only SS-11-09 and SS-11-02 do not have existing telemetry. The existing datalogger and telemetry equipment associated with the Mono Township Office precipitation gauge should be able to incorporate the soil moisture probes, or it could be replaced with an FTS Axiom datalogger.

The site distribution correspond to 3 soil class A sites, 3 class B sites, and 1 class C site. This is reflective of the overall soil classification of the watershed being predominantly class A and B (combined 70% of the watershed; Table 3 and Figure 2 and 3). No sites correspond to the D soil hydrologic class (which is muck soil, corresponding to wetlands that were intentionally avoided for soil moisture monitoring). Overall soil classification by subwatershed and physiographic region are also presented in Table 4 and Table 5, respectively. Aimed for relatively equally distribution throughout the watershed where existing monitoring sites exist, the soil moisture monitoring site distribution has 2 proposed sites in both the Innisfil Creek subwatershed and Mad River subwatershed (two of the largest subwatersheds), followed by the Willow Creek subwatershed (1 site), Lower Nottawasaga River subwatershed (1 site), and the Upper Nottawasaga River subwatershed (1 site). Note that some subwatersheds lack a proposed soil moisture site (e.g., Pine and Boyne Rivers).
Although no statistical spatial analysis was completed on the site distribution, the seven proposed soil moisture monitoring sites corresponds to approximately 471 km$^2$ spacing of the 3150 km$^2$ watershed area.

Table 2: Details for proposed soil moisture installation sites. Note GW = groundwater (level & temperature); BP = barometric pressure; R = rain gauge; S = snow gauge; SM = soil moisture (moisture, conductivity, temperature).

<table>
<thead>
<tr>
<th>Site name</th>
<th>Program area</th>
<th>Subwatershed</th>
<th>Physiographic region</th>
<th>Soil class</th>
<th>Land use</th>
<th>Existing sensors</th>
<th>Telemetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>W323 (Bradford)</td>
<td>PGMN</td>
<td>Innisfil Creek</td>
<td>Simcoe Uplands</td>
<td>B - Bondhead Sandy Loam</td>
<td>Forest/ agriculture</td>
<td>3x GW, BP, R,</td>
<td>FTS Axiom</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Steep Phase</td>
<td></td>
<td>3x SM</td>
<td></td>
</tr>
<tr>
<td>W232-2 (Wasaga Beach)</td>
<td>PGMN</td>
<td>Lower Nottawasaga River</td>
<td>Simcoe Lowlands</td>
<td>A - Tioga Loamy Sand</td>
<td>savannah grassland</td>
<td>2x GW</td>
<td>LT1 pilot program</td>
</tr>
<tr>
<td>W244-2/W245-2 (Midhurst)</td>
<td>PGMN</td>
<td>Willow Creek</td>
<td>Simcoe Lowlands</td>
<td>A - Sargent Gravelly Sandy Loam</td>
<td>Forest</td>
<td>2x GW, BP</td>
<td>FTS Hopper</td>
</tr>
<tr>
<td>W505-1 (Redickville)</td>
<td>PGMN</td>
<td>Mad River</td>
<td>Dundalk Till Plain</td>
<td>B - Honeywood Silt Loam</td>
<td>agriculture</td>
<td>3x GW, BP, R</td>
<td>FTS Axiom</td>
</tr>
<tr>
<td>SS-11-09 (Glencairn)</td>
<td>SGMP</td>
<td>Mad River</td>
<td>Horseshoe Moraines</td>
<td>B - Bookton Sandy Loam</td>
<td>agriculture</td>
<td>2x GW</td>
<td>none</td>
</tr>
<tr>
<td>NVCA precipitation gauge, Mono</td>
<td>NVCA</td>
<td>Upper Nottawasaga River</td>
<td>Horseshoe Moraines</td>
<td>A - Dumfries Loam</td>
<td>Forest/ rural residential</td>
<td>R, S, T</td>
<td>GPRS Link Direct IP</td>
</tr>
<tr>
<td>SS-11-02 (Bond Head)</td>
<td>SGMP</td>
<td>Innisfil Creek</td>
<td>Peterborough Drumlin Field</td>
<td>C - Schomberg Silty Clay Loam</td>
<td>agriculture</td>
<td>2x GW, BP</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 3: NVCA soil classification. The area of unclassified soil is primarily within CFB Borden.

<table>
<thead>
<tr>
<th>Soil Classification</th>
<th>Area (km$^2$)</th>
<th>Percent of watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>1014</td>
<td>32%</td>
</tr>
<tr>
<td>Class B</td>
<td>1200</td>
<td>38%</td>
</tr>
<tr>
<td>Class C</td>
<td>494</td>
<td>16%</td>
</tr>
<tr>
<td>Class D</td>
<td>318</td>
<td>10%</td>
</tr>
<tr>
<td>Unclassified</td>
<td>121</td>
<td>4%</td>
</tr>
</tbody>
</table>

Table 4: Soil Classification of the NVCA by subwatershed breakdown (km$^2$).

<table>
<thead>
<tr>
<th>Subwatershed</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Unclassified</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Mountain</td>
<td>33.9</td>
<td>114.8</td>
<td>69.0</td>
<td>1.2</td>
<td>1.8 (1%)</td>
<td>220.7 (7%)</td>
</tr>
<tr>
<td></td>
<td>(15%)</td>
<td>(52%)</td>
<td>(31%)</td>
<td>(1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boyne River</td>
<td>119.4</td>
<td>81.1</td>
<td>22.3</td>
<td>14.9</td>
<td>2.2 (1%)</td>
<td>239.9 (8%)</td>
</tr>
<tr>
<td></td>
<td>(50%)</td>
<td>(34%)</td>
<td>(9%)</td>
<td>(6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Innisfil Creek</td>
<td>111.1</td>
<td>177.7</td>
<td>160.9</td>
<td>39.3</td>
<td>1.0 (0%)</td>
<td>490.0 (16%)</td>
</tr>
<tr>
<td></td>
<td>(23%)</td>
<td>(36%)</td>
<td>(33%)</td>
<td>(8%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subwatershed</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>Unclassified</td>
<td>Total</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>Lower Nottawasaga River</td>
<td>103.5(23%)</td>
<td>124.1(27%)</td>
<td>121.5(27%)</td>
<td>98.6(22%)</td>
<td>7.6(2%)</td>
<td>455.4(14%)</td>
</tr>
<tr>
<td>Mad River</td>
<td>83.3(18%)</td>
<td>261.4(58%)</td>
<td>22.5(5%)</td>
<td>62.4(14%)</td>
<td>22.3(5%)</td>
<td>451.9(14%)</td>
</tr>
<tr>
<td>Middle Nottawasaga River</td>
<td>104.5(35%)</td>
<td>127.2(43%)</td>
<td>32.5(11%)</td>
<td>17.9(6%)</td>
<td>14.7(5%)</td>
<td>296.8(9%)</td>
</tr>
<tr>
<td>Pine River</td>
<td>135.3(39%)</td>
<td>104.4(30%)</td>
<td>29.5(8%)</td>
<td>16.3(5%)</td>
<td>61.6(18%)</td>
<td>347.2(11%)</td>
</tr>
<tr>
<td>Upper Nottawasaga River</td>
<td>211.7(63%)</td>
<td>67.7(20%)</td>
<td>25.6(8%)</td>
<td>26.1(8%)</td>
<td>7.0(2%)</td>
<td>338.1(11%)</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>111.1(36%)</td>
<td>141.6(46%)</td>
<td>10.1(3%)</td>
<td>41.6(14%)</td>
<td>2.3(1%)</td>
<td>306.6(10%)</td>
</tr>
</tbody>
</table>

Table 5: Soil Classification of the NVCA by physiographic region (km²).

<table>
<thead>
<tr>
<th>Physiographic Region</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Unclassified</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dundalk Till Plain</td>
<td>41.1(14%)</td>
<td>177.4(60%)</td>
<td>25.5(9%)</td>
<td>50.4(17%)</td>
<td>0.8(0%)</td>
<td>295.2(9%)</td>
</tr>
<tr>
<td>Edenvale Moraine</td>
<td>21.5(38%)</td>
<td>18.8(33%)</td>
<td>12.9(23%)</td>
<td>1.9(3%)</td>
<td>1.5(3%)</td>
<td>56.6(2%)</td>
</tr>
<tr>
<td>Guelph Drumlin Field</td>
<td>4.6(88%)</td>
<td>0.1(1%)</td>
<td>0.0(0%)</td>
<td>0.6(11%)</td>
<td>0.0(0%)</td>
<td>5.3(0%)</td>
</tr>
<tr>
<td>Hillsburg Sandhills</td>
<td>2.7(79%)</td>
<td>0.4(12%)</td>
<td>0.0(0%)</td>
<td>0.3(8%)</td>
<td>0.0(0%)</td>
<td>3.4(0%)</td>
</tr>
<tr>
<td>Horseshoe Moraines</td>
<td>344.3(53%)</td>
<td>234.4(36%)</td>
<td>36.5(6%)</td>
<td>30.2(5%)</td>
<td>4.5(1%)</td>
<td>649.9(21%)</td>
</tr>
<tr>
<td>Niagara Escarpment</td>
<td>68.6(33%)</td>
<td>102.5(50%)</td>
<td>27.8(14%)</td>
<td>3.8(2%)</td>
<td>3.2(2%)</td>
<td>205.9(7%)</td>
</tr>
<tr>
<td>Oak Ridges Moraine</td>
<td>73.2(81%)</td>
<td>12.9(14%)</td>
<td>4.3(5%)</td>
<td>0.1(0%)</td>
<td>0.0(0%)</td>
<td>90.4(3%)</td>
</tr>
<tr>
<td>Oro Moraine</td>
<td>38.2(82%)</td>
<td>7.6(16%)</td>
<td>0.5(1%)</td>
<td>0.3(1%)</td>
<td>0.0(0%)</td>
<td>46.5(1%)</td>
</tr>
<tr>
<td>Peterborough Drumlbin Field</td>
<td>31.7(14%)</td>
<td>128.9(59%)</td>
<td>55.0(25%)</td>
<td>3.8(2%)</td>
<td>0.4(0%)</td>
<td>219.8(7%)</td>
</tr>
<tr>
<td>Schomberg Clay Plains</td>
<td>11.5(9%)</td>
<td>23.3(19%)</td>
<td>89.0(71%)</td>
<td>0.8(1%)</td>
<td>1.0(1%)</td>
<td>125.6(4%)</td>
</tr>
<tr>
<td>Simcoe Lowlands</td>
<td>313.6(27%)</td>
<td>299.4(26%)</td>
<td>219.7(19%)</td>
<td>221.4(19%)</td>
<td>109.3(9%)</td>
<td>1163.3(37%)</td>
</tr>
<tr>
<td>Simcoe Uplands</td>
<td>62.8(22%)</td>
<td>194.1(68%)</td>
<td>22.0(8%)</td>
<td>4.9(2%)</td>
<td>0.0(0%)</td>
<td>283.8(9%)</td>
</tr>
</tbody>
</table>
Figure 2: Map of established monitoring stations with soil hydro class. Proposed soil moisture monitoring installation locations are indicated by a down arrow.
Figure 3: Physiographic Regions of the NVCA overlaid with existing monitoring sites. Proposed soil moisture sites indicated by downward arrows.
5.4 Network Cost

Cost estimates following the established MECP guidelines (HydraProbe sensors connected to Axiom telemetry) to modify established monitoring stations are outlined in Table 6. The estimated total cost for installing the network as proposed is $58,530.61, costing approximately $10,000 per station that requires telemetry upgrades. An alternate to adding or upgrading telemetry to all stations would be to have data recorded and manually download data when onsite. The soil moisture networks at CVC operates without telemetry using Decagon sensors connected to a datalogger. The total cost for such a station (3 Decagon soil moisture probes; 10HS or EC5, $230 each, and a datalogger (HOBO USB Micro Station; $316) powered by 4 lithium ion AA batteries would be approximately $1005.

Table 6: Estimate cost to incorporate soil moisture monitoring at established stations.

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Location Name</th>
<th>SDI-12 Cable</th>
<th>Terminal Cables (min. 3)</th>
<th>SDI-12 Expansion Cable</th>
<th>Soil Moisture Probes (3)</th>
<th>Axiom</th>
<th>Cost per Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>W232-2</td>
<td>Wasaga Beach</td>
<td>$363.86</td>
<td>$90.40</td>
<td>$288.15</td>
<td>$636.19</td>
<td>$6,651.18</td>
<td>$9,663.76</td>
</tr>
<tr>
<td>W244-2</td>
<td>Midhurst</td>
<td>$452.00</td>
<td>$288.15</td>
<td>$1,908.57</td>
<td>$6,651.18</td>
<td>$9,299.90</td>
<td></td>
</tr>
<tr>
<td>W323-4</td>
<td>Bradford</td>
<td>$452.00</td>
<td>$288.15</td>
<td>$1,908.57</td>
<td>$6,651.18</td>
<td>$9,299.90</td>
<td></td>
</tr>
<tr>
<td>W505-1</td>
<td>Redickville</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0.00</td>
</tr>
<tr>
<td>SS-11-02-S</td>
<td>Bond Head</td>
<td>$1,091.58</td>
<td>$542.40</td>
<td>$288.15</td>
<td>$1,908.57</td>
<td>$6,651.18</td>
<td>$10,481.88</td>
</tr>
<tr>
<td>SS-11-09-S</td>
<td>Glencairn</td>
<td>$727.72</td>
<td>$452.00</td>
<td>$288.15</td>
<td>$1,908.57</td>
<td>$6,651.18</td>
<td>$10,027.62</td>
</tr>
<tr>
<td>NVCA rain gauge Mono</td>
<td>$271.20</td>
<td>$288.15</td>
<td>$1,908.57</td>
<td>$6,651.18</td>
<td>$9,119.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$2,183.16</td>
<td>$2,169.60</td>
<td>$1,440.75</td>
<td>$11,451.42</td>
<td>$33,255.90</td>
<td>$58,530.61</td>
</tr>
</tbody>
</table>

6.0 Recommendations

Researchers from many disciplines have contributed to recent developments in soil moisture monitoring, and it is anticipated that future progress will remain interdisciplinary, ranging from soil science, remote sensing, geodesy, to meteorology (Ochsner, et al., 2013). One of the challenges with monitoring soil moisture is that it is highly spatially variable, reflecting the spatial variability of precipitation patterns, vegetation type, soil type and compaction and hydrological properties including runoff potential (Scott, et al., 2010; Quinte Conservation, 2012). This report undertook a desktop evaluation of existing soil moisture monitoring networks, technologies used currently by the MECP, considerations of a soil moisture indicator, and outlined a proposed soil moisture monitoring network for the NVCA watershed. The following recommendations are provided for consideration:

1. The proposed NVCA soil moisture monitoring network is envisioned to be strongly linked to the PGMN program and other provincial programs. In its infancy and given the strong link to the PGMN program, it is recommended to collaborate with the various provincial agencies involved in soil moisture monitoring (e.g., MECP, MNRF, and OMAFRA) to determine a long term vision for soil moisture monitoring for Ontario including delineation of the program objectives, scope, and organizational leadership to execute this deliverable. This long term vision is also required to be complimented by appropriate level of sustainable funding and staffing both at the appropriate provincial levels and at the partner on the ground delivery agents (e.g., conservation
authorities) to allow for the program maturation in which data interpretation will be statistically sound.

2. The development of a soil moisture indicator is considered premature given the lack of a cohesive soil moisture monitoring network operational in Ontario presently and the corresponding lack of temporal data sets.

3. Evaluate the need and the potential solicitation of the development of regional to provincial scale remote sensed soil moisture models in order to assess soil moisture conditions over large spatial areas. It is envisioned that the use of the in-situ soil moisture monitors will be used to calibrate the model with long term and continued soil moisture monitoring.

4. Building on the program objectives, evaluation of linkages to remote sensing opportunities, and long term vision of soil moisture monitoring it is recommended to undertake a province wide network design exercise comparable to the creation of the PGMN rationale areas. This exercise should be complimented by statistical analysis to evaluate the appropriate level of proposed sites and locations to satisfy the local and regional scale and vertical and horizontal dissemination of the data.

5. Consideration should be given for future soil moisture installs to include a probe installed a 100 cm depth to capture below root soil moisture.

6. The development of both field based and data quality assurance and control protocols and guidelines are required to be developed for the soil moisture site and associated data management.

7. A reporting structure should be developed outlining processes and opportunities for the utilization of the data and results, both for public facing opportunities and internal program purposes.
7.0 References


Appendix A  FTS Application Note 157 (Forest Technology Services, 2018 - unpublished)

Soil Moisture Monitoring (HydraProbe) Installation Instructions

The purpose of Application Note #157 is to outline the HydraProbe Field Installation Procedure methodology and equipment requirements and the connection methodology to the FTS Axiom Datalogger.

The HydraProbe soil moisture sensors are deployed at different soil depths (5cm, 20cm, and 50cm) in order to get a profile of the on-site soil conditions. These Stevens HydraProbe sensors are connected to an FTS Axiom Datalogger to allow the datalogger to record soil moisture, temperature, and conductivity from each of the three sensors. Sensor connection, datalogger configuration, as well as sensor deployment instructions are detailed in this application note in addition to the field equipment and generalized probe installation procedures.

1. HydraProbe Field Installation Procedure Methodology and Equipment Requirements

1.1. Equipment Requirements for soil probe installation

The following is a list of required materials required for field installation of soil probes. It is noted that additional ABS tubing, conduit, wiring, caulking, etc. will be needed based on the separation distance between the probes and the FTS Axiom datalogger.

Field Soil Monitoring Stations Check list

- Notepad and pen
- Shovel
- Knife
- Trowel
- Tape measure
- Zip ties
- Screw drivers
- Gloves
- Marker flags
- Wrench
- Toe tags
- Wire cutter and striper
- Needle nose plyers
- Rags and towels
- Handheld volt meter
- Paint scraper
- 6 soil sample containers
- Water bottle/food

The following equipment list is required for the hook up the HydraProbe sensors to the FTS Axiom datalogger

- FTS Axiom Datalogger
- Datalogger battery cable
- 12 V, absorbed glass mat battery
- 3 of FTS SDI-12 termination cables (FTS part number: CBL-SDI-TERM)
  - only required if HydraProbe sensors do not already have FTS bayonet military style connectors attached.
- 1 of FTS SDI-12 expansion cable (FTS part number: CBL-SDI-EXP)
- 3 of Stevens HydraProbe soil sensor (SDI-12 version)
- 18-3 gauge copper wire
- 2” hard conduit (ABS/PVC) with elbows/connectors to accommodate 3 lengths of wire as necessary for your site. Minimum ¾” diameter required if only running the three sensor wires with pigtail connections (no bayonet military style connectors).
1.2. **Before you go into the field**

1) Look up location of soil moisture probe installation on soil map. Soil Survey Complex Soil Surveys in Ontario Data collected from 01/01/1929 to 01/01/1998.

2) Make sure every SDI-12 sensor has a unique address (refer to section 2.3).

3) Before going into the field, test the probe in water. Parameter K should be about 78 and the EC should be 0.

4) Make sure the cable per sensor is labeled at both ends and assign the sensor an SDI-12 address. Record the HydraProbe serial numbers as Stevens can’t honor the warranty without the sensor serial number.

5) Reference the Stevens HydraProbe Manual (also available from FTS, document number 701-Stevens Hydra Probe).

1.3. **Soil Moisture Sensor Installation Methodology**

**Site Base Map and Location**

Site photo of PGMN Site 323 Bradford, looking north, prior to connection to the FTS Axiom datalogger. The FTS white enclosure corresponds to well PGMN 323-4. The black ABS tubing with the orange wooden shaft is the location of the soil moisture sensor pit. The trench to connect the soil moisture sensors to the FTS white enclosure is approximately 5-8” deep.

The selection of the PGMN soil moisture locations were collectively determined by MOECC and OMAFRA. This site is located south of Cookstown, transitioning from County Forest to a hay field. The agricultural system is Woodland but close to hay system and is within the Bondhead Sandy Loam – Steep Phase as per the soil survey.
Soil Pit Construction and Probe Installation

1. At the preferred location, excavate the soil pit to approximately 60 cm deep and about 60 cm wide. Use a paint scraper to smooth the surface of the soil where it is to be installed.

2. From the ground surface, mark soil probe depths at 5, 20 and 50 cm and collect 2 soil samples (around 200 g per sample) from each depth.

3. Insert tines of the HydraProbe into the soil. Ensure the HydraProbe base plate is flush with the soil. If there is a gap, the HydraProbe signal will average the gap into the soil measurement and create a bad measurement.

4. Cables should be slack between the HydraProbe sensor and horizontal conduit with the cable lower than the conduit to prevent water from running along the cables and to the probes or into the conduit.
Backfilling the Soil Pit

Run the HydraProbe wires in either conduit or ABS tubing as outline in the above photo. Once completed, backfill the hole. For every 30.5 cm (1 foot) of soil put back into the pit, the soil should be compacted. Compaction can be done by trampling the soil with feet and body weight. After the probes are installed, avoid foot and vehicular traffic in the vicinity of the probes.

IMPORTANT: Be sure to have the locations and serial numbers recorded. Ensure the sensors are connected to the datalogger and are properly responding prior to backfilling the soil pit.
**HydraProbe Wiring**

Each soil moisture monitor was tagged with depth and serial number at time of installation in addition to being colour coded. Due to the separation distance between the site of HydraProbe installation and the FTS Axiom datalogger, copper wiring (18-3 gauge) was used via a home run connection. The above photograph is taken from where the vertical ABS had previously been located with wires running towards the Axiom datalogger.

The HydraProbe cables were joined with copper wiring at the 4" junction box, modified with connectors. The use of the junction box allows for relatively easy access to the joint connection. The NVCA used ¾” semi rigid electrical conduit from Home Depot for the installation. It is encouraged to use a slightly larger junction box than a 4” one to avoid space restrictions. A hole saw was used to drill into the junction box.

Ideally, each cable should be run directly back to the datalogger enclosure so as to minimize connections and possible failure points. If sensors are already installed and do not have sufficient cable length to reach the datalogger enclosure then an intermediate, environmentally sealed junction box is required.
**Junction box to FTS White Box**

A second 6” junction box was used to manage the soil moisture wiring, two additional existing PGMN wells’ cables, and wiring association to the rain gauge (buried) which were collectively routed vertically through the 2” black ABS pipe to connect to the FTS white enclosure.
2. Connecting the Stevens HydraProbe sensors to the FTS Axiom Datalogger

2.1. Electrical Connection
The diagram below shows how the HydraProbe sensors are connected to an Axiom datalogger. The HydraProbe sensors are SDI-12 compliant and can connect to any of the Axiom's SDI ports. The diagram below shows all three HydraProbe sensors connected to a single Axiom SDI port as well as the sensor's conventional SDI-12 address.

The above diagram indicates that the 3 HydraProbe sensors are individually run back to the Axiom Datalogger in the white FTS enclosure. The CBL-SDI-TERM cables are not required if the HydraProbe sensor have the bayonet military style connectors already attached to the cable.

If required, the 3 HydraProbe sensors can be connected in an intermediate junction box with a single homerun cable connecting to the FTS datalogger. It is important to ensure that each HydraProbe sensor has a unique SDI-12 address prior to connecting all three sensors to a single homerun cable.
In the site picture below, the three wires from the individual soil moisture probes are connected to a CBL-SDI-EXP cable which are then connected to the FTS Axiom datalogger. A second CBL-SDI-EXP cable was used at this site to allow for the connection of the 3 wells. The other FTS Axiom ports are used for the rain gauge (not connected in above photograph) and the Solinst Barologger.
2.2. Datalogger to HydraProbe Sensors Wiring Diagram

The following HydraProbe SDI-12 Wiring picture shows the required electrical connections between the HydraProbe and the FTS CBL-SDI-TERM cable. If the HydraProbe sensor was purchased from FTS or has been sent to FTS for SDI-12 address configuration and system integration, then the CBL-SDI-TERM may not be required as the HydraProbe sensor will likely have had a military connector soldered directly to its cable.
2.3. HydraProbe SDI-12 Sensor Configuration

The only configuration required of the HydraProbe sensor is to set the sensor’s SDI-12 address.

Each sensor must have a unique address.

The convention used is:
- the shallowest sensor is set to SDI address 5,
- the mid-depth sensor is set to SDI address 6,
- the deepest sensor is set to SDI address 7.

The following procedure can be used with the FTS Axiom Datalogger to set each HydraProbe’s SDI-12 address.

1. Connect a single HydraProbe to one of the Axiom datalogger’s SDI ports. Make sure the HydraProbe is the only device connected to that particular SDI port on the Axiom datalogger.

2. Select the orange SDI-12 icon on the datalogger homescreen and then select the >_ icon on the bottom right of the screen to enter SDI-12 transparent command mode.

3. Select the desired SDI port from the Port drop-down menu and then enter the ?! command. The sensor will respond with its current address (address zero in the image below). If the sensor does not respond, check that the Port drop-down menu selection matches the port where the sensor is connected and, if required, check the sensor wiring.
4. Use the SDI-12 set address command to set the sensor to the desired address. The format of this command is aAb!
   where:  
   a is the current sensor address  
   A is the change address command  
   b is the desired new address  
   ! is the SDI command terminator

For example:
Enter **0A5!** to change the address of a sensor at address 0 (zero) to address 5. The sensor will respond with the newly set address.

5. Repeat above steps 1 to 4 for each HydraProbe sensor.
2.4. Datalogger Configuration

The steps are required to configure the datalogger to read, record (log), and report (transmit data via GOES communications) are:

A. Define HydraProbe sensors in the Axiom datalogger.
B. Configure the Datalogger to display the sensor readings.
C. Configure the Datalogger to record the sensor readings.
D. Configure the Datalogger to transmit the sensor readings.

If desired, contact FTS to help configure the datalogger. FTS can provide a datalogger configuration file which contains the information in the following steps.

A. Define HydraProbe sensor in the Axiom Datalogger

The following procedure can be used with the FTS Axiom Datalogger to define each HydraProbe sensor in the datalogger.

1. Press blue Sensors icon on the datalogger homescreen.
2. Press the + icon on the bottom of the page to add a sensor.
3. Select the SDI Generic icon

4. For the Shallowest sensor (5cm depth at SDI address 5), enter Hydra1 as the sensor name and 5 as the SDI address.

NOTE: For the Mid-depth sensor (20cm depth at SDI address 6), enter Hydra2 as the sensor name and 6 as the SDI address.

For the Deepest sensor (50cm depth at SDI address 7), enter Hydra3 as the sensor name and 7 as the SDI address.
5. Press the + icon on the bottom of the page to add an SDI command. Enter 1 hour as the command interval and, for the **Shallowest sensor**, 59 minutes 35 seconds as the command offset.

\[
\text{SDI Command Setup}
\begin{array}{|c|c|}
\hline
\text{Cmd} & \text{M} \\
\text{Interval} & 01 : 00 : 00 \quad \text{Offset} \quad 00 : 59 \quad 25 \\
\hline
\end{array}
\]

**NOTE:** For the **Mid-depth sensor**, enter 59 minutes 40 seconds as the command offset. For the **Deepest sensor**, enter 59 minutes 45 seconds as the command offset.

6. Press the + icon on the bottom of the page to add an SDI field. This process will be repeated three times for each sensor as there are three SDI values desired from each sensor.

The Field Names, Field Number, Units, and Precision for each sensor are in the Table below.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>SDI Address</th>
<th>Field Name</th>
<th>Field #</th>
<th>Units</th>
<th>Precision</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra 1</td>
<td>5</td>
<td>MS1</td>
<td>1</td>
<td>wfv</td>
<td>2</td>
<td>Soil Moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MQ1</td>
<td>2</td>
<td>S/m</td>
<td>3</td>
<td>Soil Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TV1</td>
<td>3</td>
<td>C</td>
<td>1</td>
<td>Soil Temperature</td>
</tr>
<tr>
<td>Hydra 2</td>
<td>6</td>
<td>MS2</td>
<td>1</td>
<td>wfv</td>
<td>2</td>
<td>Soil Moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MQ2</td>
<td>2</td>
<td>S/m</td>
<td>3</td>
<td>Soil Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TV2</td>
<td>3</td>
<td>C</td>
<td>1</td>
<td>Soil Temperature</td>
</tr>
<tr>
<td>Hydra 3</td>
<td>7</td>
<td>MS3</td>
<td>1</td>
<td>wfv</td>
<td>2</td>
<td>Soil Moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MQ3</td>
<td>2</td>
<td>S/m</td>
<td>3</td>
<td>Soil Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TV3</td>
<td>3</td>
<td>C</td>
<td>1</td>
<td>Soil Temperature</td>
</tr>
</tbody>
</table>
For Hydra1 (the shallowest sensor), enter the following for Field 1 and then press the green checkmark to continue to the next field.

Once all three fields have been entered for the sensor, the sensor’s SDI Command Setup screen should appear as below.

Press the green checkmark (twice) to return the main Sensors screen and the sensor will be visible.

7. Repeat steps 2 to 6 for each of the three HydraProbe sensors and then press the House icon to return to the datalogger Homescreen.
8. Once all sensors are defined and are connected to the Axiom Datalogger, press the orange SDI-12 icon from the datalogger homescreen. Only one sensor (Hydra1) is shown in the image below but you will see all three sensors if they were all configured.

<table>
<thead>
<tr>
<th>SDI Sensor Mapping</th>
<th>18:03:19</th>
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</thead>
<tbody>
<tr>
<td>Defined</td>
<td>Detected</td>
</tr>
<tr>
<td>Name</td>
<td>Addr</td>
</tr>
<tr>
<td>Hydra1</td>
<td>5</td>
</tr>
</tbody>
</table>

9. For each sensor confirm the sensor serial numbers match the desired sensor definition and then press the Vendor/Serial number box to map the sensors.

The serial number of the above connected sensor is 204013 and indicated by the last 6 numbers in the Vendor/Serial number box.

There should be no red backgrounds after all sensors have been mapped. Press the ‘house’ icon to return to the homescreen after you are done mapping all three sensors.

<table>
<thead>
<tr>
<th>SDI Sensor Mapping</th>
<th>18:10:06</th>
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<tr>
<td>Defined</td>
<td>Detected</td>
</tr>
<tr>
<td>Name</td>
<td>Addr</td>
</tr>
<tr>
<td>Hydra1</td>
<td>5</td>
</tr>
</tbody>
</table>
B. Configure Axiom Datalogger to Display Sensor readings

The following procedure can be used with the FTS Axiom Datalogger to display the HydraProbe readings on the Axiom’s Current Conditions screen.

1. Press red Current Conditions icon on the datalogger homescreen.
2. Press the ‘gear’ icon on the bottom center of the page to add sensor readings to the Current Conditions display.
3. Press the ‘pencil’ icon on the bottom right of the page to enable editing.
4. Select the desired datapoint from the left column and then press the Plus arrow to add the datapoint to the Selected list. Repeat this process for each desired datapoint and then press the green Checkmark to return to the Current Conditions screen.

5. Press the ‘exclamation mark’ icon to force an SDI reading on the sensors.

6. The sensor readings will appear on the screen.
C. **Configure Axiom Datalogger to Record Sensor readings**

The following procedure can be used with the FTS Axiom Datalogger to record the HydraProbe readings in the Axiom’s dataloggers datastore.

1. Press brown Data icon on the datalogger homescreen.
2. Press the ‘gear’ icon on the bottom left of the page to configure the datastore.
3. Press the + icon on the bottom center of the page to configure a new logging interval in the Axiom’s datastore.
4. Press the ‘pencil’ icon on the bottom right of the page to enable editing.
   Enter a logging interval of 1 hour (no offset).
   Select the desired datapoint from the left column and then press the Plus arrow to add the datapoint to the Logged Variables list. Repeat this process for each desire datapoint and then press the green Checkmark to return to the Current Conditions screen.

5. Select the desired datapoint from the left column and then press the Plus arrow to add the datapoint to the Selected list. Repeat this process for each desire datapoint and then press the green Checkmark to return to the Logging Intervals screen.

6. Press the ‘house’ icon to return to the Axiom homescreen.
D. Configure Axiom Datalogger to Transmit Sensor readings

The following procedure can be used with the FTS Axiom Datalogger to transmit the HydraProbe readings via the GOES system.

**CAUTION:** Be mindful of the number of datapoints being transmitted to ensure that the entire message can fit within your assigned GOES time window. Contact FTS if you require assistance or if you have any questions.

**NOTE:** The following steps assume that your GOES specifics have already been entered in the Axiom datalogger and that the HydraProbe datapoints are being added to an existing GOES message with WSC (SHEF code) format.

1. Press green Telemetry icon on the datalogger homescreen.
2. On the Telem A tab, press the Status button.
3. Press the ‘gear’ icon on the bottom of the page to configure the GOES transmission.
4. Select the Self-Timed tab.
5. Press the Set Message button.
6. Press the + icon on the bottom center of the page to add the desired HydraProbe parameters to the existing GOES message.

7. Enter a 1 hour transmission interval (no offset) and select the desired HydraProbe datapoint as the Input. Then press the green checkmark.

8. Repeat steps 6 & 7 for each desired HydraProbe datapoint and then press the ‘house’ icon to return to the Axiom homescreen.

The datalogger setup process is now complete.
Contact Information

Please contact FTS if you have any questions or would like further information.

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Web Page:  www.ftsinc.com
Sales:  sales@ftsinc.com
Technical Support:  techsupport@ftsinc.com

Revision History

<table>
<thead>
<tr>
<th>Revision</th>
<th>Date</th>
<th>Description</th>
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<tbody>
<tr>
<td>0.1</td>
<td>2017-08-31</td>
<td>Preliminary release</td>
</tr>
<tr>
<td>0.2</td>
<td>2018-05-30</td>
<td>NVCA update</td>
</tr>
<tr>
<td>1.0</td>
<td>2018-11-05</td>
<td>FTS additions</td>
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<tr>
<td>1.1</td>
<td>2018-11-07</td>
<td>Minor corrections</td>
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## Appendix B  Stevens HydraProbe Specifications

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil moisture for inorganic/mineral soil</td>
<td>completely dry to fully saturated</td>
<td>± 0.01 WFV for most soils; ± 0.03 max for fine textured soils</td>
<td>0.001</td>
</tr>
<tr>
<td>Real Dielectric Permittivity (isolated)</td>
<td>1 (air) to 80 (distilled water)</td>
<td>± 1.5% or 0.2 whichever is typically greater</td>
<td>0.001</td>
</tr>
<tr>
<td>Bulk electrical conductivity</td>
<td>0.0 to 1.5 S/m</td>
<td>± 2.0% or 0.02 S/m whichever is typically greater</td>
<td>0.001</td>
</tr>
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<td>Temperature</td>
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<td>± 0.3 °C</td>
<td>0.1 °C</td>
</tr>
<tr>
<td>Standard operating range</td>
<td>-10°C to + 60 °C</td>
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<td></td>
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<tr>
<td>Sensing volume</td>
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<tr>
<td>Dimensions</td>
<td>12.4 cm x 4.2 cm</td>
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<tr>
<td>Maximum cable length</td>
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<td>Weight</td>
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<td>Interface</td>
<td>SDI-12 v. 1.2</td>
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<tr>
<td>Manufacturer’s warranty</td>
<td>5 years</td>
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From FTS (2018) and Stevens Water Monitoring Systems, Inc. (2018b)