SPRUCE Enclosure Corral and Sump System: Description, Operation, and Calibration

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Version	Changes made
June 2016	Original version.
January 2017	Acknowledgments and funding sources, the *Conceptual Framework* section, Table and Figure captions, helical pile information, Vista Data Vision information, and some citations and references were added. Figure 1 was updated. Calibration values were updated.

SPRUCE: The SPRUCE experiment is collaborative research between ORNL and the USDA Forest Service. The participation of SDS in the SPRUCE Project was funded by the Northern Research Station of the USDA Forest Service. Funding for the belowground corral installation and instrumentation, and the participation of NAG was provided by the SPRUCE Project, which is supported by the Department of Energy's Office of Science, Biological and Environmental Research. ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy (DOE) under contract DE-AC0500OR22725.

Acknowledgements: We appreciate logistical support from Jeff Riggs (ORNL), W. Robert Nettles (ORNL), Les Hook (ORNL), Paul Hanson (ORNL), and Jana Phillips (ORNL). Terry Burke (Pokegama Electric) completed the final design of the sump based upon an initial concept, design, and prototyping by SDS and NAG. He also assembled, and oversaw installation of the sump system. Ron Goodrich (Campbell Scientific, Inc) coordinated customization of autosamplers for the SPRUCE project and has provided technical support on their operation and maintenance. Kyle Campbell (Campbell Scientific, Inc) provided the original version of CR1000

CRBasic code to actuate an autosampler sampling sequence. SDS further developed the code to fully operate the sump system, which includes actuation of autosamplers, measurement of sump water levels, and calculation of outflow volumes. Keith Oleheiser (XCEL Engineering) helped with dock construction. The late Pat Mulholland (ORNL) provided valuable input on the need for and concept of a corral.

Table of Contents:

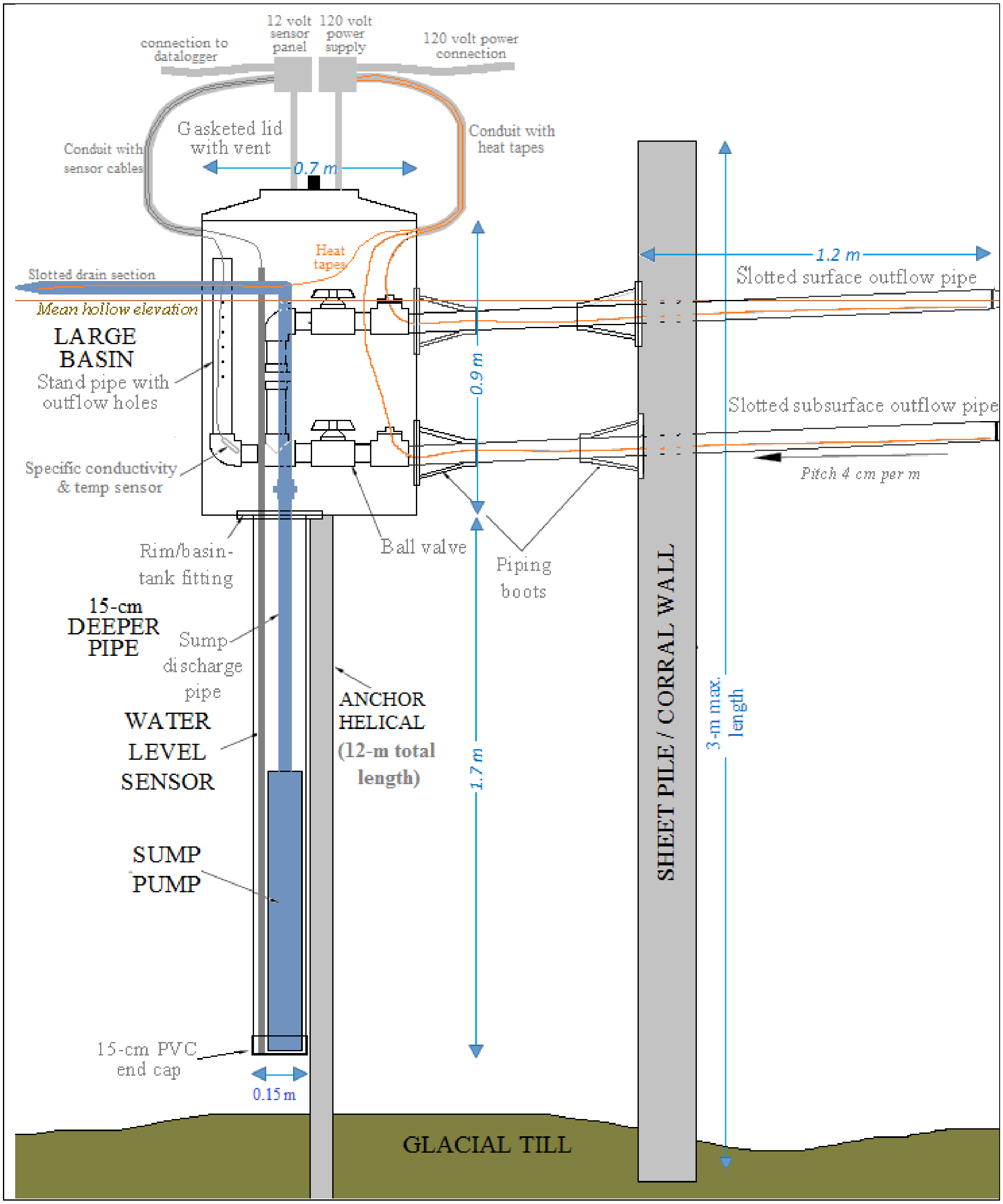
Introduction:

A subsurface corral system has been designed and constructed to measure water flow and allow the collection of water samples from the outflow of each experimental enclosure within the SPRUCE project (https://mnspruce.ornl.gov). These measurements are critical to the calculation of whole-ecosystem water, carbon, and solute effluxes. This document provides a description of the components, operation, and calibration of the corral system.

Objectives:

1. Describe belowground corrals, sump systems, and the operation of sump systems (Figure 1), which are used to calculate the volumes of water that naturally drain enclosures and to trigger automatic collection of water samples.
2. Describe the calibration between water level and water volume in the sump system. This relationship is used to calculate near-surface lateral runoff (“outflow” in L/s) from each enclosure by measuring the change in water level over time. The water volume vs. water level relationship must be re-calibrated if water level sensors (or components) are replaced.
3. Describe the data and data products that are and will be available from outflow measurements.

Figure 1. Cross-sectional diagram of the sump system. A sump system is located north of a spur boardwalk that leads to each enclosure/plot and west of any particular enclosure. An anchor helical is to the north of each sump and a sump discharge pipe exits to the south (though shown as if to the west in this diagram for simplicity) and allows water to drain underneath an adjacent boardwalk. A dock that allows access to the sump system is not shown in the diagram.

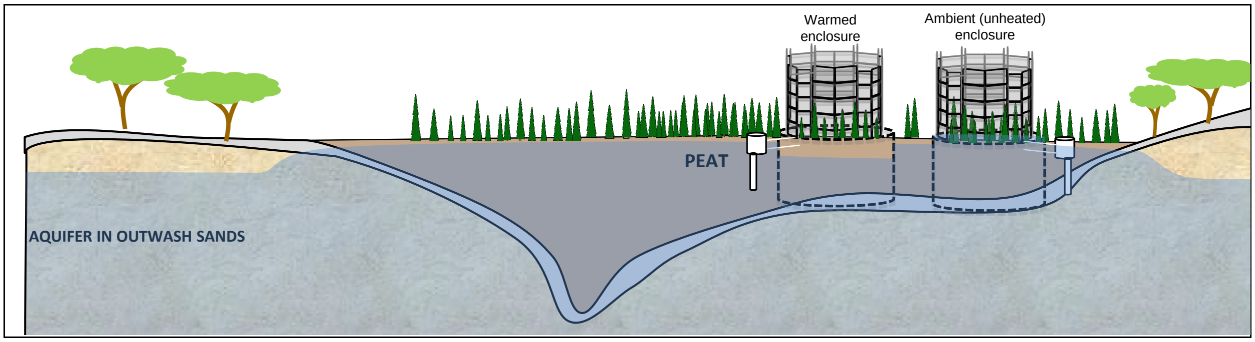


Conceptual Framework:

SPRUCE is an experiment to assess effects of 1) aboveground and belowground whole-ecosystem warming (WEW) and 2) WEW with carbon dioxide concentrations increased to about double contemporary levels, on the ecology, biogeochemistry, and hydrology of peatlands (Hanson *et al*., 2016). The SPRUCE Experiment was built in the 8-ha S1 bog, which is part of the long-term research program at the Marcell Experimental Forest (MEF) in northern MN (Kolka *et al*., 2011; Sebestyen *et al*., 2011).

Peatland water levels rise in response to rainfall and snowmelt inputs. Water levels fall in response to water withdrawals through evapotranspiration or drainage along near-surface flowpaths and deep vertical seepage to surrounding groundwater aquifers (Verry *et al*., 2011b). Most subsurface runoff through peatlands occurs as near-surface lateral flow in the acrotelm, which is about a 30-cm layer below the mean hollow elevation. The near-surface flowpath corresponds to a distinct transition in physical properties from a shallow (acrotelm) to deeper (catotelm) layer that occurs within the top meter of peat. A typical profile in the top meter of peat has exponential increases in bulk density, decreases in drainable porosity, decreases in fiber content, decreases in saturated hydraulic conductivity, and decreases in transmissivity that accompany increased degrees of decomposition and humification with depth (Verry *et al*., 2011a). The acrotelm also corresponds to the typical 30-cm annual range of water table fluctuations at five long-studied bogs on the MEF (Sebestyen *et al*., 2011). Peat in this layer readily transmits water when the water table rises into the acrotelm (Verry *et al*., 2011a) and the acrotelm is the "hydrologically active" layer of a bog. In S1 and other nearby bogs, flow through the near-surface pathway drains to and generates streamflow (Verry *et al*., 2011b), which is important in a whole-ecosystem perspective since this pathway represents how peatlands are sources of water and solutes to downstream ecosystems. From here on, we refer to lateral drainage along near-surface flowpaths from SPRUCE enclosures as "outflow."

Figure 2. Conceptual diagram showing the hydrological setting of the S1 bog and effects of the SPRUCE experiment on peatland water tables. The S1 peatland formed in an ice-block depression where a glacial till forms a low conductivity layer that retards the flow of water and isolates the peatland from a surrounding aquifer (Verry *et al*., 2011b). The raised-dome bog maintains a perched water table and hydraulic gradient that is about 1-m above the surrounding water table in the aquifer in the deep outwash sand. Water tables are expected to be lower inside heated enclosures/corrals than the surrounding bog and ambient enclosures.



Within heated WEW enclosures, we expect more precipitation to occur as rain versus snow, less accumulation of snow, earlier snowmelt timing, longer growing season lengths, higher maximum annual air temperatures, increased evaporation, and increased transpiration relative to ambient enclosures and the surrounding bog. These changes will have cascading effects on the timing and magnitudes of fluctuations in water tables and outflow. Though the typical annual range in water table fluctuations is about 30 cm, long-term data from the S1 bog and other peatlands at the MEF show that fluctuations in water levels have ranged up to 1.4 m depth over the course of a 50-year record (Sebestyen *et al*., 2011). The lowest water table elevations occurred during a year with the lowest amount of annual precipitation. While the WEW experiment, with operation expected through 2025, may or may not include such a dry year, the experiment is expected to increase the partitioning of water to evapotranspiration, which may result in similar or even greater water table drawdowns during seasonal or prolonged dry periods (Figure 2). The interactive effect of greater evapotranspiration and an equivalent severe drought may lead to unprecedented drawdowns in water table elevations inside of warmed enclosures.

Figure 3. Photo of SPRUCE enclosures at plots 19 and 20, 3/7/16. The photo shows the spur boardwalk that leads to the enclosure. Electrical, datalogging, and control system panels are in the lower left of the photo. An autosampler (white), which is part of the sump system, is visible above the control system panels.

Infrastructure to maintain passive, natural drainage along near-surface pathways from SPRUCE enclosures was developed to preclude the inflow of water from the surrounding bog into the footprints of experimental enclosures. Open-topped aboveground enclosures (Figure 3) allow rain and snow to fall into the experimental space and water vapor to be exchanged with the atmosphere. A belowground corral was constructed by vertically inserting interlocking vinyl sheet piles through peat into glacial till that forms the basin of the ice-block depression in which the bog developed (Verry *et al.*, 2011c). Like the open-topped aboveground enclosure, the corral is open on the bottom to allow exchange of water and solutes through outseepage to the groundwater aquifer, even though this pathway of water transport is < 10% of the annual precipitation amounts (Nichols and Verry, 2001). With this infrastructure in place, the enclosures functionally operate as catchments – intact ecosystems with water inputs from the atmosphere and water outputs through evaporation, transpiration, surface overland flow, shallow subsurface runoff, and deep seepage to a groundwater aquifer. Blockage of near-surface inflow from outside to inside enclosures through the acrotelm is the most important function of the corral. By placing shallow, lateral drains in the corral and maintaining an open bottom:

- The effects of warming and enhanced evapotranspiration on water tables can be measured as a response variable in the WEW experiment.
- The enclosures will still drain via near-surface flowpaths when water tables rise into or above the acrotelm. This hydrological process is analogous to natural drainage of outflow to a stream, like that occurring from the surrounding bog.
- Outflow can be collected in a sump and outflow drainage volumes can be estimated.
- Deep, vertical seepage to the aquifer, which is controlled by hydraulic gradients and peat physical properties, still occurs.

Sump Components:

- A belowground corral (Everlast vinyl sheet pile with Pro-Seal 34 sealant and Pro-Seal Flash Guard Tape; Table 1) isolates the movement of water from the surrounding bog into the enclosed area of a plot. Sheet piles were driven through peat into underlying glacial tills, unless the peat was too deep. About 0.5 m of each sheet pile sticks aboveground. Belowground corrals were installed during the 2014-2015 winter.

Table 1. Belowground corral component specifications

Components	Product info
Everlast vinyl sheet pile	Model EP31G1120, 0.6-cm thick, http://everlastseawalls.com/seawall-products/vinyl-sheet-piling/.
Pro-Seal 34	A single component M34 elastoplastic, polycarbon/polycarbonate sealant that expands by 1200% during contact with water and curing, http://www.prosealproducts.com/productDisplay.asp-id=185.html, applied inside panel joints.
Pro-Seal Flash Guard Tape	http://www.prosealproducts.com/productDisplay1.asp-id=374.html.

Before installation, peat depths were probed to estimate the needed lengths, and sheet piles were pre-cut from the original 3.7 m lengths when peat depths were less than about 3.2 m deep (Table 2). In places where peat depths were 3.2 to 4.1 m deep, sheet piles did not reach the underlying till.

Table 2. Peat depths (meter) along each side of octagonal plots, by experimental enclosure.

Plot#	Side								Mean depth
	N	NE	E	SE	S	SW	W	NW	
4	2.9	3.1	3.4	3.65	3.5	3.1	2.8	2.26	3.1
6	2.9	2.8	2.5	2.7	2.5	2.7	2.8	2.8	2.7
8	1.9	2.6	3	3.2	2.8	2	1.8	1.85	2.4
10	3.2	3.3	2.4	3	3	2.8	2.4	2.8	2.9
11	2.8	2.4	2.4	3.3	3.1	2.2	3	2.5	2.7
13	2.1	2.9	3	3.1	2.9	2.7	2.4	2.3	2.7
16	3.5	2.6	2.4	2.6	2.8	2.9	2.4	2.4	2.7
17	2.7	2.5	2.3	1.9	1.8	1.7	2.0	2.5	2.2
19	2.8	3.1	3.0	2.5	2.0	1,8	1.9	3.3	2.5
20	4.1	4.4	4.3	3.4	2.9	3.0	3.7	4.1	3.7

Data courtesy of PJ Hanson and J Phillips, ORNL.

The sheet piles interlock, with 10 panels on each side of an octagonal corral (Figure 4). Pro-Seal 34 was injected into the female interlocking groove prior to the mechanical driving of a panel into the peat. Upon contact with water, the sealant expanded to fill each joint. As a further measure to seal the belowground corrals, ~30-cm lengths of Pro-Seal Flash Guard Tape were applied to the outside of each joint, roughly centered above- and belowground where joints intersected peat surfaces.

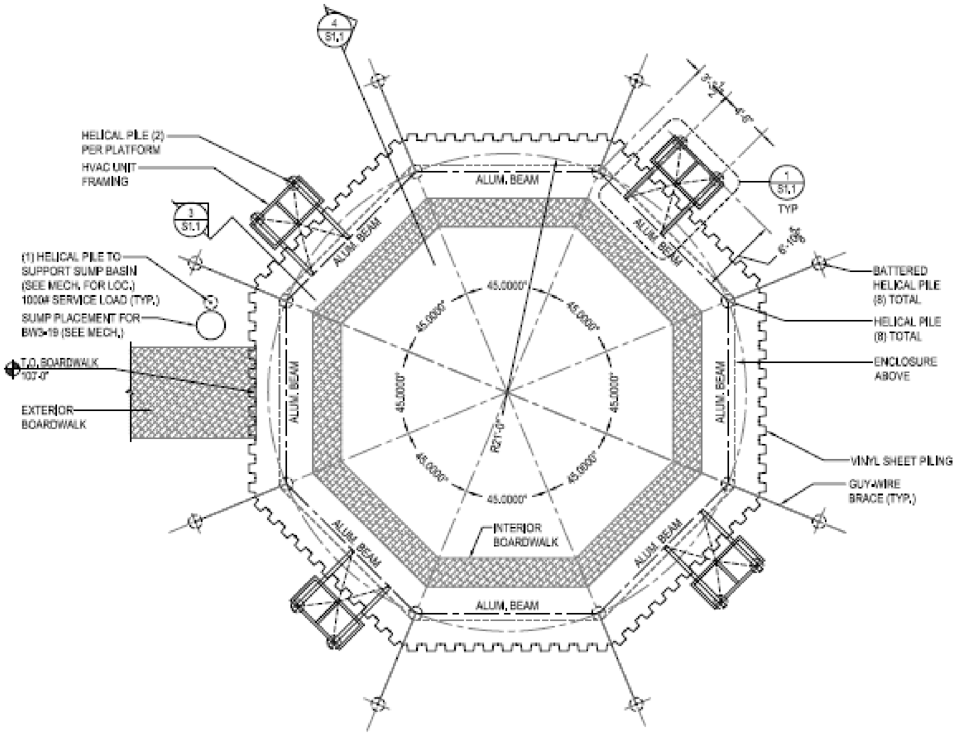
Belowground corrals are outside the aboveground enclosures, which causes rain falling on the frustrum and sides of enclosure walls (Figure 3) to drain into the footprint of a corral.

Figure 4. Belowground corral.

Diagrams showing cross-sectional dimensions of an individual sheet pile (left) and a universal corner (next image to the right), and a single piece of sheet pile (far right).[1]

Photo (left) showing construction of the below-ground corral on enclosure 13, 1/30/15. The sheet pile is outside of the octagonal boardwalk and the aboveground chamber (Figure 3) was later built between the boardwalk and the sheet pile. Photo (right) of sealed sheet piles.

Diagram showing the layout of the below-ground corral, sump, boardwalks, heaters, and other enclosure infrastructure.



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[1] Images taken from http://everlastseawalls.com/wp-content/uploads/2012/12/esp-3.1-spec-sheet.pdf or http://everlastseawalls.com/wp-content/uploads/2012/12/esp-universal-corner.pdf.

- The sump system includes a collection and measurement basin with a large basin and a deeper pipe that is capped on the bottom (Figure 5 and Table 3). The deeper pipe holds about 25 L of water before water starts to accumulate in the large basin. The volume of a large basin when filled to the lowest hole in the stand pipe is about 75 L and about 275 L if allowed to completely fill to the peat surface. About 60 cm of the large basin is below the peat surface. A removable lid on the large basin is gasketed to prevent inflow of water and evaporation of water from a sump. The lid of each sump has an anti-siphon vent. A sump was anchored to a helical pile that was driven through peat into underlying glacial till. The helical has a total belowground length of about 12 m. Sumps were installed during July and August 2015.

  A wooden, access dock was built adjacent to or around each sump (Figure 5). Docks were built of pressure treated dimensional lumber, with 2x10” frames and 2x6” decking. A dock was built around Sump 4 during March 2016. All other docks were built from August to November 2015.

Figure 5. Sump system.

Photo (left) of a sump basin prior to construction of access docks around the sump. Photo (right) of a sump system prior to installation.

Photo (left) of a dock that surrounds and allows access to a sump basin (sump/enclosure 13). The photo also shows an autosampler, which houses a CR1000 datalogger/controller that measures the water level and operates the sump pump. Photo (right) showing the bottom of a large tank and the transitional rim (gray ring in right center of the photo) to the 15-cm deeper pipe.

Table 3. Sump system component specifications.

Components	Product info
Large basin	90-cm high x 65-cm wide polyethylene basin, FlexWorks PSL-3630, http://www.opwglobal.com/products/us/retail-fueling-products/below-ground-products/piping-containment-systems/tank-transition-special-application-sumps/special-application-sumps-extensions.
15-cm deeper pipe	170-cm high x 15-cm internal diameter (ID) SCH-80 PVC pipe.
Vent	Sioux Chief Manufacturing, 3.8-cm diameter anti-siphon auto vent, catalog number 239, http://www.gotomahawk.com/products/plumbing-specialty/lav-sink-specialties-and-repair/other-lav-sink/anti-siphon-auto-vent.
Helical pile	Helical anchors are galvanized steel round shaft anchors, Earth Contact Products. Each helical has one 1.5 m lead section (TAF-288L-60-10-12) with multiple 1.5 m extensions (TAE-288L-60). Both types of helicals have 15-cm cross-sections. Helical plates on lead sections have 25-cm cross sections of 1-cm thick plate.

- Standing and shallow-subsurface water inside an enclosure may drain into one of two 120-cm long by 5-cm internal diameter (ID) slotted outflow pipes (Figure 6). The horizontal drain pipes shallowly slope (pitch of 1.25 cm per 30 cm) towards a sump basin (Figure 1). One pipe allows surface water to flow from the enclosed plot when the water level rises above the hollow surface. A second pipe, 37.5 cm below the surface pipe allows subsurface flow from an enclosed plot. Outside of a sheet pile corral, all pipe, connections, and valves are 5-cm ID diameter SCH-80 PVC. Each pipe has a ball valve inside the sump to shut off drainage from an enclosed plot. Down-flow of the ball valves, the pipes merge. Water from the drain pipes flows into the sump through six 0.3 cm diameter holes in a vertical stand-pipe. The top hole was drilled at the mean elevation of hollow surfaces inside an enclosure (REFERENCE[2]) with additional holes drilled at 5-cm intervals from 0 to 25-cm below the mean hollow elevation. All pipe connections were threaded and sealed with PTFE tape.

  During winter and snow melt, the ball valve on a surface drain should remain open to allow drainage over frozen soils and to prevent surface ponding during melt. After concrete soil frost melts, the surface drain valves should be almost completely closed to prevent unrealistic, rapid drainage of standing water. The valves should be closed to the point that resistance is felt, but the valve is still slightly open. This restriction to flow is intended to limit surface outflow during unfrozen periods when surface runoff would typically be limited by pooling of surface water in the interconnected, yet slowly draining hollows.

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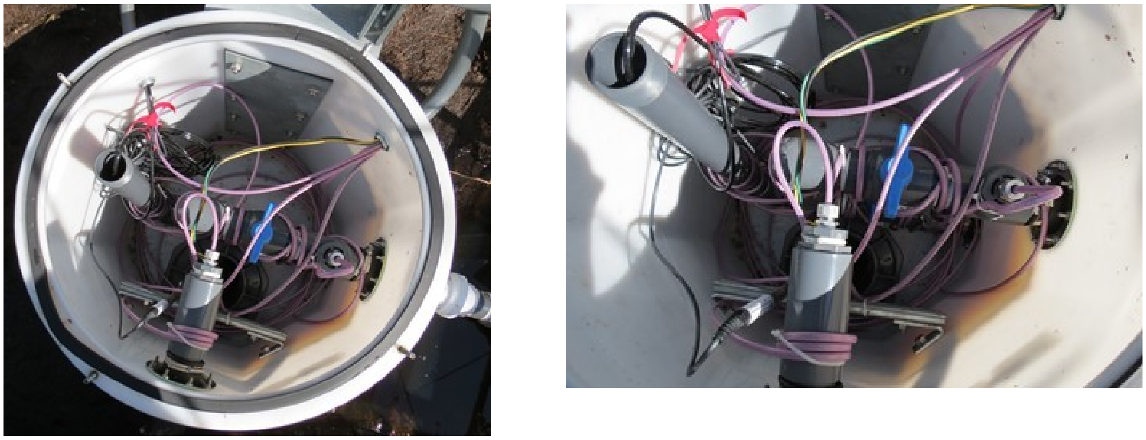
[2] Add reference to forthcoming metadata and data on mean hollow elevations in plots.

Figure 6. Enclosure drainage and sump stand pipe.

Photo showing the slotted surface drain pipe that allows water to flow from an enclosure. The sheet pile runs from top to bottom in the center of the photo. The sump is on the far left of the photo. The pipe between the sheet pile and sump is not slotted. The aluminum frame of the enclosure is to the right of the sheet pile. Photo from sump/enclosure 20, 7/21/15, prior to construction of docks around the sumps and addition of the greenhouse glazing in the walls of the enclosure.

Photo (left) of the sump interior. The surface outflow pipe is visible to the right on the outside of the sump basin. Photo (right) of the sump interior. The stand pipe is the vertical pipe in the far upper left. The blue handle of a shutoff valve for the surface outflow pipe is visible near the middle of the photo. Heat tapes are visible throughout the photos as the mauve colored cables that are wrapped around piping and draped in the basin.



- Three heat tapes (Table 4) are used to prevent freezing and damage to sump components by freezing. A heat tape was placed inside each horizontal segment of outflow pipes. The heat tape that enters the sump effluent discharge pipe (visible in Figures 5 and 6) wraps around the exterior of the standpipes, ball valves, pump, and vertical pump outflow pipe, and is drape throughout the interior of the large basin (full length of heat tapes was not drawn in Figure 1). Heat tapes are manually turned on and off at a 120-V electrical panel and only energized during periods when freezing is expected, typically November through April.

Table 4. Heat tape specifications

Components	Product info
Arctic Trace Heat Tape	Arctic Trace submersible heat tape, TL series, 5 watt/ft at 120 volt AC, with ethylene tetrafluoroethylene (ETFE) overjacket, model no. Z120512CBTL/TEZ. ETFE is a non-reactive, food grade plastic that is expected to be non-reactive to outflow chemistry.

- A TruTrack Water and Temperature Voltage Output (WT-VO) sensor with a sensor interface is used to measure water level in the sump system. Each 2.0-m long WT-VO sensor rests on the bottom PVC end cap of a sump system and extends to nearly the top of a sump basin. The analog sensor output is 0-2000 mV DC and scales linearly relative to water height along the 2.0-m long measurement segment of the sensor. There are 10-cm long segments at the top bottom of each sensor that do not respond to water height.

Table 5. Sensors and control system component specifications.

Components	Product info
TruTrack Water and Temperature Voltage Output sensor	Model WT-VO 2000 having an RS-232 interface for calibration and connection to the datalogger, http://www.trutrack.com/wt-vo.php.
autosampler	Campbell Scientific composite stationary outdoor automatic liquid sampler, model BVS4300C-S3-R-3-G-NP-H-S-NCF-NE-N with 3/8" ID system, small refrigerator, insulated NEMA3R cabinet, cabinet circulation fan, heater c/w thermostat, integral battery with charger, 0.5L acrylic chamber, 20L Nalgene bottle.
water conductivity and temperature sensor	Campbell Scientific model CS547, https://www.campbellsci.com/cs547-l.
datalogger	Campbell Scientific model CR1000, https://www.campbellsci.com/cr1000.

Voltage from a WT-VO sensor is measured every one second on a datalogger inside of an autosampler cabinet. Water volume in a sump is calculated using a linear equation that relates voltage and measured volume of water.

A water conductivity and temperature probe measures the specific conductivity and temperature of water that drains from the enclosure. The sensor is placed inside the stand pipe.

An autosampler is programmed to sample 200 mL of water with every 75 L increment of outflow that drains from an enclosure. Aliquots are composited in a 20-L acid-washed carboy and a sample for chemical analyses is retrieved once a week, typically on a Thursday. The sampler collects water from the standpipe through flexible 0.8 cm ID PVC tubing. The sampler pulls a vacuum on two different acrylic metering chambers, one for an initial rinse of tubing and one for sample collection. First, 500 mL of water is suctioned into a metering chamber. Then, 200 mL of water is suctioned into the sample collection chamber. Both chambers are simultaneously released: the sample drains into a carboy inside a refrigerator and the rinse water drains to the bog. After draining, the chambers are pressurized to expel air through the tubing to drain any water between the sampler and the standpipe. The entire sampling sequence occurs in about 1 min.

- A sump pump in the 15-cm deeper pipe is used to remove water when the sump system fills (Table 6). Sump pumping is triggered when the volume of water exceeds a threshold value (currently set at 23 L). The datalogger records volumes when pumping starts and ends. The pumped volume is calculated as the difference between the volume at the start and end of pumping, and volumes of pumped water are summed for each day and month. Pumps were installed with the sump system, but not operated until the dataloggers and control systems were completed during March 2016. Ball valves on inflow pipes were opened between March 2 to 4, 2016 to allow enclosure drainage as control programs were sequentially loaded and tested for each sump. Pumps can be disabled by toggling the variable PumpDisable in the control program from the default value of False (0) to True (typically -1, but could be any non-zero integer). Pumps should remain on except when malfunctioning sensors falsely trigger pumping, during calibration, or during routine maintenance. SDS (ssebestyen@fs.fed.us) and Robert Nettles (nettleswr@ornl.gov) should be informed immediately when pumps are disabled or are thought to be malfunctioning.

Table 6. Pump specifications.

Component	**Product info**
Sump pump	Simer model 2845G, 115 V 1/2 HP, 2-wire submersible well pump, rate = 54 L min^{-1}.

NOTE: Sumps were originally intended to restrict filling to the 15-cm deeper pipe under low flow, while letting water rise into the large basin during high flow. Measurements in the 15-cm deeper pipe of the sump would be more accurate than measurements in the large basin. At fast flow rates, the deeper pipe may have filled too quickly and the sump pump may have caused excessive pump use and unnecessary wear on the pump. As such, water was intended to flow into the large basin at high flow rates. However, it was noticed that the sump calibrations were unstable over time, which corresponded to changing water tables in the bog. SDS suspected the tank was buoyant and rising and falling with changes in bog water table, or that the volume of the large tank decreased as hydrostatic pressure caused greater inward deflection of basin walls and overall compression of the volume of the large basin. Since the WT-VO vs. volume relationship was not consistent, filling was restricted to the rigid 15-cm PVC section where the calibration would be more stable and the breakpoint transition into the tank no longer mattered to volume calculations. While capacity for high flow measurement was originally thought desirable from an operations standpoint, restricting pumping to the 15-cm PVC sump seemed fine after several months of evaluation during 2016. Inflow rates of >2 L min^{-1} were infrequent during high flow periods, such as snowmelt. Under such flow conditions, the water height measurement system when restricted to the 15-cm deeper pipe was more than adequate for measuring water levels at the resolution of 0.1 L and the pump was not overly burdened by the frequency of pumping under the observed ranges of inflow rates from March to June 2016.

Data and Data Products:

The dataloggers and control systems to trigger sump operation were first powered in March 2016.
As defined by the SPRUCE data policy (https://mnspruce.ornl.gov/node/8), there are multiple levels of data management. Level 0 data are the automatic (or manually) collected data, which can be available to manage instrument performance. Level 1 data are processed and quality assured data products for use among SPRUCE participants including SPRUCE project members at ORNL and the Forest Service as well as approved external SPRUCE project participants. Level 2 data allow, "access to mature data products by the broader scientific community and public. Public access will be concurrent with open literature or web site publication of SPRUCE results."

Level 0 data tables are generated by program runnings on CR1000 dataloggers and stored in data tables as defined in Table 7. Level 0 data are provisional and subject to change. For example, the relationship of sump water volume vs. the WT-VO is reassessed at least annually (see below) or if sensors fail. As such, calibrations may be backcast to improve estimates of daily, monthly, and annual volumes of water that flowed to and were pumped from the sump, and those data corrections will not appear in level 0 data. In addition, programs on dataloggers are occasionally updated. Whenever a program on a CR1000 datalogger is updated, some variables in data tables default to zero (0) and need to be recalculated offline from saved raw data or data stored on a datalogger and will only be entered in level 1 and 2 data tables.

Table 7. Level 0 data tables.

Table name	**Recording frequency**	**Recorded variables**
Sampler#_SumpData	Every 4 hours when the sump volume is not changing; otherwise, with every change of 1-L of water in the sump.	TimeStamp = Date and time that data were logged. Record = Record number. SumpVolume = Calculated volume (L) of water in the sump. SumpVolume = *calibrated slope**SumpWTVO + *calibrated intercept* SumpWTVO = Voltage output (mV) that is linearly related to water level in the sump. SumpWTVOTemp = Voltage output (mV) that is linearly related to the integrated temperature along the length of the WT-VO sensor. SumpWTVOTempC = Temperature (deg. C) measured along the length of the WT-VO sensor. SumpWTVOTempC = SumpWTVOTemp*0.05 – 20. PumpOn = True if the sump was being pumped. Pumping = Yes if the sump was being pumped. SumpLow = A variable used to track volume (L) changes in a sump. InflowRate30Sec = Inflow rate (L/min) calculated over a 30 sec interval.

		DailyVolume = Volume (L) of water that had been pumped from a sump up to that timestamp. DailyPumpCount = Count of times that a sump had been at that timestamp. Resets to zero (0) at 23:59:59. SumpHigh = Maximum sump volume (L) prior to pumping. PumpLow = Minimum sump volume (L) prior to pumping. Resets each time that a sump is pumped. SampleVolume = Volume (L) of water since the last sample was collected. SampleVolumeLow = A variable (L) used to calculate SampleVolume. SampleVolumeOver = A variable (L) used to calculate SampleVolume. SamplerOn = True if the sampler is turned on to collect a sample. StartSample = True if a sample is being collected.
Sampler#_DailyVolume	Daily at 23:59:59.	TimeStamp = Date and time that data were logged. Record = Record number. DailyVolume = Daily volume (L) of water that was pumped from a sump. DailyPumpCount = Daily count of how many times a sump was pumped. DaysPerMonth = Count of days per month. Resets to 0 at 23:59:59 on the last day of a month. Batt = battery voltage of backup battery.
Sampler#_MonthlyVolume	Monthly at 23:59:59 of the last day of the month.	TimeStamp = Date and time that data were logged. Record = Record number. MonthlyVolume = Monthly volume (L) of water that was pumped from a sump DaysPerMonth = Count of days per month. Resets at 23:59:59 on the last day of a month.
Sampler#_SampleTaken	Every time that a sample is taken, or the sampler fails to sample, or that a weekly sample is collected and the sampler is reset.	TimeStamp = Date and time that data were logged. Record = Record number. SampleNum = Count of samples that have been taken each week. SampleFailCount = Count of failed attempts to actuate sample collection. SampleStep = Shows sampling process that was being executed when the sampler failed to sample. SumpWTVO = Water level (mV) in the sump at the time of sampling. SampleVolume = Volume of water (L) since the last sample was collected. DailyVolume = Daily volume (L) of water that had been pumped from a sump up to the time of sampling.

		SampleVolumeLow = A variable (L) used to calculate SampleVolume. SampleVolumeOver = A variable (L) used to calculate SampleVolume. Pumping = Yes if the sump is being pumped during at the time of sample collection, no if the pump is off. SamplerTest = True if the sampling was triggered for testing or demonstration purposes.

Level 0 data are accessible through the visualization and downloading platform of Vista Data Vision (http://sprucedata.ornl.gov/vdv/vdv_historical.php, Figures 7-13).

Level 1 and 2 data tables will be described when the variables and formats are finalized.

Figure 7. Screen shot of data from the sump on enclosure 19, 10/25 to 10/26/16.

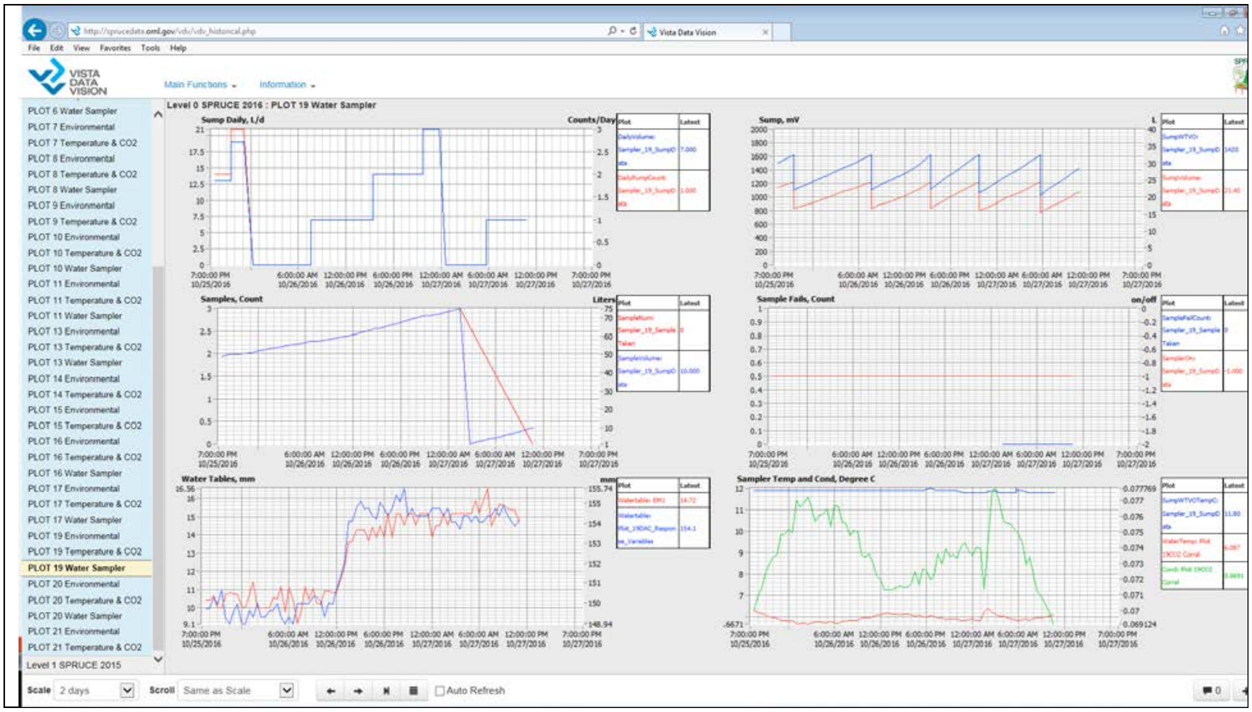
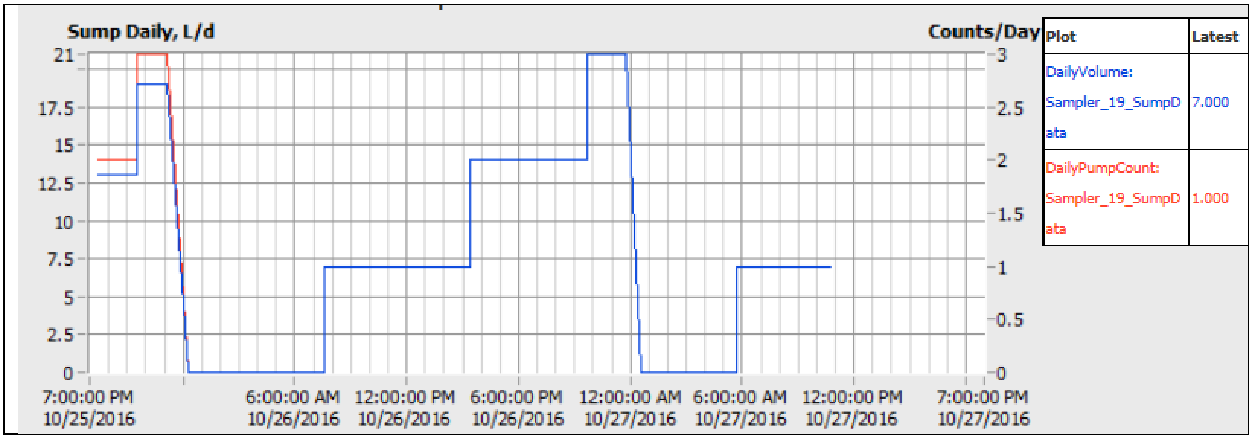
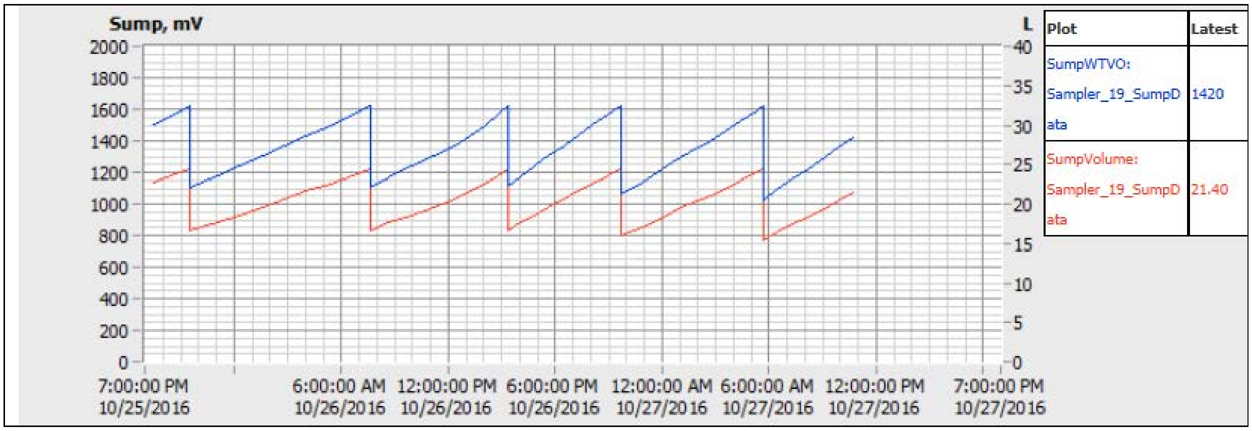


Figure 8. Close-up view of the upper left panel that shows the variables DailyVolume (L) and DailyPumpCount. The patterns are typical of periods when water flows from an enclosure. Each time that the sump was pumped, 6 to 8 L of water accumulates in the DailyVolume variable and the DailyPumpCount incremented by 1. Both values reset to zero (0) at 23:59:59.



Plot	Latest
DailyVolume: Sampler_19_SumpData	7.000
DailyPumpCount: Sampler_19_SumpData	1.000

Figure 9. Close-up view of the upper right panel of Figure 7 that shows the variables SumpWTVO (mV) and SumpVolume (L). The patterns are typical of periods when water flows from an enclosure. SumpWTVO and SumpVolume increased until SumpVolume was >= 24.5 L and decreased during pumping.



Plot	Latest
SumpWTVO: Sampler_19_SumpData	1420
SumpVolume: Sampler_19_SumpData	21.40

Figure 10. Close-up view of the middle left panel of Figure 7 that shows the variables SampleNum (count) and SampleVolume (L). The patterns are typical of periods when water flows from an enclosure and the autosampling sequence is completed. SampleNum incremented by 1 each time that a sample was collected and was reset to zero (0) each time that a sample was retrieved for chemical analysis, once a week. A sample was collected and SampleVolume was reset to 0 when SampleVolume >= 75 L.

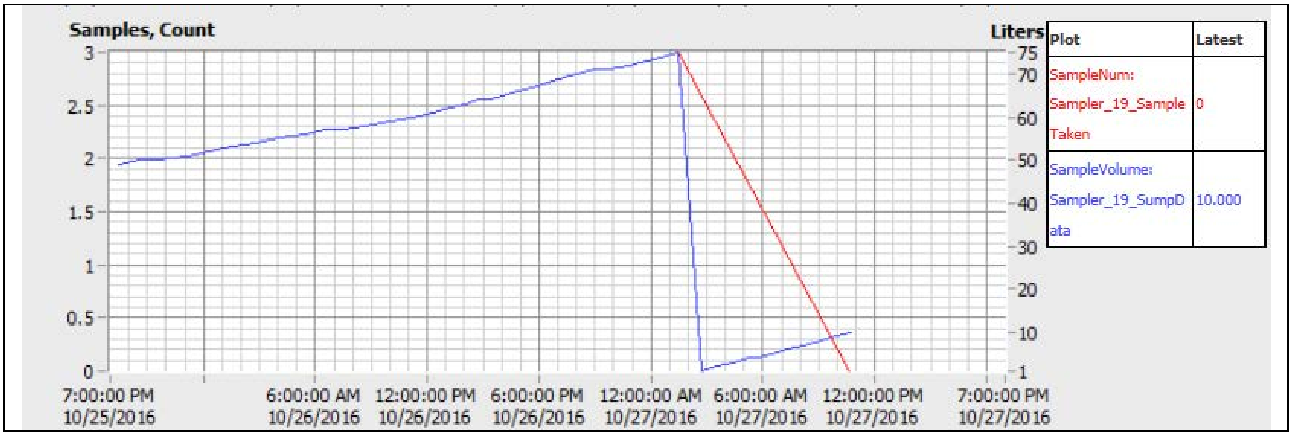


Figure 11. Close-up view of the middle right panel of Figure 7 that shows the variables SampleFailCount (count) and SamplerOn (Boolean, 0 = false, -1 = true). The patterns are typical of periods when water flows from an enclosure and the autosampling sequence is completed. SampleFailCount incremented by 1 each time that a sample was not collected and was reset to zero (0) each time that a sample was retrieved for chemical analysis, once a week. SamplerOn is set to 0 (false, or off) by an operator when a sample is collected or the autosampler is disabled for maintenance.

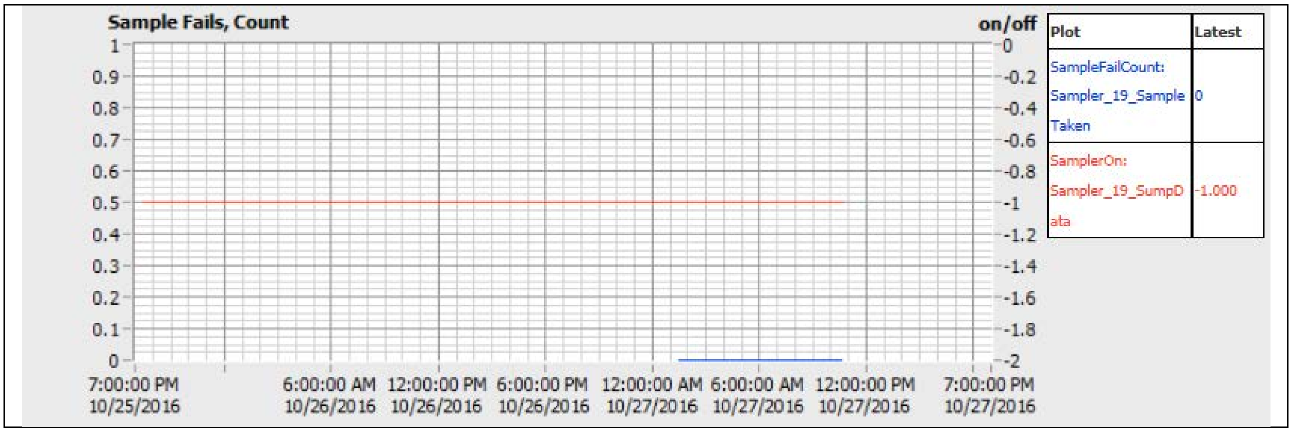


Figure 12. Close-up view of the bottom left panel of Figure 7 that shows water tables in an enclosure and at the EM1 environmental monitoring station (http://mnspruce.ornl.gov/sites/default/files/webpost-user-guide/spruce_em_data_2010_2011_20111123.pdf). The patterns show variations in water tables relative to datums that were measured each year as the local hollow surface near a water level well.

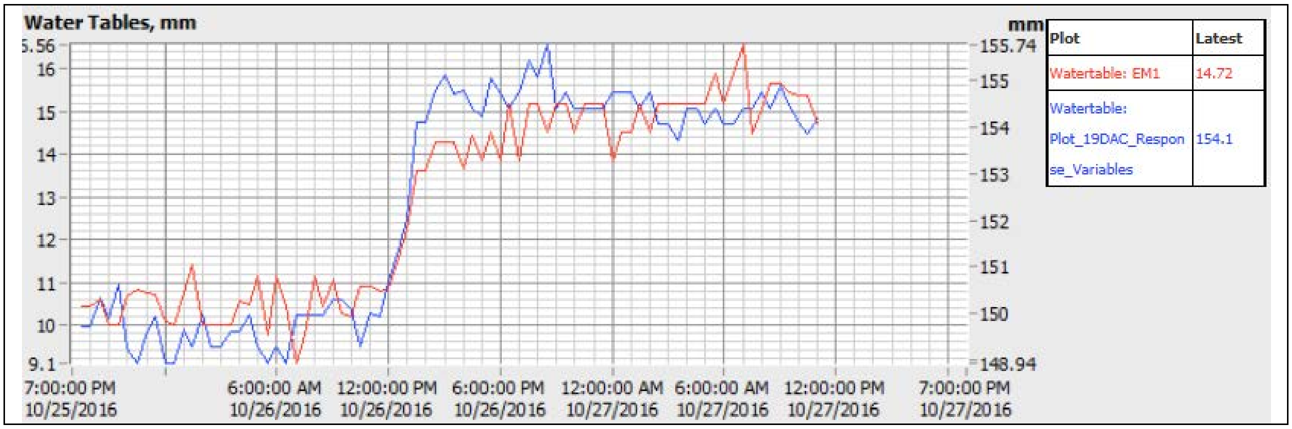
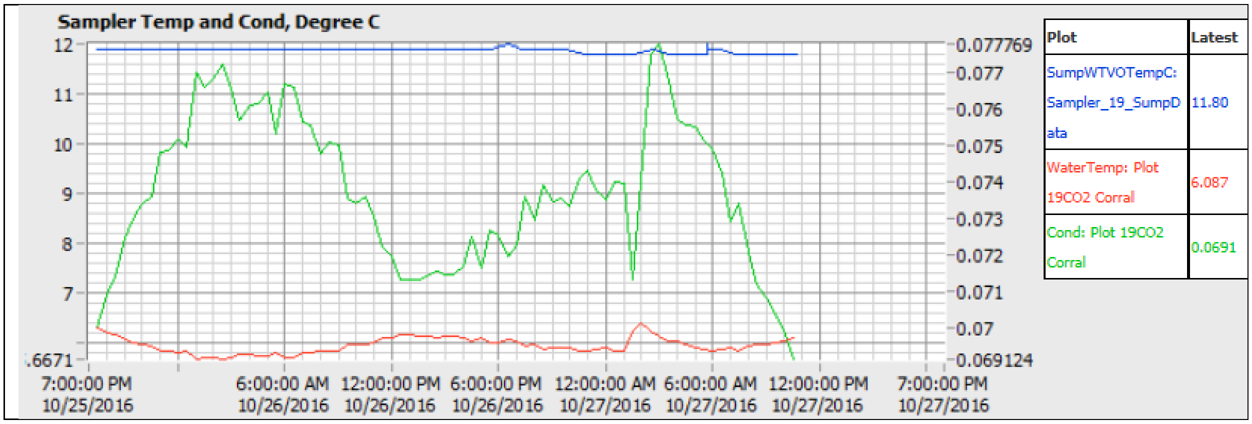


Figure 13. Close-up view of the bottom left panel of Figure 7 that shows water temperature measured by the WT-VO sensor (SumpWTVOTempC (degrees C) and CS547 sensor (WaterTemp, degrees C), and specific conductivity (Cond, microSiemen/cm).



Calibrations:

1. The calibration is the linear relationship between voltage (mV) and water volume (L) in a sump (Figure 7). In October and November 2015, two calibrations were calculated for each sump: one for the 15-cm deeper pipe, and one for the large basin. After summer 2016, when filling was restricted to the deeper pipe, only the deeper pipe was calibrated.
2. Re-calibrations occur:
   - Yearly (initially) to determine if calibrations changed due to compression, heaving, or some other physical change to the sump or sensor instability.
   - If the water level sensor or interface failed and a new sensor or interface was installed.

Calibration Equipment (Table 8):

1. A hand pump to manually remove water from the sump system.
2. 1 to 10-L graduated cylinders or beakers, to measure volumes of water that were pumped from the sump system.
3. Field data sheets to record measurements and observations (Appendix 1).
4. A computer with RS-232 port and RS-232 cable connected to the RS-232 port on the WT-VO sensor interface, an Archer Field PC with an RS-232 cable connected to the RS-232 port on a Campbell Scientific CR1000 datalogger in the CO_2 data acquisition panel (Krassovski *et al*., 2015), or a wireless connection via LoggerLink to the CR1000 in a Campbell Scientific BVS-4300C-SC-NF-NP-H-S autosampler. Any of these connections can be used to read the voltage output from the WT-VO sensor.
5. Water level sensor to measure the depth to the water level surface and the bottom of the 15-cm deeper pipe. A piece of angle aluminum was placed atop the large basin and aligned above the 15-cm deeper pipe to provide a datum for depth measurements.
6. A meter stick to measure the depth from the top of an open large basin to the top of the rim/basin tank fitting. A piece of angle aluminum was placed atop the large basin and aligned above the 15-cm deeper pipe to measure the depth to the rim/basin fitting.

Table 8. Calibration equipment specifications.

Equipment	Product info
Pump	Bosworth Company Guzzler self-priming, diaphragm hand pump with check valves and flexible 0.8 to 1.3-cm ID tubing. http://www.thebosworthco.com/bselectp.php. Any pump with a pump rate of 3 L/min is adequate.
Measuring containers	1 to 10-L graduated cylinders or beakers.
Archer Field PC	http://www.junipersys.com/Juniper-Systems-Rugged-Handheld-Computers/products/Archer-2.
Campbell Scientific LoggerLink	https://www.campbellsci.com/loggerlink, version 1.3.2 or subsequent updates.
Water level sensor	Durham Geo Slope Indicator water level sensor, http://www.durhamgeo.com/Ground-Water/water-level-indicator.html, product 51690303, 30-m water level indicator with 1-cm increments. Any sensor with millimeter resolution of measurements is adequate.
Meter stick	A 1 m long meter stick.
Angle aluminum	A ~0.5 m long piece of aluminum angle (or other similar rigid material) to place across the top of an open large basin for depth measurements to the rim/basin tank fitting, water surface, and bottom of the 15-cm deeper pipe.

Calibration Procedure:

1. The sump pump was turned off, either at a 120-V circuit breaker to prevent water from being automatically pumped out of a sump, or by changing the Boolean variable SumpDisable in the operation program from False to True for the duration of the calibration procedure.
2. Sump valves were opened and water from the enclosure was allowed to drain into the sump. The sump was filled with water to the lowest drainage hole in the stand pipe when the large basin was calibrated, or to the rim when the deeper pipe was calibrated. When sumps were full to the desired level, the ball valves on outflow pipes were shut until the calibration was completed.
3. The water level in the sump was measured using a WT-VO sensor. Water level was measured as WT-VO (mV) to calculate the volume (L) vs. WT-VO (mV) relationship.
4. The depth from the top of the basin to the rim on the 15-cm deeper pipe was measured.
5. After the initial depth (mm) to water in the sump from the top of the basin was measured, water was manually pumped out of a sump and measured in graduated beakers (2, 3, or 10 L) or a 1-L graduated cylinder. Withdrawn water volumes typically ranged from 6-15 L. The depth to water was measured every time that volumes were recorded. About 10

measurements were completed before the large basin was emptied and the water level had reached, but not dropped below the rim of the 15-cm pipe.

6. The pump and measurement process was continued to determine a volume (L) versus WT-VO (mV) relationship for the 15-cm pipe, as described above for the large basin. Approximately 10 measurements were made, with 2-3 L pumped out between each measurement.
7. When all of the water was pumped from the sump, the final volume (L) and WT-VO (mV) were recorded.
8. Data were entered into spreadsheets and linear calibrations were calculated for the large basin and deeper pipe of each sump (Figure 7, Tables 9-12).

Figure 7. Example calibration curve from enclosure 19. Blue symbols show data points collected in the field. The segment with a lower slope is for the 15-cm deeper pipe, and the higher slope segment is for the large basin.

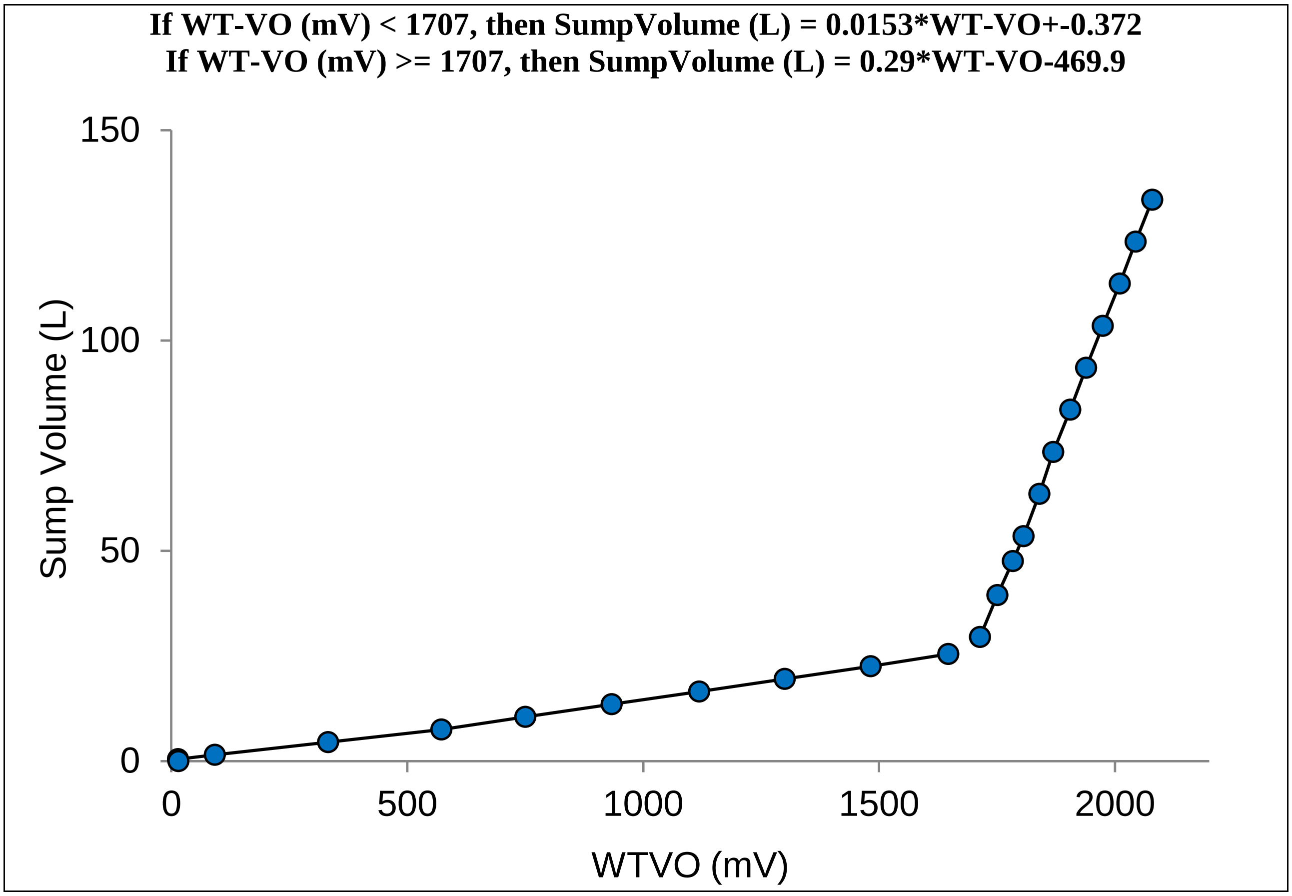


Table 9. Initial calibrations, October 8, 2015 and November 24, 2015.

SUMP	BASIN SEGMENT	WT-VO threshold (mV)	SLOPE (L/mV)	INTERCEPT (mV)
4	15-cm pipe	<1581	0.0157	0.716
4	Large basin	≥1581	0.308	-461.5
6	15-cm pipe	<1574	0.0157	1.062
6	Large basin	≥1574	0.288	-428.3
8	15-cm pipe	<1580	0.0153	0.098
8	Large basin	≥1580	0.304	-456.1
10	15-cm pipe	<1559	0.0161	0.743
10	Large basin	≥1559	0.295	-434.5
11	15-cm pipe	<1600	0.0157	0.312
11	Large basin	≥1600	0.296	-448.4
13	15-cm pipe	<1579	0.0147	0.233
13	Large basin	≥1579	0.296	-443.4
16	15-cm pipe	<1755	0.0149	-0.792
16	Large basin	≥1755	0.334	-560.4
17	15-cm pipe	<1717	0.0144	-0.413
17	Large basin	≥1717	0.301	-492.7
19	15-cm pipe	<1707	0.0153	-0.372
19	Large basin	≥1707	0.290	-469.9
20	15-cm pipe	<1820	0.0142	0.343
20	Large basin	≥1820	0.263	-452.8

Table 10. Calibration, May 13, 2016.

After failures and replacements, sensors were calibrated for 3 sumps. The calibrations were only determined for the 15-cm PVC, not the large sump basin.

SUMP	BASIN SEGMENT	WT-VO threshold (mV)	SLOPE (L/mV)	INTERCEPT (mV)
10	15-cm pipe	<1766	0.0144	-1.15
11	15-cm pipe	<1780	0.0145	-1.018
13	15-cm pipe	<1593	0.0158	-0.805

Table 11. Calibration, September 7, 2016.

After failure and replacement, the WT-VO sensor for sump 20 was replaced with a new sensor. The sump was calibrated for the failing and replacement sensors. Sump 19 was also recalibrated.

SUMP	BASIN SEGMENT	WT-VO threshold (mV)	SLOPE (L/mV)	INTERCEPT (mV)
19	15-cm pipe	<1707	0.0106	-0.207
20 (pre-replacement)	15-cm pipe	<1820	0.0106	-0.207
20 (new WT-VO sensor)	15-cm pipe	<1820	0.0158	-0.210

Table 12. Recalibration, October 13 and 14, 2016.

SUMP	BASIN SEGMENT	WT-VO threshold (mV)	SLOPE (L/mV)	INTERCEPT (mV)
4	15-cm pipe	<1956	0.0123	-0.055
6	15-cm pipe	<1767	0.0133	-0.009
8	15-cm pipe	<2019	0.0115	0.642
10	15-cm pipe	<1819	0.0138	-0.593
11	15-cm pipe	<1966	0.0120	0.031
13	15-cm pipe	<1711	0.0140	0.109
16	15-cm pipe	<1997	0.0122	-0.398
17	15-cm pipe	<1938	0.0125	0.354
19	15-cm pipe	<1882	0.0136	-0.887
20	15-cm pipe	<1635	0.0145	0.328

References:

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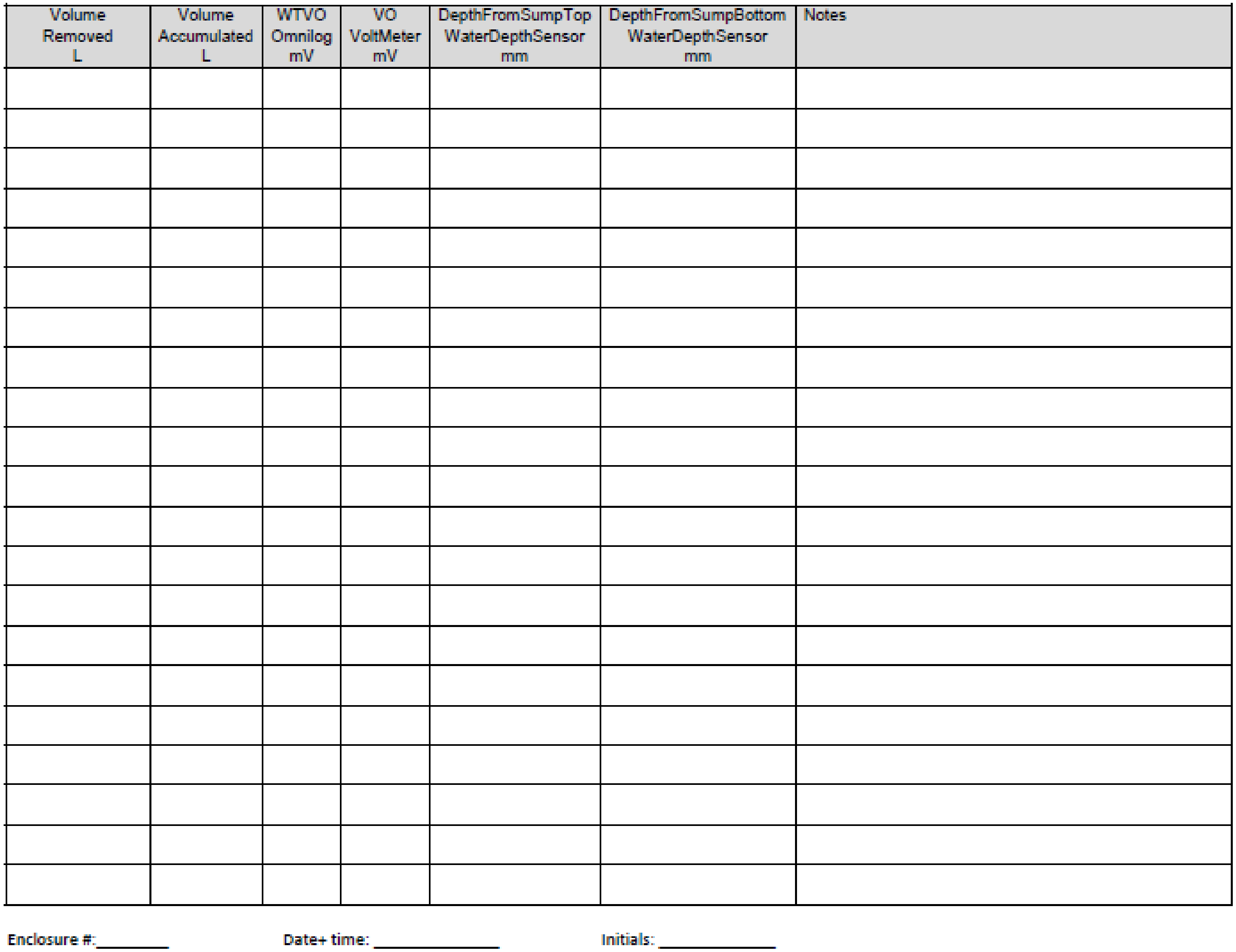
Verry ES, Brooks KN, Nichols DS, Ferris DR, Sebestyen SD (2011b), Watershed hydrology, in Peatland biogeochemistry and watershed hydrology at the Marcell Experimental Forest, edited by Kolka RK *et al*., pp. 193-212, CRC Press, Boca Raton, FL.

Verry ES, Janssens J (2011c), Geology, vegetation, and hydrology of the S2 bog at the MEF: 12,000 years in northern Minnesota, in Peatland biogeochemistry and watershed hydrology at the Marcell Experimental Forest, edited by Kolka RK *et al*., pp. 93-134, CRC Press, Boca Raton, FL.

Appendix I. Field data form:



Volume Removed L	Volume Accumulated L	WTVO Omnilog mV	VO VoltMeter mV	DepthFromSumpTop WaterDepthSensor mm	DepthFromSumpBottom WaterDepthSensor mm	Notes

Enclosure #:_________ Date+ time: _______________ Initials: ______________

Notes:

- “Volume accumulated” is the accumulated volume of water that was removed from the sump, calculated by adding the volume removed to the previous value in the volume accumulated column, or simply the volume that was removed in the first row.
- The “VO Voltmeter mV” column is the mV output from the WT-VO sensor.

Photo (left) showing a volt meter with the positive probe connected to the height terminal on the WT-VO sensor interface and the negative probe connected to the common terminal (GND) on the WT-VO sensor interface. Sump 11. Photo (right) showing a WT-VO interface.

- The “DepthFromSumpBottom” column is calculated by subtracting the value in the “DepthFromSumpTop” column from the total depth to the bottom of the basin (15-cm deeper PVC pipe).