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Short note

Monitoring soil moisture and water table height with a low-cost data logger

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1. Introduction

Comprehensive temporal data sets are often needed in geosciences to understand and model environmental phenomena. Time series data sets in the geosciences have traditionally been captured by costly commercial sensors and data loggers ($100–1000s). Dedrick et al. (2000) presented a less costly ($10 s) and publicly available device known as the Hobart and William Smith Data Logger (HWSDL) (Halfman and McKinney, 2001). Parts list, plans, schematics, manuals, software and other essential items to build your own HWS Data Loggers are available on the Internet to educators and researchers.[1] Two recent projects required adaptations of the HWS Data Logger technology to: (1) record soil moisture by incorporating a dielectric aquameter, and (2) record subsurface water levels by reworking the circuit board layout and instrument housing to fit the logger and a pressure transducer sensor into a 5 cm (2 in) diameter well.

The HWSDL includes three independent components, a logger, a sensor and a reader. The original design utilized an 8-bit digital value and had a storage capacity of 4K. An upgraded version increased the data resolution to 12-bit values and memory capacity to 16K (McKinney and Halfman, 2002). This work incorporates these upgrades into two new sensor designs. The updated logger is based on Microchip's PIC16C773 microcontroller, which digitizes and records an analog voltage from a sensor at a programmable sample period. The unit is still powered by AA and 9 V batteries. The logger stores the data in a non-volatile EEPROM (24LC256, Microchip Technologies). The system interfaces to a PC compatible computer and communication is performed through the computers RS-232 serial port to transfer sample period information and collected data. Data sets are saved on the PC as delimited text files.

A variety of sensors exist for the HWSDL system, including devices for measuring temperature, light intensity, and water pressure (see footnote 1). All sensors have a number of features in common. To save battery life the sensor toggles on and off by solid-state relay connected to a control line from the loggers microprocessor. The control line is turned on (+Vss) approximately 0.5 s before sample time to provide power to sensor circuit. This allows the sensor to warm up, stabilize and then provide output to the logger. It is turned off (ground) after digitizing and storing sensor output. An optional LED illuminates whenever the control line is on (Dedrick et al., 2000). Sensors transmit an analog signal to the logger, and the logger digitizes this signal as the ratio of the signal to the reference voltage (usually 5 V). This digital value is calculated as

$$\text{Digitized value}^{*} = \left[\frac{V_{out}}{V_{ref}}\right] \times 255^{+}, \tag{1.1}$$

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[1] HWS Data Logger Web Site. http://academic.hws.edu/geo/logger/logger.html.

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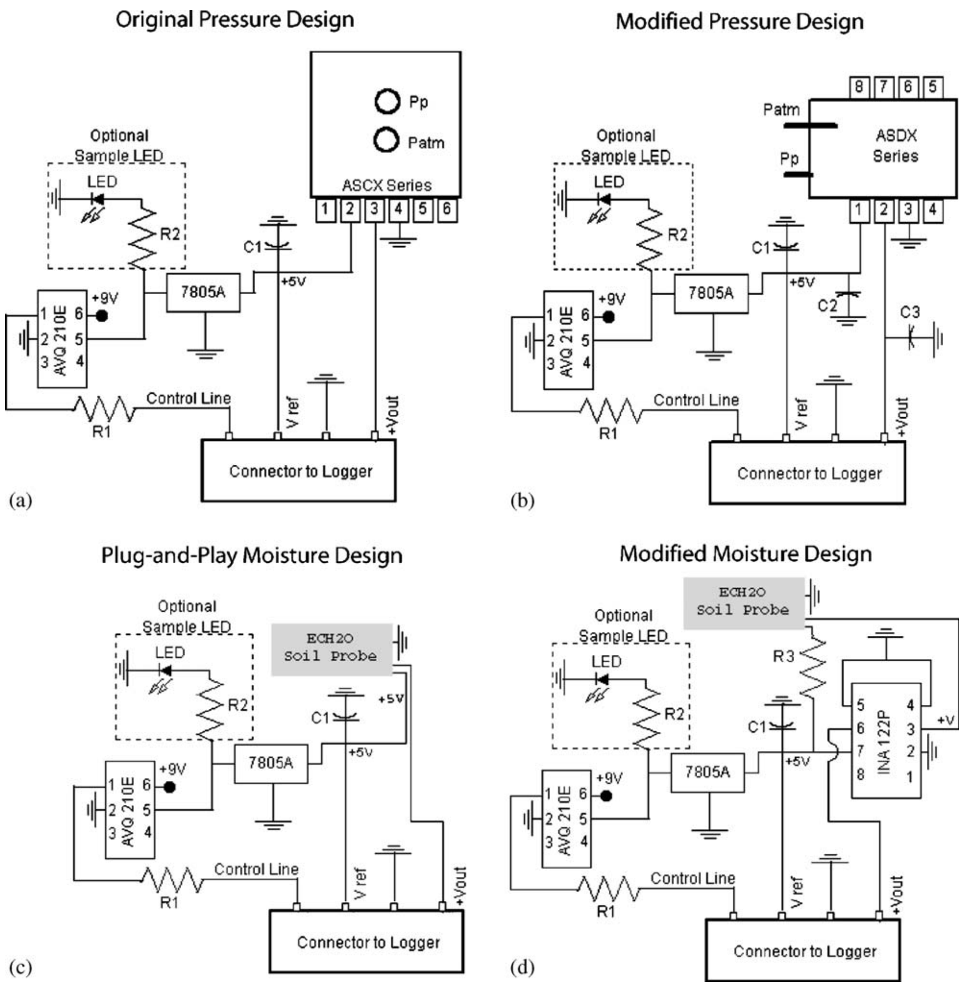

Fig. 1. HWS Data Logger sensor board (A) as it was originally created for water pressure sensing, and adaptations (B) for pressure sensing in 2-in diameter well, (C) for soil moisture sensing with little modification, and (D) for soil moisture sensing with amplification. Designs shown will work with any variable-resistance/variable-voltage sensor. Power is from separate 9 V battery, regulated to 5 V. V_{ref} is voltage reference line used to scale maximum 8/12-bit data value to 255/4096, respectively. Voltage in this line cannot exceed voltage supply to microcontroller by more than 0.3 V and has a minimum acceptable value of 3.0 V. V_{out} is data voltage from sensor to logger, which should have a maximum range from ground to V_{ref} to increase analog-to-digital resolution.

where * is rounded to nearest decimal and $^+$ replaces 255 with 4096 when using the 12-bit logger.

This simplicity of Eq. (1.1) makes the HWSDL adaptable to a variety of sensors, but new sensors may require voltage amplification to maximize sensor resolution. Details of the sensor boards discussed in this research are provided in Fig. 1 and Table 1.

2. Soil moisture sensor

The Decagon Devices ECH$_2$O Dielectric Aquameter (20 cm length) (Decagon, 2002) was identified as a potential cost-saving tool for monitoring soil moisture in a study of infiltration rates in urban soils within Syracuse New York. This probe is preferred over other possibilities because of minimized interference from salinity (Campbell, 2001a) and temperature (Campbell, 2001b) as well as its low cost. Adaptations described below generated the working prototype data logger plus sensor for less than \$70. Once parts are assembled, someone with moderate experience with electronic circuitry can complete the construction of the described system in less than an hour.

The ECH$_2$O soil probe requires an excitation voltage between 2.5 V (2 mA) and 5 V (7 mA). The expected output voltage of the probe ranges from 10% of the excitation voltage when in dry soil, to 40% of the

Table 1
Properties of sensor boards illustrated in Fig. 1A–D

Universal components	Universal component description	Unique components	Unique component description	Unique to
V_{out}	Sensor output	$\mathrm{ASCX}_{\mathrm{XXX-DM}}$[a]	ASCX differential pressure	A
V_{ref}	Reference voltage	P_{atm}	Atm. reference port.	A & B
Control	+5 V control line signal	P_p	P_p pressure port	A & B
7805 A	7805 A voltage regulator	$\mathrm{ASD}_{\mathrm{XXX}}\mathrm{G24R}$[a]	ASDX differential pressure	B
+9 V	Sensor power supply, +9 V	C2	0.2 μf capacitor	B
C1	1.0 μf capacitor	C3	0.3 μf capacitor	B
R1	220 Ω resistor	ECH_2O	Soil probe	C & D
R2	510 Ω resistor	R3	1.05 kΩ resistor ±5%	C
AVQ21OE	PhotoMos solid-state relay	INA122P	5× Voltage amplifier	D
LED	Optional sample LED			

[a] XXX = Pressure range.

Table 2
Soil probe variable performance given 'plug and play' and amplified set-up

Variable	'Plug & Play'	Amplified
Soil probe excitation (V)	4.83	2.53
V_{ref} voltage (V)	4.83	4.98
V_{out} (10–40%) (V)	0.53–1.66	1.32–4.37
Calculated digitized range[a]	27–87	99–241
Calculated soil probe resolution (cm^3/cm^3)[b]	0.0066	0.0028

[a] Digitized range with use of 8-bit logger.
[b] Assumes 40% volumetric water content is saturated soil.

excitation when in saturated soils.[2] This device could 'plug-and-play' with the original HWSDL because its sensor board was designed for a 5 V excitation (Fig. 1c). However, the output was limited within 10–40% of the excitation, constraining the output resolution of the sensor from utilizing its entire 8/12-bit range (see Table 2). Eq. (1.2) defines soil with a volumetric moisture content of $0.40\,\mathrm{cm}^3/\mathrm{cm}^3$ as saturated, where $V_{out-sat}$ and $V_{out-dry}$ are soil type specific, and V_{ref} is typically 5 V. Values of 255 are replaced by 4096 for a 12-bit logger design.

$$\text{Resolution} = \left[\frac{0.4\,\mathrm{cm}^3/\mathrm{cm}^3}{(V_{out-sat}/V_{ref} \times 255)(V_{out-dry}/V_{ref} \times 255)}\right]. \tag{1.2}$$

The soil moisture voltage range ($V_{out-dry}$ to $V_{out-sat}$) was increased using a redesigned circuit board that incorporated a signal amplifier (INA122 Instrument Amplifier by Texas Instruments), which has a minimum gain (amplification) of 5× (Brown, 1997). Using the INA122 with the soil probe yielded V_{out} voltage up to 10 V, which was too large for the A/D converter in the Microchip PIC16C73A. Placement of a 1.5 kΩ resistor on the circuit board, just prior to the soil probe excitation lead (Fig. 1d), resolved this problem by decreasing the soil probe's excitation voltage to below 2.5 V and limiting the V_{out} range to 0.25–1 V. When coupled with the 5× amplification of the INA122, the V_{out} voltage theoretically ranges from 1.25 to 5 V, allowing the utilization of a larger band within the digitized range and consequently improving probe resolution (see Table 2) (Fig. 2).

Resolution of the soil moisture probe increased 58%, from 0.0066 to $0.0028\,\mathrm{cm}^3/\mathrm{cm}^3$, after the INA122 and resistance modifications (Table 2). Laboratory tests with the HWSDL–ECH_2O soil probe combination suggest that a one-time preliminary calibration of each logger/sensor pair is required. Calibration curve data (Table 3) can then be used to convert the logger's unit-less digital values to soil moisture values. The average R^2 value of 0.998 indicates that each probe/logger pair has a near linear response, yet small differences in slope and Y-intercept of each trend line equation (Table 3) suggest the need for individual calibration. Data collected from within Syracuse, under different amounts of tree canopy and within different soils reveal promising results (Fig. 3). Differences in the wetting front and dry down behavior are both attributed to differing levels of

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[2] EcH2O Probe Web Site: http://www.ech2o.com/specs.html.

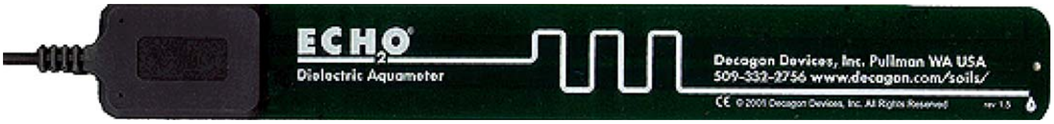

Fig. 2. Image of 20 cm ECH_2O soil moisture probe, manufactured by Decagon Devices.

Table 3
Equation for calibrated fit and coefficient of explanation in four separate ECH_2O soil moisture probes and 8-bit loggers, along with average fit

Logger & probe #	Line of best fit equation	R^2
31	$Y = 0.299\ X–29.886$	0.999
35	$Y = 0.291\ X–28.771$	0.999
38	$Y = 0.300\ X–29.860$	0.999
41	$Y = 0.281\ X–28.114$	0.996
Average	$Y = 0.293\ X–29.158$	0.998

Y is detected soil moisture (%) and X is raw logger data.

overhead canopy, as probe #3 has no overhead canopy, and probes #2 #1 have increasing levels of overhead canopy.

3. Groundwater monitoring sensor

The HWSDL was designed for sub-aqueous monitoring of surface water elevations (Riley and Halfman, 2001). However, the logger's casing diameter, pressure transducer, and 8-bit chip resolution prohibited its use in typical 5-cm (2-in) diameter groundwater monitoring wells. Additionally, the 8-bit resolution is inadequate to resolve mm-scale changes in water table elevation (Table 4). A narrower circuit board, the 12-bit HWSDL, and a new differential pressure sensor (model ASCX) from SenSym, facilitated an inexpensive, submersible data logger for use in standard 5-cm (2-in) or greater diameter groundwater monitoring well. This new configuration is capable of mm-scale resolution over a depth range of 21 m (30-psi sensor) (Table 4).

The groundwater system also required a component redesign. The original HWSDL was designed as a component system, allowing one logger to be used with any number of different sensors. This multi-component feature increased the size of the system, requiring a section of 10 cm (4 in) diameter × 25 cm (10 in) long section of PVC pipe as the housing (Rumpf, 2000). To decrease the size of the system, the printed circuit boards for the sensor and logger were integrated and hard-wired together, limiting each logger/sensor pair to a specific monitoring task.

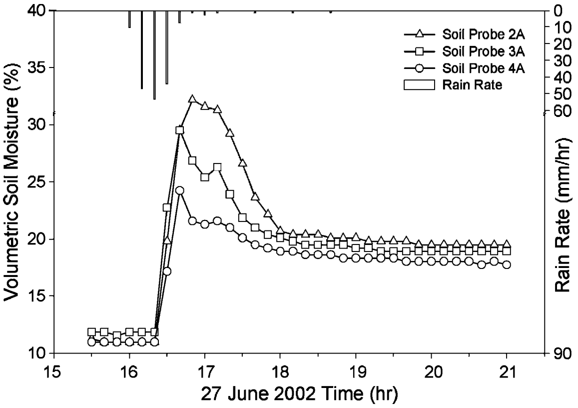

Fig. 3. Soil moisture (%) data in response to precipitation (mm h^{-1}) in Syracuse, NY using three different amplified HWS Data Logger/ECH_2O soil moisture probes. Differences in soil wetting and drying behavior can be attributed to differing levels of overhead canopy. Probe 2A had no overhead canopy, and probes 3A and 4A had increasing levels of overhead canopy.

Table 4
Theoretical resolution (cm) and maximum water depth (cm) for 8- and 12-bit microchip A/D processors when used with different pressure sensors

Sensor range (psi)	Water depth max (cm)	8-Bit resolution (cm)	12-Bit resolution (cm)
0–1	70	0.273	0.0170
0–5	351	1.37	0.0856
0–15	1054	4.117	0.257
0–30	2109	8.283	0.5148
0–100	7030	27.460	1.7163

Design constraints on a new logger housing included the need for it to be watertight, submersible, and smaller than 2 in in diameter, leaving enough room for vertical water movement in the well. A suitable housing based on a non-standard, thin-walled, 1-in diameter SDR21 PVC pipe by Genova, which has the same outside diameter as a 1-in standard schedule 40 PVC, but with a 33% larger interior cross-section. This increased cross-section allows the sensor's largest component, a 9 V battery, to fit inside the housing. The use of the 0–5 psi ASCX SenSym sensor required a 1/16th brass-barb male

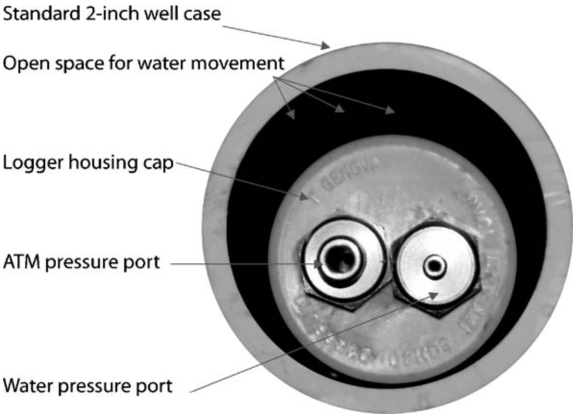

Fig. 4. Top view of new submersible logger housing as it sits within a 2-in groundwater well casing. Housing parts not readily available include 1/16th inch brass barb fittings from Swagelok (www.swagelok.com) and a mechanical watertight plug available from Taylor Made Plastics (www.thepipplug.com).

Table 5
Equation for calibrated fit and coefficient of explanation in three separate 0–5 psi pressure probes and 12-bit loggers, along with average fit

Logger/sensor pair ID	Trend line equation	R^2
#53	$Y = 0.0453\ X–17.425$	0.997
#62	$Y = 0.0463\ X–19.166$	0.998
#60	$Y = 0.0452\ X–15.719$	0.998
Average	$Y = 0.0456\ X–17.437$	0.998

Y is piezometric head (cm) and X is raw logger data.

fitting to accommodate the 1/16th tubing needed to fit snugly to the small nipples on the new sensor. Other parts not easily found include an expandable female mechanical plug, sized to fit the SDR21 PVC pipe. The redesigned system decreased the logger housing volume by 400% from the design by Rumpf (2000). (Fig. 4)

Laboratory tests of the 12-bit logger, smaller circuit board, and 0–5 psi ASCX sensor revealed noise of 70 logger units (approximately ±3 cm water depth) corrupting the signal. This noise was removed with two capacitors used as filters (Fig. 1b), smoothing the data. Subsequent laboratory calibrations of the new logger design have an average R^2 of 0.998, a near-linear response to changes in pressure head. Differences in the calibration equations are small but suggest the need for individual calibration depending on the level of accuracy required (Table 5). Access to an agricultural field site along Spafford Brook, which enters Otisco Lake, NY, allowed for drilling and gathering piezometric head (pressure and elevation) data with the modified HWSDL (Fig. 5). Data were used to understand whether Spafford Brook was gaining or losing water and inform co-located farm nutrient transport studies Data show the deepest piezometers (21 and 22) with dampened behavior, and the shallowest piezometers (19 and 20) with flashy responses.

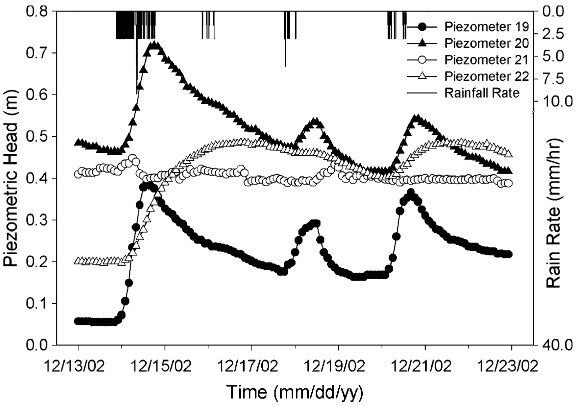

Fig. 5. Head data from two pairs of nested Piezometers at Spafford Brook, NY, gathered using newly designed groundwater monitoring sensor and HWS Data Logger. Piezometer screen elevations are 19: −1.35 m, 20: −0.62 m, 21: −2.86 m, 22: −2.40 m, all relative to stream bed elevation. Precipitation data are from a site 24 km northeast.

4. Conclusions

Modifications of the HWSDL presented in this paper expand upon the original logger design described by Dedrick et al. (2000). Increased digital resolution of the logger and sensor modifications allow for a greater variety of measuring and monitoring applications, including (1) soil moisture and (2) ground water elevation or piezometric head in a groundwater well.

1. Decagon Devices suggest the ECH_2O probe has a typical accuracy of ±3% (.03 m/m) and as great as ±1% with soil specific calibration (see footnote 2). Electrical limitations of the dielectric probe required modification to the HWSDL system, including the use of a voltage amplifier. Laboratory test of the HWSDL and ECH_2O probe show a linear response of the HWSDL to increases in soil water content as measured by the ECH_2O probe resulting in a resolution (sensitivity) of 0.0028 cm^3/cm^3 per 8-bit logger unit.
2. Modifications of the circuit board layout and a newly released ASCX differential pressure transducer by SenSym allow the system's housing to be reduced in volume by 400%, a sufficient decrease to allow the logger to be placed in a 2-in ground water well. Utilization of the newly released 12-bit 16K

version of the HWSDL system, coupled with the new housing design, allows for a submersible monitoring system with meter range and millimeter resolution.

Advantages to the modified HWSDL include its low cost and simplicity, while disadvantages include construction and laboratory calibration time.

Acknowledgements

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