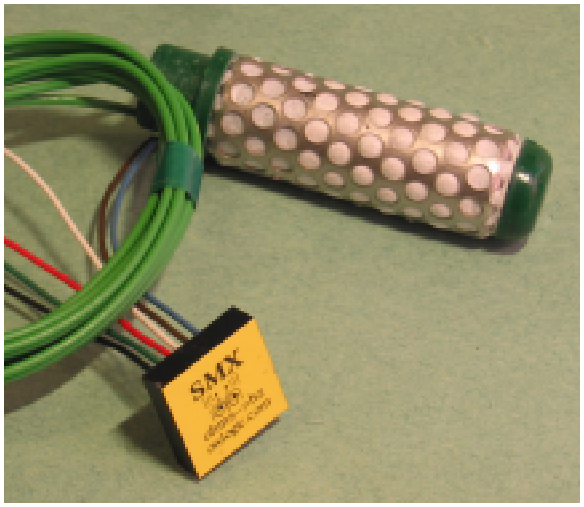
SMX

Electrical Interface for Watermark™ or Gypsum Block Sensors.

Watermark™ sensors are available from Irrometer Company* and their distributors world wide, including EME Systems. These soil moisture sensors are to be buried in intimate contact with soil at root depth, where they will reach equilibrium with the local soil moisture. The measurement correlates well with soil water potential. This is fine for agriculture, because water potential (in units of kilo-Pascal or centibar) best quantifies the work plant roots do to extract moisture from the soil. Of course, plants and soils have their individual characteristics. The bottom line is that the readings are related to plant stress and well being.



The signal is electrical resistance, which decreases with increasing soil moisture (and also temperature, which can be compensated). The sensor construction is ingenious: A perforated stainless steel cylinder supports a permeable membrane, inside which there is a tightly packed sand aggregate, the “granular matrix”, and at one end there is a wafer of gypsum, and concentric electrodes, which are attached to wires that emerge to the soil surface. The gypsum wafer serves as a buffer against differences in soil acidity and salinity, so that the electrical resistance between the electrodes depends on moisture and temperature only.

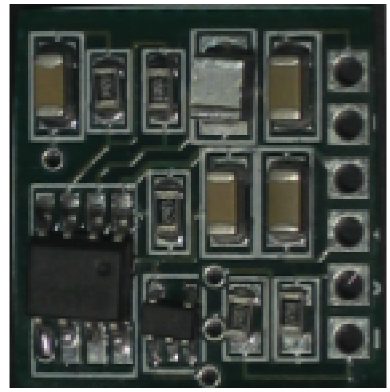
A special circuit is needed to measure the electrical resistance of the Watermark sensor. DC currents must not be allowed to flow through the wet part of the circuit, or else irreversible reactions will occur and spoil the readings. AC excitation avoids these problems, by reversing the polarity of the current many times per second, so that no net reaction takes place at either electrode. The circuit must also isolate the sensor electrodes from galvanic currents in the soil environment. Metal objects such as ground rods or pipes or tanks or other sensors that contact the soil can give rise to underground electrical currents in relation to the electrodes of the Watermark sensor, and those too can spoil the reading and degrade the sensor.

The SMX circuit provides the AC excitation and galvanic isolation required by the Watermark sensor. The output signal is a voltage, or alternatively, from the same module, a current or a frequency, that depends on the AC electrical resistance, from which the soil moisture tension can be calculated by an intelligent data logger or nomograph. Two wires go to the Watermark sensor, and the SMX output is routed to a data logger, controller or meter. The SMX module allows the Watermark sensors to be used with a wide range of general purpose equipment that does not have built in the special circuitry required to read the Watermark AC resistance.

The SMX is available as a module potted in industrial epoxy, with 6 wire leads, suitable for outdoor deplooyment, and the module is also available as an assembled circuit board, suitable for incorporation into custom systems.

* Watermark is a trademark of Irrometer Company, Riverside CA 909/689-1701 <http://www.irrometer.com>

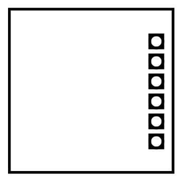
Specifications:



• Supply Voltage: 4–15 VDC
• Voltage output
  0.2 volts dry to 1.0 volts wet typical
  (as high as 1.7 V with sensor short circuit)
• Frequency output 50 hz dry to 7 khz wet
  open collector square wave (needs pullup
  resistor to read out frequency.)
  (as high as 13 khz with sensor short circuit)
• Current output (also supply current)
  0.2 mA dry to 1.0 mA wet
  (as high as 1.7 ma with sensor short circuit)
• less than 0.01% per Volt supply variation.
• **http://www.emesystems.com**

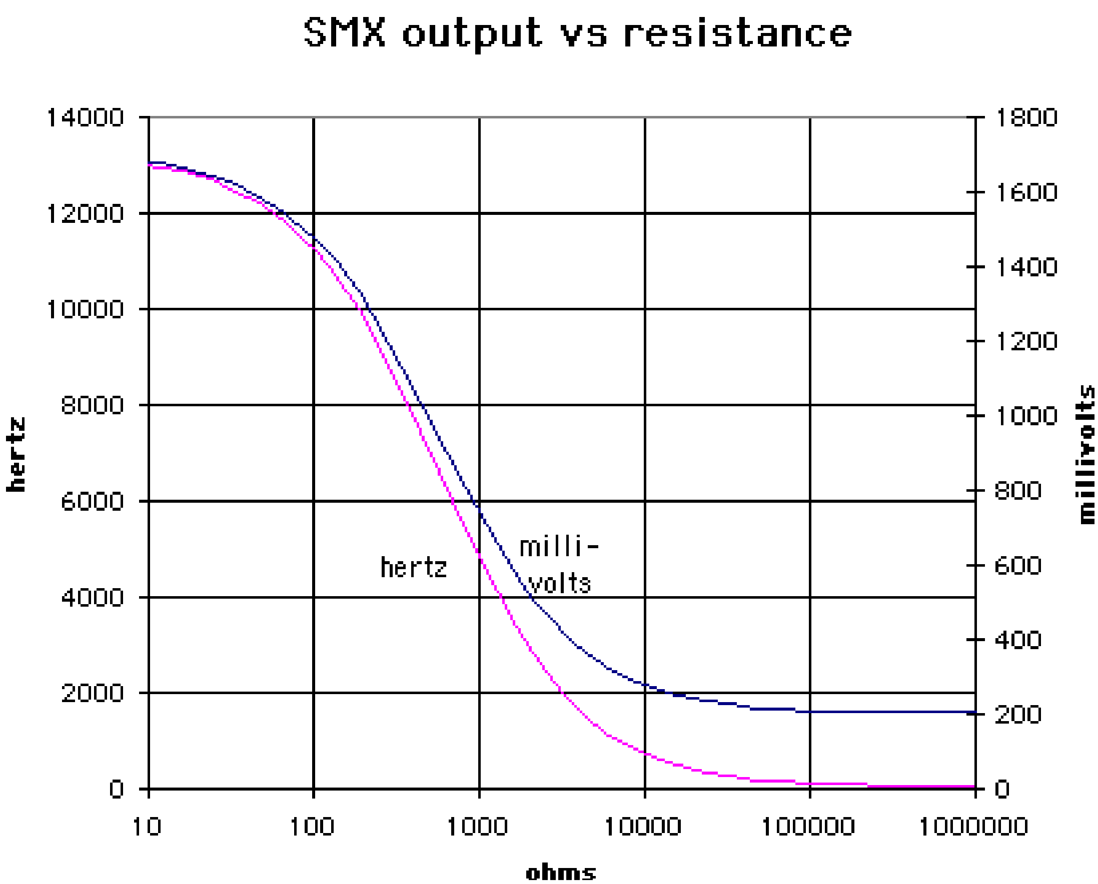
The SMX is a potted module (0.825" sqaure x 0.25" thick) for placement in the field near the sensor. There are two wires for connection to the Watermark or gypsum block sensor, and four wires for connection to the data logger or other equipment.

• connections
  red: + 5 to 15 volts DC
  green: signal frequency, needs pull-up to +V
  white or yelow: voltage signal
  black: common
  blue wires: soil moisture block
• Operating Temperature: -0°C to +50°C
  no meaningful signal below 0°C



SMX rev 2, top view (component side)
blue sensor
blue, sensor
yellow, volts out
green, frequency out, open collector
red, power +3.5 to 15 volts
black, common

Figure 1



Wiring the SMX to the data logger

The two blue wires from the module connect to the Watermark sensor terminals, either polarity is okay. Use wire nuts or other standard means of wiring. Insulate the connections, because water or other conductive material between them would give a false signal.

The SMX needs a power supply in the range of 3.5 to 15 volts DC. The SMX draws 1 milliamp or less of supply current, so it is possible to provide power from a switched output pin from a microcontroller. If more than one SMX is to be installed at a single location, power each one of them separately, in order to avoid interactions between the sensors.

Figure 2 shows how to connect the sensor for digital frequency output. The pullup resistor shown (4.7 kohms, value not critical) can pull up to any voltage from 3 to 7 volts DC. The output signal is a square wave, and its frequency varies from 50 hz when the sensor is bone dry, up to 10000+ hertz when the sensor is soaking wet. This output can be measured using a COUNT or PERIOD function on the data logger. Note that the white and the black wires are connected together.

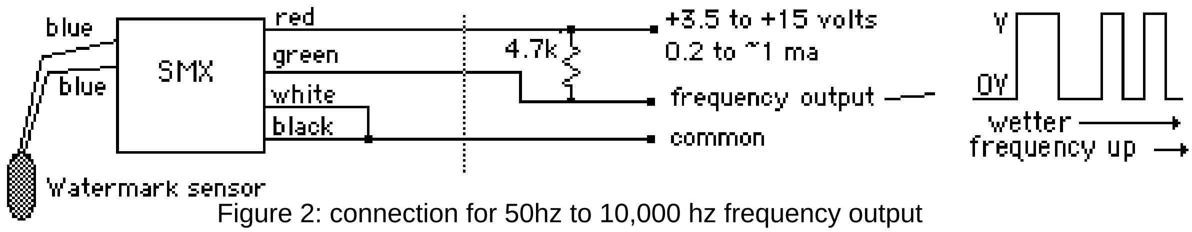


Figure 2: connection for 50hz to 10,000 hz frequency output

Figure 3 shows how to connect the sensor for voltage output. The green wire should be connected to the white wire. The minimum power supply is 4.5 volts in this configuration. The output signal is a voltage that varies from 0.2 volts when the sensor is bone dry, up to 1+ volt when the sensor is soaking wet. For best smoothing of the signal, add a capacitor of 100 µF from the voltage signal line to common. That will smooth out the remaining low frequency ripple.

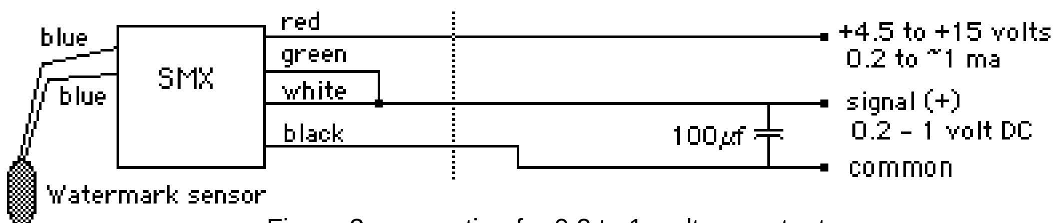
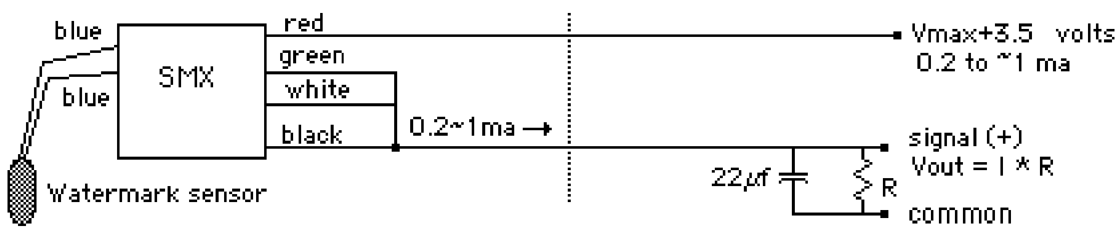


Figure 3: connection for 0.2 to 1 voltage output

Figure 4 shows how to connect the sensor for two wire current output. The black, green and white wires are joined. The output signal is a current that varies from 0.2 milliamp when the sensor is bone dry, up to over 1 milliamp when the sensor is soaking wet. The current on the two wire circuit may be converted to a voltage at the input of the data logger. A 1 kΩ resistor will convert the 0.2–1.0 millamp current into a 0.,2–1 volt signal. The power supply voltage must be a high enough voltage to sustain the maximum expected voltage across that resistor, plus the line loss in the wiring, plus the 3.5 volts required by the SMX module itself. For example, with a 15 volt supply and a 10kohm resistor, it is possible to achieve a signal output of 0 to 10 volts. DC across the resistor. Add a capacitor across the resistor to smooth the residual ripple

Figure 4: connection for two-wire 0.2 to 1 ma current output.



Watermark installation:

"Plant" the sensors, following the Watermark instructions for presoaking. Install the sensors while they and the soil are wet, and maintain good contact with the surrounding soil. Use a slurry as "glue" if necessary.

The sensors will interact with one another slightly if they are planted too close together. Keep them a foot or two apart if possible.

Install a temperature sensor at the same depth as the sensor, in order to implement the temperature compensation.

Lightning protection:

This circuit, like any that is installed in intimate contact with the soil, is subject to danger from lightning This is especially a problem if the soil moisture sensor is installed at a distance from the data logger or readout device that is monitoring the wetness, and the data logger has its own ground connection. If lightning strikes nearby, there can be large differences in ground potential between the two locations and currents will attempt to flow through the interconneting wires and through the sensitive circuit elements. The inputs on the blue and brown wires are protected to ±25 volts, however, this might not be enough in frequent lightning areas. Solutions:

1) Use a TVS (transient voltage suppressor, surge protector) rated at 12 volts across the sensor leads, with the ground of the TVS attached to the cable shield that leads up to the ground terminal on the data logger.

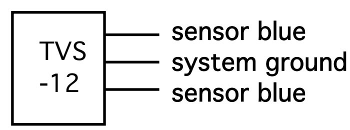
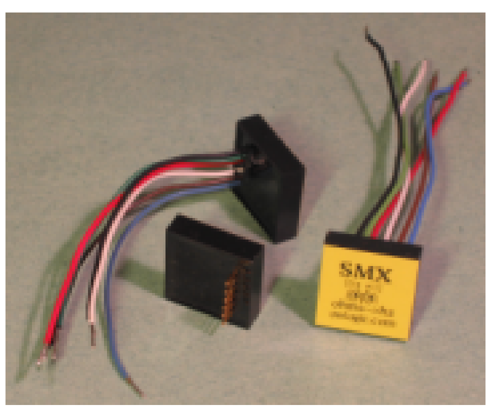


Figure 5: surge protector.

2) power the SMX from a separate battery, and transmit the data as a frequency using optical isolation.

3) install the data logger and the SMX in close physical proximity.



Notes on basic reading of the sensor signal.

Connect the SMX as in figure 2, for frequency output. This program is written in PBASIC for the BASIC Stamp, using the command COUNT to determine the SMX oscillation frequency.

```
' simple test of the SMX operation, count input.
result   var  word
loop:
  count 12,1000,result   ' count on Stamp P12 for 1 second
  debug ? result         ' show the result in counts
goto loop
```

The result should be between 50 Hertz (dry) to 10000 Hertz drenched (550 Ω) or 13000 Hertz with a direct short circuit across the grid.

Alternatively, here is code using the voltage input version. Connect the SMX as in figure 3, for voltage output, and connect the voltage to an analog to digital converter, as for example an analog input of an OWL2e data logger.

```
' simple test of the SMX operation, voltage input.
result   var  word
DO
  GOSUB ADread          ' not shown here
  DEBUG ? result        ' show the result in millivolts
  PAUSE 1000            ' slow it down
LOOP
```

The result should come out between 200 millivolts (dry) to 1000 millivolts (drenched, ~550 Ω), to 1700 millivolts (direct short circuit across the grid). **IMPORTANT:** If two or more sensors are located in close proximity, the power should be turned on to only one at a time, to avoid interaction.

```
' simple test of the SMX operation, voltage input.
result var  word
DO
  HIGH power1           ' turn on power to the 1st SMX module
  PAUSE 1000            ' allow reading to settle
  GOSUB ADread          ' read the value
  LOW power1            ' turn off power to the 1st SMX
  DEBUG ? result        ' show the result in millivolts
  HIGH power2           ' turn on power to the 2nd SMX module
  PAUSE 1000            ' allow reading to settle
  GOSUB ADread          ' read the value
  LOW power2            ' turn off power to the 2nd SMX
  DEBUG ? result        ' show the result in millivolts
LOOP
```

The raw readings above can be used to establish thresholds for irrigation or other actions, based on observation of plant stress and well being. On the other hand, in order to obtain quantitative results that can be compared to the Irrometer tables and advice for use of the Watermark, the raw voltage or raw count can be transformed to resistance, temperature compensated, and converted to moisture units in kilopascals. The following paragraphs describe this procedure, and a reference PBASIC program is listed in the appendix.

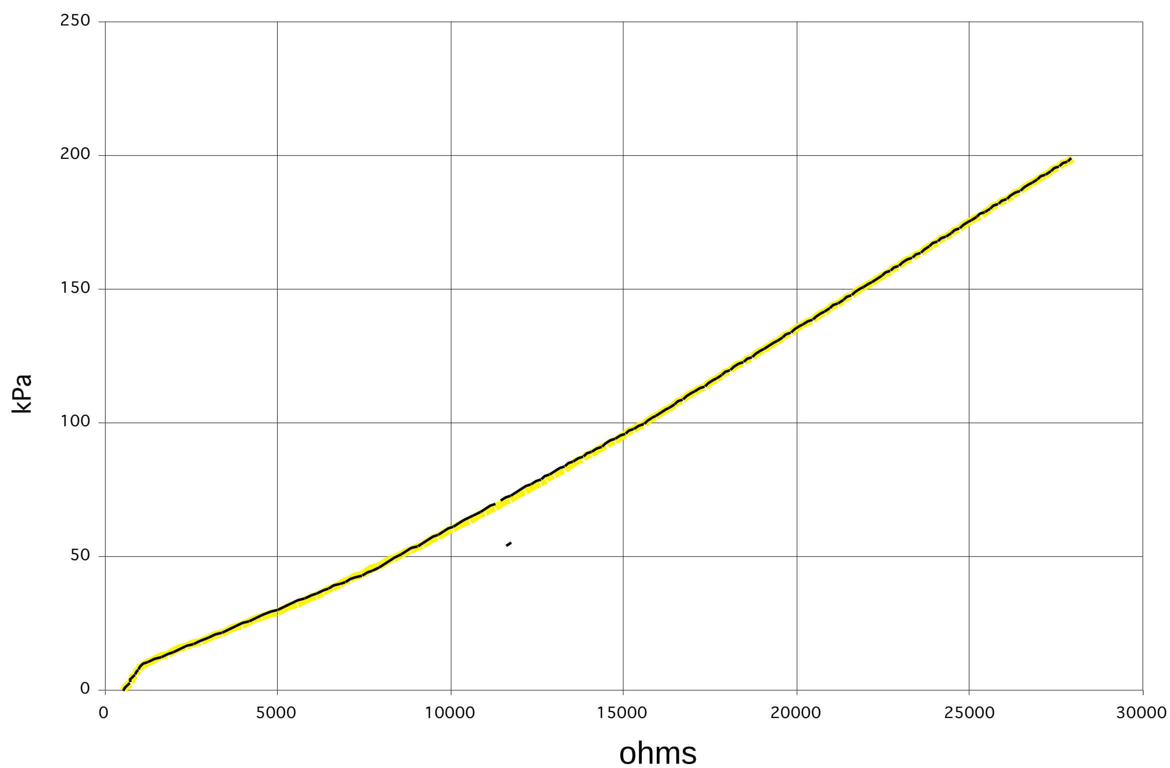
ohms	volts	μ-amps	hertz
0	1707	1707	13233
1	1704	1704	13209
2	1702	1702	13186
3	1699	1699	13162
4	1697	1697	13139
6	1691	1691	13092
8	1686	1686	13047
12	1676	1676	12962
16	1666	1666	12871
24	1645	1645	12708
32	1625	1625	12526
48	1588	1588	12200
64	1552	1552	11893
96	1485	1485	11312
128	1426	1426	10802
192	1320	1320	9882
256	1230	1230	9104
384	1089	1089	7878
512	980	980	6932
768	828	828	5596
1024	726	726	4697
1536	596	596	3557
2048	517	517	2862
3072	427	427	2071
4096	377	377	1623
6144	323	323	1135
8192	295	295	874
12288	265	265	612
16384	250	250	476
24576	234	234	335
32768	226	226	264
49152	218	218	194
65536	214	214	157
98304	210	210	122
131072	208	208	103
196608	206	206	85
262144	205	205	76
10000000	201	201	48

TABLE 1
Table of voltage, current and frequency output by the SMX module, when the given resistance is placed across its input terminals.

Table 2:
Showing the resistance values that correspond to certain levels of soil water potential. Summary of Irrometer "Chart #3", composed of piecewise linear segments. The resistance values are taken or temperature compensated to 75 degrees Fahrenheit (24 degrees Celsius).

SWP kPa	ohms	slope ohms/kPa
0	550	
		50
9	1000	
		100
10	1100	
		180
15	2000	
		200
35	6000	
		160
55	9200	
		150
75	12200	
		135
100	15575	
		125
200	maximum: 28075	

Figure 6: Soil Moisture in kiloPascal vs Watermark resistance in ohms.



Interpret the readings.

Soil moisture tension is given in terms of the electrical resistance of the Watermark sensor. Table 1 on the previous page shows the voltage, current and frequency output of the SMX as a function of resistance across the input. This data is also graphed in figure 1. Table 2 and figure 5 show soil moisture as a function of resistance. The two tables provide means to go from the volts or Hertz reading of the SMX, through resistance, to the corresponding soil moisture in kPa. The microcomputer or the spreadsheet can do this automatically, by a process of interpolation. There is actually one more small step in between table 1 and table 2, and that is that the resistance reading needs to be temperature compensated. The graph

Observe in table 1 that mVolts and µAmps are numerically the same, this being due to the fact that the voltage is determined by the current passed through a precision 1kΩ resistor.

The shape of this curve in table 1,and figure 1,is due to the design of the electrical circuit. It's output is proportional to one over the resistance of the sensor and other resistors that limit the low and high frequency of oscillation. This is by design. (Refer to the appendix 1 for more circuit information.)

The region of the curve in figure 1 that is of interest for irrigation will be the center part, from 500 ohms to 10000 ohms. Incidentally, the relationship of millivolt and current output is linear in relation to frequency. output (R^2>0.999).

Here is another way to express the information in table 2 and figure 6. This frames the relation between kPa and ohms (@75°F) terms of a piecewise linear computation:

kPa = (ohms - 550) / 50	**for 550 <= ohms <= 1000**
kPa = 9 + (ohms - 1000) / 100	**for 1000 <= ohms <= 1100**
kPa = 10 + (ohms - 1100) / 180	**for 1100 <= ohms <= 2000**
kPa = 10 + (ohms - 2000) / 200	**for 2000 <= ohms <= 6000**
kPa = 10 + (ohms - 6000) / 160	**for 6000 <= ohms <= 9200**
kPa = 10 + (ohms - 9200) / 150	**for 9200 <= ohms <= 12200**
kPa = 10 + (ohms - 12200) / 135	**for 12200 <= ohms <= 15575**
kPa = 10 + (ohms - 15575) / 125	**for 15575 <= ohms <= 28078**

The value of ohms on the right side of the equation is the temperature-compensated resistance of the Watermark sensor. At temperatures higher than the standard (75 degrees Fahrenheit), the Watermark sensor will have a lower resistance than it does at the standard temperature. The measured resistance will be multiplied by a correction factor that increases its resistance by 1% per degree F so as to estimate the value of resistance (higher) that it would have at 75 °F.

Use this formula:

$$\mathbf{R_{compensated} := R_{raw} * (1 + 0.01 * (°F - 75))}$$

This is embodied in the PBASIC program in appendix 2. The program 1) turns on the power to the SMX module, 2) allows the reading to stabilize for 1 second, 3) reads the raw millivolt value., 4) converts the raw millivolt value to ohms using a lookup table, 5) appliies the temperature correction, and 6) looks up the SWP in kilopascals in a second lookup table. That is the reading that is displayed. There may be an additional step, to average the readings over some period of time to go into the log file.

It is also possible to replace the lookup tables with calculations. The lookup table is better suited to the integer math of the BASIC Stamp. The calculations are better suited to larger computers that have better math libraries. For example, the raw millivolts and temperature can be imported into Excel on a PC and the moisture calculation made there. Appendix 3 shows these calculations.

Background, resistance to soil moisture potential, Irrometer chart #3.

Irrometer Corporation has published a table of electrical resistance values in relation to soil moisture in kPa. (table 2 and figure 5 above are taken from "chart #3") The resistance ranges from 550 ohms in saturated soil, 0.0 kPa, to 27950 ohms in bone dry soil, 199 kPa. That is at 75 degrees Fahrenheit, 24 degrees Celsius. This table is the basis of the readings produced by the Watermark Meter model 30KTCD-NL and for the new Watermark data logger and the Hanson model AM400 soil moisture data logger . Crop irrigation typically takes place in the range of 10 (sandy soils) to 60 (clay soils), depending on the crop and many factors. That is a resistance range of 1000 to 10000 ohms sensor resistance.

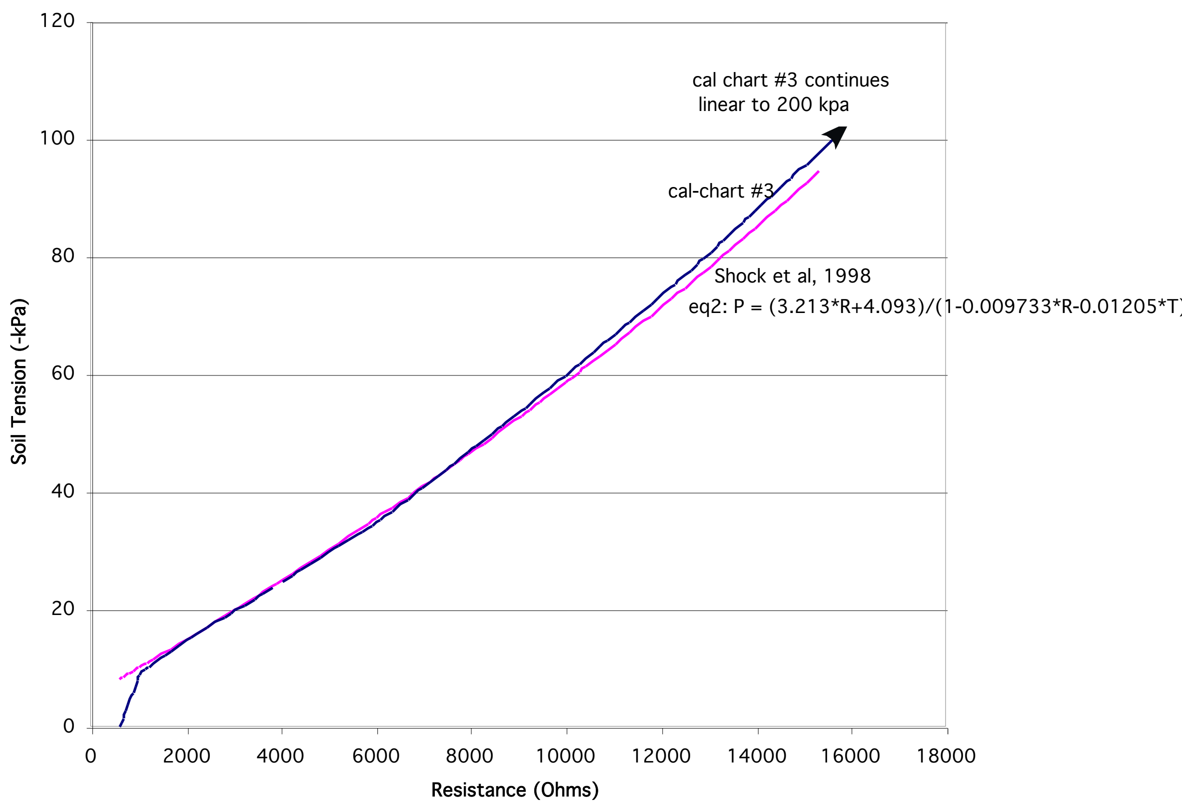
It is informative to understand where this comes from. Irrometer "chart #3" is based on a careful study of the Watermark sensors carried out by Shock, Barnum and Seddigh ("Calibration of the Watermark soil moisture sensors for irrigation management", *Proceedings of the 1998 Irrigation Association Technical Conference*). The study was set up in a temperature controlled environment in a sandy loam soil, with 24 model 200SS Watermarks along with standard tensiometers and temperature sensors. The main part of the Irrometer calibration chart is based those readings, averaged across the 24 sensors for each wetness and temperature. The experiments were done at both 25 degrees C and at 15 degrees C, so that the temperature compensation is validated over that range. The experiments covered the range of roughly -2 to -75 kPa, which is the range of the tensiometers used as the standard.

The range from -10 to -75 kPa is in fact the most important for agriculture, because irrigation schemes typically maintain tension in that range. Shock et al came up with the following equation as the best fit to the data, with the two variables (resistance and temperature) over the -10 to -75 range.

kPa = (3.213 * kohms + 4.093) / {1 - 0.009733 * kohms - 0.01205 * Celsius)

A graph of that function in relation to the Irrometer calibration is also shown on figure 6. It is important to note

Figure 8: Soil Tension vs. Resistance



that the fit outside the -10 to -75 range is bad.

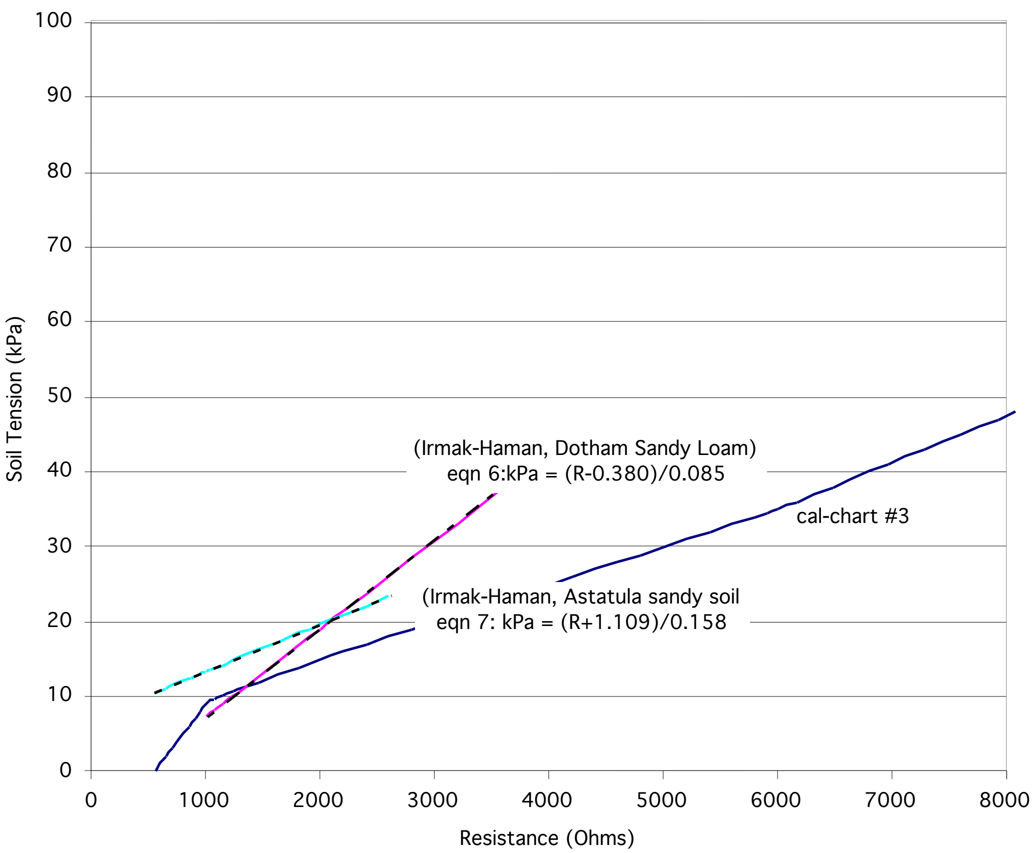
For suction less than -10 kPa (very wet soils), the slope of the empirical graph has a very different slope. A small range of resistance values covers a relatively large range of soil moistures.   In terms of soil physics, that is probably due to the falloff in chemical and capillary forces that bond to soil the water as the soil approaches saturation.

The study did not cover higher absolute levels of tension, because tensiometers do not function below about -80 kPa. The Irrometer Watermark calibration chart extends up to -200 kPa. This seems to be a simple extrapolation of the experimental data,

Caveats.

We have to realize that the data in the calibration chart comes from empirical results in a certain type of soil. Fgure 10 below shows results of resistance vs independently measured moisture in a study of sandy soils, instead of the loam. (Irmak & Haman, "Performance of the Watermark Granular Matrix Sensor in Sandy Soils", *Applied Engineering in Agricultur*e, 17(6):787-795 2001) This is compared to the Irrometer calibration chart #3. Any given

figure 10: Irmak-HermanGMS vs. Irrometer Cal. Chart #3

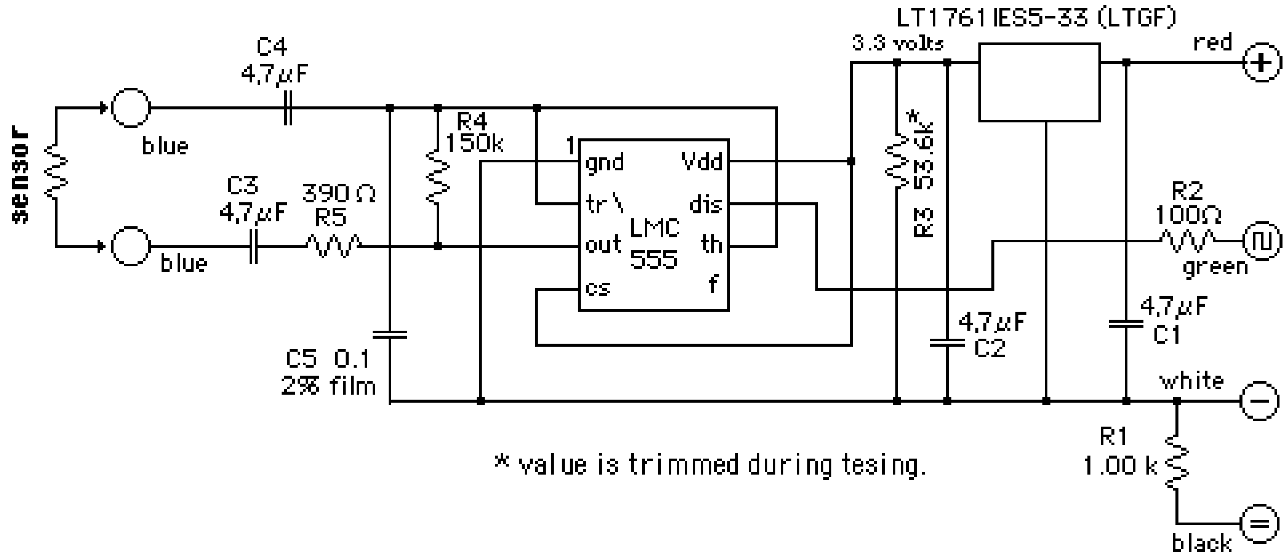


resistance value corresponds to a higher soil tension value than it would in the standard loam soil. This comparison should serve to emphasize how important calibration in locals soils is for the best accuracy.

On-site calibration can be done by comparing the Watermark output to a tensiometer. Over time, this can be developed into a relation between the variables of resistance, temperature, and soil moisture tension, applicable to the local situation. Even a few quick spot checks can fix a few points on the curve. Practical observation of plants establish the critical points for irrigation. Local agricultural extension agents can help with advice about the optimal level of irrigation for productivity and water usage of local crops in local soils.

There is variation from sensor to sensor, due to actual differences in moisture distribution and timing, or due to differences in installation, or due to variation in the Watermark sensors themselves and their aging. * install multiple sensors. • follow the Irrometer instructions for installation. • do reality checks on the sensors and reinstall sensors on a rotating schedule. (

Appendix 1: Technical information:

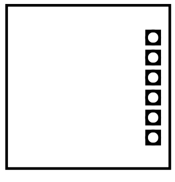


The power supply voltage is regulated at 3.3 volts DC by the micropower regulator. The power supply + input can be as low as 4 volts and as high as 15 volts. Filter capacitors are provided for stability and averaging of the supply current. The LMC555 timer operates in its direct feedback mode, with a square wave on the totem pole output from pin 3 charging or discharging the 0.1 µf polyester film timing capacitor through the network of fixed resistors in series/parallel with the moisture sensor. When the sensor is dry, the 150kΩ resistor sets a minimum oscillator frequency of 50 hertz. When the sensor is wet, or a short circuit, the 390Ω in series with the grid limits the upper frequency to about 13 khz. The current through the sensing grid is AC. Nonpolar ceramic capacitors isolate the circuit from the sensor, to assure that the average current is AC and to forestall galvanic interactions in the soil environment. The output frequency is transmitted to the logger from the open collector DIS output pin, protected from miswiring by the 100 Ω resistor. Normally a pullup resistor will be provided to give voltage transitions at the logger. The current drawn by the circuit varies linearly with the frequency due to the charge and discharge cycles of the 0.1¨F capacitor. The supply current is proportional to wetness, a voltage signal can be taken from across the 1kΩ resistor. The quiescent current is trimmed by R3, the 53..6 kΩ resistor.

There will be a small AC component on the DC output signal, that can be averaged in software. A 10µf capacitor in parallel with the output resistor will reduce the AC component to <5 millivolts.

The brown wire is the low impedance ouput of the oscillator. the blue wire is the high impedance input to the comparator.

There is still an issue about how this circuit measures the resistance of the sensor, in comparison to the Watermark standard meter, and in comparison with the Campbell CR10X + AM416 multiplexer that was used to collect the data used to construct "chart #3". The Watermark meter uses a low frequency AC half-bridge circuit, operating at around 100 hz. The CR10 + AN416 uses low voltage DC pulses a few milliseconds long per reading, in a half bridge, isolated through reed relays. The SMX uses a complex AC waveform at a frequency that varies from 50 hz (dry) to 10000 hz, (wet). We are still investigating how much difference the readout method makes in the result. The sensor is not just a simple resistor, but a chemical system with reactions and mobility of ions to take into account.



SMX rev 2, top view (component side)
blue sensor
blue, sensor
yellow, volts out
green, frequency out, open collector
red, power +3.5 to 15 volts
black, common

Appendix 2: PBASIC Snippets to read the SMX and convert to kPa

```
' ---- routine to service an SMX module ----
' ---- enter with channel number for power and for the signal
' ---- return with the result, and result shown on terminal screen
getkPa1:
  HIGH kPaPwr       ' turn on the power to this SMX
  INPUT kPaCh       ' be sure this channel is an input
  PAUSE 1000        ' allow reading to stabilize
  ADch=kPaCh        ' prepare to read this channel
  GOSUB ADread      ' do it, read voltage
  LOW kPaPwr        ' turn off the power to this SMX
  GOSUB calcOhms    ' calculate ohms from voltage
  GOSUB tcompOhms   ' temperature compensate ohms
  GOSUB calcSWP     ' calculate SWP in kPa from ohms
  GOSUB showdec1    ' show the result with one decimal place
  RETURN

' ---- lookup table, relating ohms to millivolts from SMX
ohms DATA Word 65535, Word 49152, Word 32768, Word 24576
     DATA Word 16384, Word 12288, Word 8192, Word 6144
     DATA Word 4096, Word 3072, Word 2048, Word 1536
     DATA Word 1024, Word 768, Word 512, Word 384
     DATA Word 256, Word 192, Word 128, Word 96
     DATA Word 64, Word 48, Word 32, Word 24
mVs  DATA Word 214, Word 218, Word 226, Word 234
     DATA Word 250, Word 265, Word 295, Word 323
     DATA Word 377, Word 427, Word 517, Word 596
     DATA Word 726, Word 828, Word 980, Word 1089
     DATA Word 1230, Word 1320, Word 1426, Word 1485
     DATA Word 1552, Word 1588, Word 1625, Word 1645

' ---- routine to calculate ohms, given millivolts
' ---- looks up millivolts in the table and interpolates ohms
calcOhms:
  ' enter with millivolts from smx
  IF mV<214 THEN ohms=65535 : RETURN    ' the ohms is greater than 65535, clamp that
  mV =mV MAX 1644                       ' clamp maximum millivolts too
  LOOKDOWN wx                           ' find position of millivolts in category
,<[0,218,226,234,250,265,295,323,377,427,517,596,726,828,980,1089,1230,1320,1426,1485,
1552,1588,1625,1645], cat
  READ (cat-1)*2+mVs,Word ww,Word wz    ' read lower and upper bound of category
  wy = mV - ww                          ' position in catagory
  ww = wz-ww                            ' width of catagory
  FOR ix=7 TO 0                         ' find the BS2 */ multiplier
    wy = wy//ww<<1
    wz0.BIT0(ix) = wy/ww
  NEXT
  READ (cat-1)*2+ohms,Word wy,Word ww   ' read lower and upper bound of ordinate
  wx = wy-((wy-ww)*/wz0)                ' interpolate using */ multiplier
  RETURN
```

```
' ---- temperature compensate the ohms reading
' ---- to the value the SMX would have at 75 degrees F
TcompOhms:
  ' enter with ohms in wx, soil degF in TFsoil
  ' Rx = (1 + 0.01*(TFsoil - 75)) * Rx  Implements this formula
  wx= (TFsoil*/655)-192+256 */ wx
  RETURN


' ---- lookup table, relating SWP to ohms from SMX
' ---- the ohms values adjusted to 75 degrees F
ohms2 DATA Word 550,Word 1000,Word 1100,Word 2000
      DATA Word 6000,Word 9200,Word 12200,Word 15575
      DATA Word 28075
swp   DATA 0,9,10,15
      DATA 35,55,75,100
      DATA 200


' ---- routine to calculate SPW in kPa, given ohms at 75 °F
' ---- looks up ohms in the table and interpolates kPa
calcSWP:
  IF wx<550 THEN kPa=0 : RETURN   ' don't bother, soil is saturated
  ohms =ohms MAX 28074            ' maximum ohms for SWP determination
  LOOKDOWN ohms ,<[0,1000,1100,2000,6000,9200,12200,15575,28075], cat
  READ (cat-1)*2+ohms2,Word ww,Word wz        ' find position in lookup tables
  wy=ohms-ww    ' position in category        ' position of ohms wrt category
  ww=wz-ww    ' width of category
  FOR ix=7 TO 0                               ' find BS2 */ multiplier for wy/wx
    wy=wy//ww<<1
    wz0.BIT0(ix)=wy/ww
  NEXT
  READ (cat-1)+swp,wy,ww  ' span of ordinate   ' width of SWP category
  kPa=wy*2+((ww-wy*2)*/wz0)*5  ' calc to 0.5   ' interpolation using */ multiplier
  RETURN

  END
' ===== end of snippets ====
```

The above program is meant to illustrate the principle, not to be a complete program. There are no variable declarations, nor is there a main program. The variable names and the subroutine names and the comments are chosen to be self-explanatory.

The linear interpolation process on the BASIC Stamp may appear strange, due to the integer math, but the process is really very straightforward.

Please contact Eme Systems or look on the web site for more complete examples using the OWL2pe data logger, and for further tutorial explanation of the integer math.

Appendix 3--Online Resources on Soil Moisture:

www.emesystems.com/smx.htm

www.irrometer.com

http://www.sowacs.com/
The main clearinghouse for all aspects and techniques of soil moisture measurement
http://www.sowacs.com/archives/
Sowacs mail
archive--The mail list covers a wide range of questions and answers.
Moderated by Bruce Metelerkamp
http://www.sowacs.com/archives/98-02/msg00000.html
Resurrecting the Gypsum Block for Soil Moisture Measurement
http://www.sowacs.com/archives/01-02/msg00027.html
Sowacs-mea-gypsum block email

http://www.cropinfo.net/granular.htm
GMS Malheur OSU - Clinton Shock
Malheur experiment station at Oregon State University,
bibliography of experimental research

http://www.kimberly.uidaho.edu/water/swm/Calibration_Watermark2.htm
Watermark calibration
http://www.kimberly.uidaho.edu/water/swm/
Soil Water Management
http://www.kimberly.uidaho.edu/water/swm/WM_Hobo2.htm"
Watermark to HOBO data logger
Articles from Rick Allen at the University of Idaho
http://soil-physics.nmsu.edu/sp/tutorials/

http://www.hwr.arizona.edu/globe/train/smchanges.html
UArizona/GLOBE Soil Moisture Project
University of Arizona educational project on parameters of global environmental importance

http://www.mea.com.au/
Measurement Engineering Australia - Environmental Monitoring Systems
Articles by Andrew Skinner of Measurement Engineering
Australia (MEA), and a link to the company web site.
http://www.Delmhorst.com/
Delmhorst Instrument Company
www.soilmoisture.com
Soil Moisture Corporation
http://www.measure.com/how2measure.html
Remote Measurement Systems - Sensors and Techniques