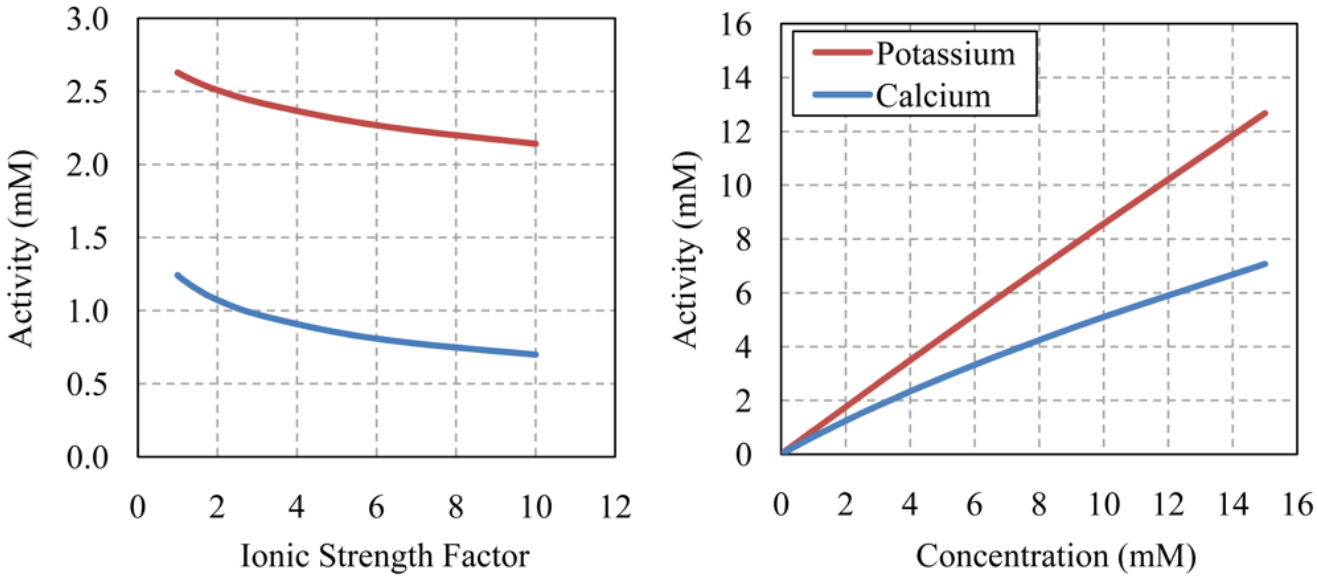
Electrolyte Conductivity vs. Ionic Activity: Why EC Alone Can Mislead Your Nutrient Decisions

Your EC meter is telling you only part of the story. Two nutrient solutions reading identical EC values can produce dramatically different plant growth outcomes in controlled studies. The reason lies in a fundamental measurement limitation: electrical conductivity reports total dissolved ions without distinguishing nutrient species from growth-limiting salts. This bulk measurement masks the specific ionic composition that drives membrane transport, competitive inhibition at root uptake sites, and toxicity thresholds. Understanding what EC actually measures will help you recognize when additional monitoring becomes necessary.



Activity versus concentration for monovalent potassium (K^+) and divalent calcium (Ca^{2+}) in half-strength Hoagland nutrient solution. The left panel shows how ionic activity declines as solution ionic strength increases, with divalent calcium affected far more severely than monovalent potassium. The right panel demonstrates that activity diverges substantially

from concentration as levels increase, with the effect being much stronger for divalent ions. This explains why calcium and magnesium deficiencies can appear in high-EC systems even when solution analysis shows adequate concentrations. Taken from (1).

EC measures bulk conductivity, not what plants actually absorb

Electrical conductivity provides an indiscriminate measure of total dissolved ions in solution. Your meter detects all charged particles without distinguishing whether they are essential nutrients or growth-limiting salts. As detailed in a review on ion-selective sensing in controlled environment agriculture, EC cannot differentiate among nutrient species, and different ions contribute disproportionately to measured values (1).

Why EC alone proves insufficient has multiple explanations. Ion identity matters: sodium and chloride at high concentrations cause specific toxicities independent of osmotic effects. Ion ratios matter: excess potassium competitively inhibits calcium and magnesium uptake at membrane transporters. And the effective concentration of ions in solution, termed **ionic activity**, also plays a role. Activity represents the concentration available for chemical reactions, always lower than measured concentration due to ionic interactions in solution.

Plants do not directly sense ionic activity. They respond to membrane transport kinetics, electrochemical gradients, competitive inhibition at transporters, and rhizosphere chemistry. Ionic activity influences these processes, but ion identity, ratios, and specific toxicities provide the more actionable framework for understanding when EC measurements mislead.

Parameter	What It Measures	Plant Relevance
EC (electrical conductivity)	Total dissolved ion charge carriers	Indirect indicator only
Ion concentration	Absolute quantity of each ion species	Laboratory reference value
Ionic activity	Effective concentration for chemical reactions	Influences uptake kinetics and ion availability

The Debye-Hückel equation predicts activity coefficient changes with ionic strength in ideal solutions (1). At typical nutrient solution concentrations, divalent cations like calcium and magnesium might show activity coefficients around **0.36**, suggesting reduced effective availability.

However, Debye-Hückel works best at low ionic strength with simple solutions. Real hydroponic systems are multi-ion mixtures with chelators, buffers, and temperature fluctuations. Activity coefficients are not static, generalizable values. The conceptual value is recognizing that concentrated solutions have reduced effective nutrient concentrations, with divalent ions more affected than monovalent ones. But this thermodynamic consideration is only part of why EC measurements can mislead. Ion-specific toxicities, competitive uptake, and ratio imbalances often matter more in practice.

Identical EC readings can mask specific ion toxicities

The clearest evidence that EC measurements conceal important information comes from controlled salt stress experiments comparing solutions matched for EC but differing in ionic composition. Research on faba bean exposed plants to sodium-dominant, chloride-dominant, and sodium chloride treatments, all maintained at the same EC range of 8.4 to 9.0 dS/m with

identical osmotic potentials (2).

These were deliberately extreme compositions designed to test toxicity mechanisms, not optimized fertigation protocols. The results show what EC masks under stress conditions. At matched EC levels, chloride-dominant solutions reduced shoot dry weight by **24 to 40 percent** compared to controls, while sodium-dominant solutions caused only **5 to 23 percent** reduction. The NaCl treatment combining both ions produced the largest growth inhibition at **36 to 55 percent**, demonstrating additive toxicity effects (2).

Salt Composition	EC (dS/m)	Osmotic Potential (MPa)	Shoot Dry Weight Reduction
Sodium-dominant (Na_2SO_4, Na_2HPO_4, $NaNO_3$)	8.8	-0.49	5-23%
Chloride-dominant ($CaCl_2$, $MgCl_2$, KCl)	8.4	-0.48	24-40%
NaCl combined	9.0	-0.50	36-55%

The point is not that growers routinely leave 40% yield on the table by relying on EC. The point is that EC provides no information about which specific ions contribute to the measured value. Two solutions at identical EC can have completely different ionic compositions, and those differences matter when toxic ions accumulate or when antagonistic interactions suppress nutrient uptake. The experiments demonstrate that specific ion toxicity operates independently of bulk conductivity measurements.

Activity coefficients and competitive uptake

Plant nutrient uptake follows Michaelis-Menten kinetics, with roots responding to effective ionic concentrations at membrane transport sites. Research on ion uptake kinetics across crop

species found that uptake rates depend on transporter properties and the concentration gradients driving diffusion and active transport (3).

However, plants are not passive. They actively regulate transporter expression in response to nutrient status. Root exudates, rhizosphere pH shifts, and microbial interactions create a dynamic environment that activity coefficients alone cannot predict. In recirculating systems, root-zone biology often dominates availability more than solution thermodynamics.

Each nutrient ion has an optimal concentration range. Deviation causes deficiency or toxicity. High potassium suppresses magnesium and calcium uptake through competitive inhibition at transporters, even when those nutrients appear adequate (1). This operates through membrane competition rather than activity coefficients.

The charge on an ion affects both its activity coefficient and its behavior at root membranes:

Ion Charge	Example Ions	Activity Coefficient at I = 0.01 M	Activity Coefficient at I = 0.1 M
Monovalent (+1)	K^+, NO_3^-, Na^+	~0.90	~0.76
Divalent (+2)	Ca^{2+}, Mg^{2+}, SO_4^{2-}	~0.68	~0.36
Trivalent (+3)	Fe^{3+}, Al^{3+}	~0.45	~0.04

Calcium and magnesium deficiencies can appear in high-EC systems even when solution analysis shows adequate concentrations. Multiple factors contribute: reduced activity coefficients at elevated ionic strength, competitive inhibition from excess monovalent cations, precipitation reducing free ions, and inadequate transporter expression in some cases.

A practical framework for knowing when EC suffices

Understanding EC limitations does not mean abandoning it as a management tool. The question is when EC monitoring alone provides adequate control and when additional measurements become necessary.

EC works adequately when:

- Using stable, tested nutrient recipes with known water sources
- Operating within established EC ranges for your crop (typically 1.5-2.5 dS/m for most vegetables)
- Observing normal growth with no unexplained deficiency or toxicity symptoms
- Running drain-to-waste systems where solution composition stays close to input values

Move beyond EC-only monitoring when:

- Source water contains significant sodium, chloride, or bicarbonate (>50 ppm of concerning ions)
- Running recirculating systems where selective uptake changes ratios over time
- Pushing high EC strategies (>3.0 dS/m) for crop steering or stress conditioning
- Observing nutrient disorders that do not resolve with EC adjustments
- Using fertilizer blends high in chloride-based salts (muriate of potash, calcium chloride)

Monitor ion ratios alongside EC. Track potassium to calcium ratios (typically 1:0.7 to 1:1 molar basis for greenhouse vegetables), calcium to magnesium around 3:1 to 5:1, and watch

for sodium and chloride accumulation. These targets vary by crop, growth stage, temperature, and transpiration rates, but maintaining balanced ratios matters for preventing competitive uptake regardless of activity calculations.

Account for ionic strength effects on divalent nutrients. When operating at elevated EC for generative strategies, calcium and magnesium may require 10-20% higher concentrations above 2.5 dS/m.

Consider periodic solution analysis. Laboratory testing provides ground truth for whether EC correlates with intended composition. Test quarterly for established protocols, monthly when developing new strategies (1).

Watch for ion-specific symptoms. Chloride toxicity produces marginal leaf burn, sodium affects older leaves first, calcium deficiency appears in growing points. When symptoms appear at moderate EC with no disease, investigate ionic composition.

The measurement matters, but so does the biology

The hydroponic industry invested heavily in EC monitoring because it is simple and inexpensive. This created reliance on a parameter that cannot distinguish nutrient species from non-nutrient salts. Plant roots respond to individual ions through specific transporters, adjust those transporters based on status, and modify rhizosphere chemistry (3).

Understanding ionic activity provides one lens for recognizing EC limitations, but ion identity, ratios, and toxicities matter more for practical management. The primary insight is simpler: EC cannot tell you which ions are present or whether problematic species like sodium and chloride are accumulating.

The practical approach combines EC monitoring with awareness of when it suffices. For stable systems with proven recipes

and clean water, EC provides adequate control. When water quality varies, in recirculating systems with selective depletion, or when pushing high-EC strategies, monitor individual ions. Two growers at identical EC will achieve different results based on water quality, fertilizer choices, and ionic composition.

Research on matched-EC salt stress shows specific ion toxicities operate independently of bulk conductivity. Your EC meter remains useful for routine monitoring, but recognizing its limits prevents misdiagnosis. Understanding that EC measures total ions rather than ion identity or ratios transforms it from a complete system into one point within a fuller framework.

Connecting a low cost TDR moisture content/EC/temp sensor to a NodeMCUv3

I have discussed moisture content sensors extensively in the past. I have written posts about the use of capacitive moisture sensors to measure volumetric moisture content, including how to create sensor stations and how to calibrate them. However, while capacitive moisture content sensors can be a low cost alternative for low resolution monitoring of moisture content, more precise applications require the use of higher accuracy sensors, such as Time Domain Reflectometry (TDR) sensors. In this post I am going to show you how to connect a low cost microcontroller (NodeMCUv3) to a low cost TDR moisture content sensor. *Note, some of the product links below are amazon affiliate links, which help support this blog*

at no additional cost to you.

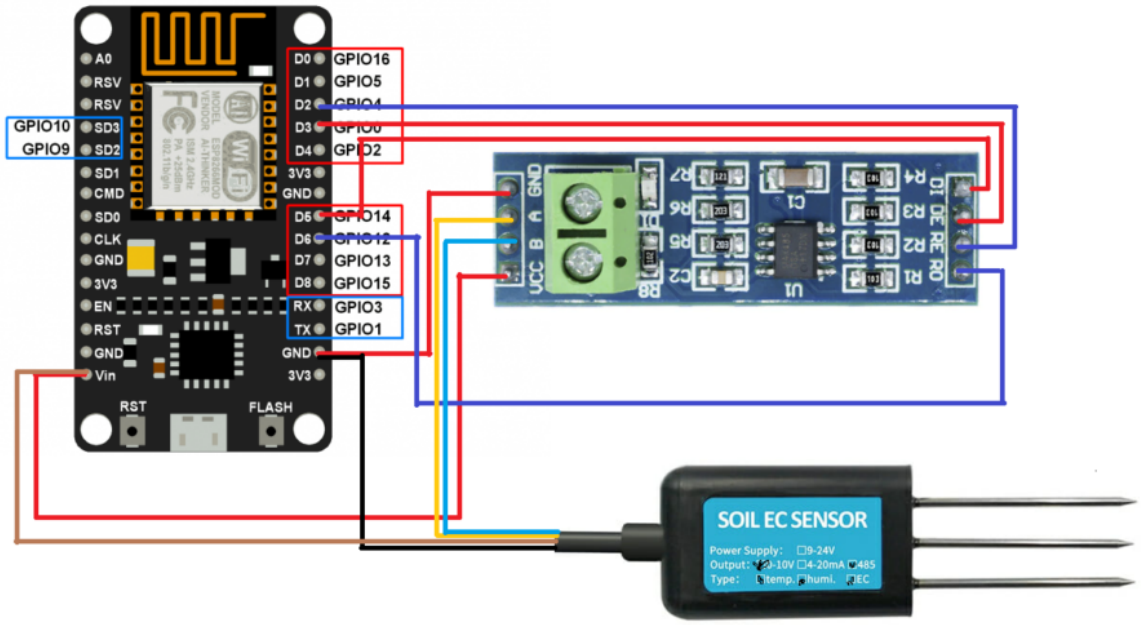


Diagram showing cable connections between moisture content sensor NodeMCUv3 and communication board.

While popular sensors like Teros-12 sensors cost hundreds of dollars, lower cost alternatives have been created by Chinese manufacturers. Using this github repository by git user Kromadg, I have been able to interface some of these low cost TDR sensors with a NodeMCUv3. The NodeMCUv3 is a very low cost microcontroller unit that you can get for less than 5 USD a piece. It is also WiFi enabled, so this project can be expanded to send data through Wifi to use in datalogging or control applications. For this project you will need the following things:

1. Micro USB cable
2. NodeMCUv3
3. THC-S RS485 sensor (Make sure to get the THC-S model)
4. TTL to RS485 communication board
5. Breadboard and jumper cables to make connections or cables and a soldering kit to make final connections.

The above diagram shows you how to connect the sensor, TTL-to-RS485 communication board and the NodeMCUv3. You will also

want to make sure you install the ESP Software serial library in your Arduino IDE, as the normal Software Serial library won't work. You can do this by downloading the zipped library from github and then using the Sketch->Include Library menu option. Once you do so, you can upload the following code into your NodeMCUv3.

```
#include <SoftwareSerial.h>
#include <Wire.h>

// This code is a modification of the code found here (https://github.com/kromadg/soil-sensor)

#define RE D2
#define DE D3

const byte hum_temp_ec[8] = {0x01, 0x03, 0x00, 0x00, 0x00, 0x03, 0x05, 0xCB};
byte sensorResponse[12] = {0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00};
byte sensor_values[11];

SoftwareSerial mod(D6, D5); // RX, TX

void setup() {
    Serial.begin(115200);
    pinMode(RE, OUTPUT);
    pinMode(DE, OUTPUT);
    digitalWrite(RE, LOW);
    digitalWrite(DE, LOW);
    delay(1000);
    mod.begin(4800);
    delay(100);
}

void loop() {
    /************** Soil EC Reading ******************/
    digitalWrite(DE, HIGH);
    digitalWrite(RE, HIGH);
    memset(sensor_values, 0, sizeof(sensor_values));
    delay(100);
```

```
    if (mod.write(hum_temp_ec, sizeof(hum_temp_ec)) == 8) {
        digitalWrite(DE, LOW);
        digitalWrite(RE, LOW);
        for (byte i = 0; i < 12; i++) {
            sensorResponse[i] = mod.read();
            yield();
        }
    }

    delay(250);

    // get sensor response data
     float soil_hum = 0.1 * int(sensorResponse[3] << 8 |
sensorResponse[4]);
     float soil_temp = 0.1 * int(sensorResponse[5] << 8 |
sensorResponse[6]);
       int soil_ec = int(sensorResponse[7] << 8 |
sensorResponse[8]);

      /************* Calculations and sensor corrections
************/

    float as_read_ec = soil_ec;

     // This equation was obtained from calibration using
distilled water and a 1.1178mS/cm solution.
    soil_ec = 1.93*soil_ec - 270.8;
    soil_ec = soil_ec/(1.0+0.019*(soil_temp-25));

     // soil_temp was left the same because the Teros and
chinese sensor values are similar

    // quadratic aproximation
     // the teros bulk_permittivity was calculated from the
teros temperature, teros bulk ec and teros pwec by Hilhorst
2000 model
    float soil_apparent_dieletric_constant = 1.3088 + 0.1439 *
soil_hum + 0.0076 * soil_hum * soil_hum;

                float    soil_bulk_permittivity    =
soil_apparent_dieletric_constant;    ///  Hammed  2015
```

```
(apparent_dieletric_constant is the real part of permittivity)
    float soil_pore_permittivity = 80.3 - 0.37 * (soil_temp -
20); /// same as water 80.3 and corrected for temperature

    // converting bulk EC to pore water EC
    float soil_pw_ec;
    if (soil_bulk_permittivity > 4.1)
         soil_pw_ec = ((soil_pore_permittivity * soil_ec) /
(soil_bulk_permittivity - 4.1) / 1000); /// from Hilhorst
2000.
    else
        soil_pw_ec = 0;

    Serial.print("Humidity:");
    Serial.print(soil_hum);
    Serial.print(",");
    Serial.print("Temperature:");
    Serial.print(soil_temp);
    Serial.print(",");
    Serial.print("EC:");
    Serial.print(soil_ec);
    Serial.print(",");
    Serial.print("READEC:");
    Serial.print(as_read_ec);
    Serial.print(",");
    Serial.print("pwEC:");
    Serial.print(soil_pw_ec);
    Serial.print(",");
    Serial.print("soil_bulk_permittivity:");
    Serial.println(soil_bulk_permittivity);
    delay(5000);
}
```

Note that RE and DE are not placed on digital pins 2 and 3, as other pins in the NodeMCUv3 carry out other functions and the board will not initialize if it has the RS485-to-TTL communicator connected through those pins. The R0 and RI pins are connected to digital pins D5 and D6, this is because in the NodeMCUv3 pins D7 and D8 are used in serial communication by the Serial swap command and therefore create conflicts if you use them with SoftwareSerial. The above digital pin

distribution is one of the few that works well. Note that connecting RE or DE to digital pin 4 also works, but this means the blue LED on the NodeMCUv3 is powered on every time there is serial communication, a potentially undesirable effect if you're interested in battery powering the device.

The board should now be printing all the measurements on your serial connection, so you should be able to see the readings through the Serial Monitor in the Arduino IDE. In the future I will be sharing how to expand this code to include WiFi and MQTT communication with a MyCodo server.

If you use this code please share your experience in the comments below!

The ultimate EC to ppm chart and calculator

Electrical conductivity (EC) meters in hydroponics will generally give you different types of readings. All of these readings are conversions of the same measurement – the electrical conductivity of the solution – but growers will often only record one of them. The tools presented in this page will help you convert your old readings from one of these values to the other, so that you can compare with reference sources or with readings from a new meter. In this page you can figure out the scale of your meter, convert from ppm to EC and from EC to ppm.

The TDS reading of different meters will be done on different scales, so it is important to know the scale of your meter in order to perform these conversions. These scales are just different reference standards depending on whether your meter

is comparing the conductivity of your solution to that of an NaCl, KCl or tap water standard. To learn more about how TDS scales work I would suggest you watch my youtube video on the subject. **To compare the readings from different meters, always compare the EC (mS/cm) reading, do not compare ppm readings unless you are sure they are in the same scale.**



My go-to EC meter recommendation is the Apera EC60

To figure out the scale of the meter, measure the EC (mS/cm) and TDS (ppm) of the exact same solution with your meter. After this, input the values in the first calculator below. You can then use this scale value to convert between EC and ppm using the other two calculators below. If you already know the scale of your meter you can use the other two calculators and skip the first step. The meter scale will usually be 500, 600 or 700.

Figure out the Scale of the Meter

TDS (ppm) reading:

EC (mS/cm) reading:

Calculate

Meter scale:

Convert ppm to EC

TDS (ppm) reading:

Meter scale:

Calculate

EC in mS/cm:

Convert EC to ppm

EC reading mS/cm:

Meter scale:

Calculate

TDS (ppm) reading:

Create a table for reference

Meter scale:

Generate Table

If you would like to learn more about EC readings in hydroponics I would suggest reading the following posts on my blog:

- Comparing the conductivity of two different solutions
- Improving on HydroBuddy's theoretical conductivity model, the LMCv2
- FAQ – Electrical Conductivity (EC) in Hydroponics

Improving on HydroBuddy's theoretical conductivity model, the LMCv2

Hydrobuddy's theoretical conductivity estimates have never been good. As I discussed in a previous post, the program uses a very simple model based on limiting molar conductivities to calculate the EC. The software knows how much each ion conducts when it's all by itself, so it adds all these conductivity values multiplied by the concentration and assumes there are no additional effects. The conductivity values resulting from this assumption are very large – because there are effects that significantly reduce the conductivity of ions at larger concentrations – so HydroBuddy just cuts the estimation by 35% hoping to reach more accurate values. This works great for some cases, but very badly for others.

The reason why this happens is that the actual conductivity contribution of some ions decreases more drastically as a function of concentration and due to the presence of other ions compared to others. This means that we need to account for these decreases in conductivity in an ion-specific way. One way to approach this, is to forget about theoretical

approximations and just create an empirical model that uses experimental data. This is what I did when I created the empirical model that is present in HydroBuddy from v1.7. This model works really well, provided you are using the exact list of salts that were used to create the model and you stay within the boundaries of concentration values that were used to create it.

1) $$EC = \sum_i \Lambda^0_{m,i} (\gamma_i)^\alpha c_i$$

2) $$\alpha = \begin{cases} 0.6 / |z_i|^{0.5} = const & \text{if } I \leq 0.36 |z_i| \\ \sqrt{I} / |z_i| & \text{otherwise} \end{cases}$$

3) $$\ln \gamma_i = -(\ln 10) A z_i^2 \sqrt{I}$$

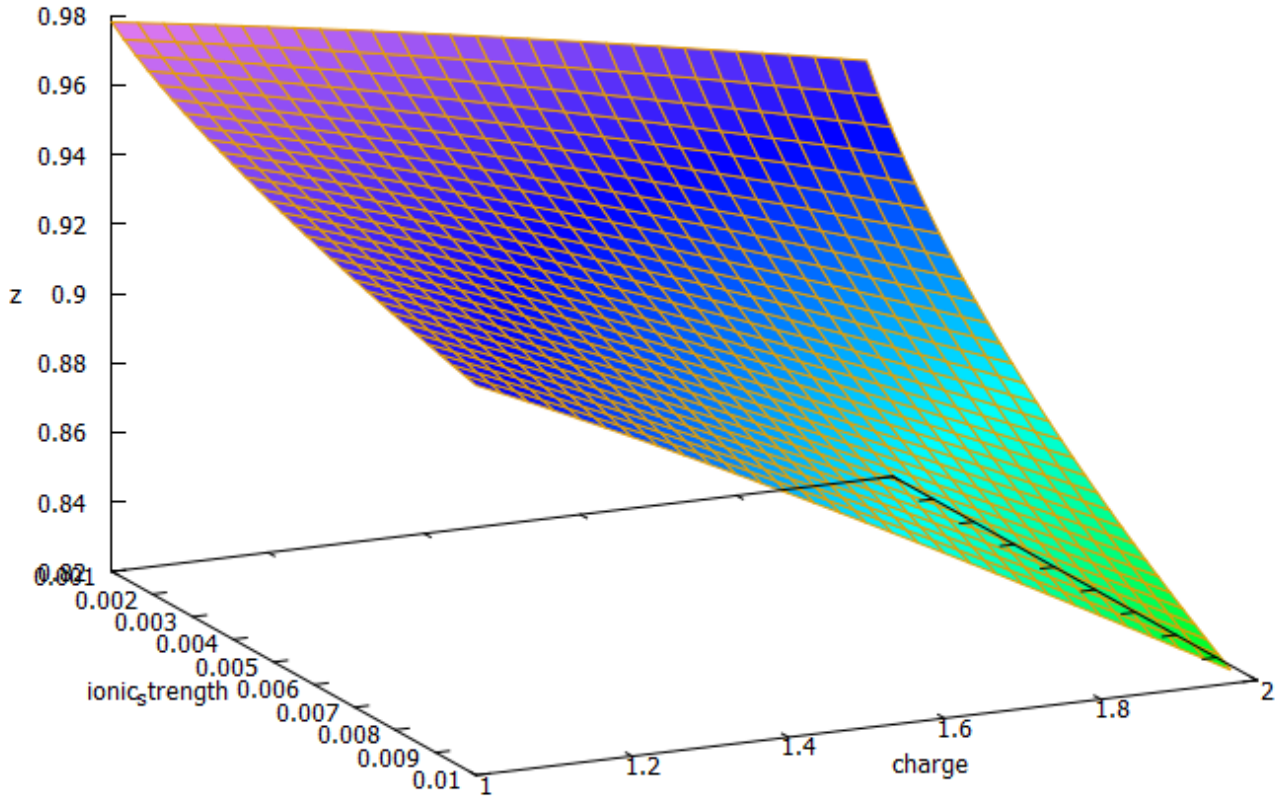
4) $$EC = \sum_i \Lambda^0_{m,i} \left(e^{-0.7025148 {z_i}^{1.5} \sqrt{I}} \right) c_i$$

Equations 1-3 were taken from here. I have then used these equations to derive equation 4, which is going to be the new LMCv2 model for HydroBuddy from v1.9. Where $\Lambda^0_{m,i}$ is the limiting molar conductivity of each ion, z_i is each ion's charge, I is the ionic strength of the solution and c_i is the molar concentration of each ion..

This experiment-based solution can be great. It is in fact, a technique I've used to create custom versions of HydroBuddy for clients who want to have high accuracy in their EC estimations within the salts that they specifically use. The process is however cumbersome and expensive, my wife and I – both of us chemists – do all the experimentation, and it generally requires an entire day, preparing more than 80+ solutions using high accuracy volumetric material, to get all the experimental data. It is also limited in scope, as any salt change usually requires the preparation of a substantial number of additional solutions to take it into consideration.

It would certainly be great if we could create a better, fully

theoretical, conductivity model. Diving into the literature and programs used for conductivity-related calculations, I found a program called Aqion that implements a more accurate model compared with HydroBuddy's LMC model. You can read more about their approach here. They use the limiting molar conductivities but introduce additional terms to make ion-specific corrections that are related to both ionic charge and ionic strength. The ionic charge is the electrical charge of each ion, for example, +1 for K^{+} and +2 for Fe^{+2}, etc. The ionic strength is the sum of the molar concentration of each ion times its charge.



3D plot of equation 4 showing the magnitude of the correction factor (z) as a function of charge and ionic strength.

The plot above shows you how this correction factor affects a solution as the ionic strength and charge of the ions change. As a solution gets more diluted, the equation approaches the sum of the conductivities at infinite dilution. Conversely, as the solution becomes more concentrated or the ion charge becomes higher, the drop in the conductivity becomes more

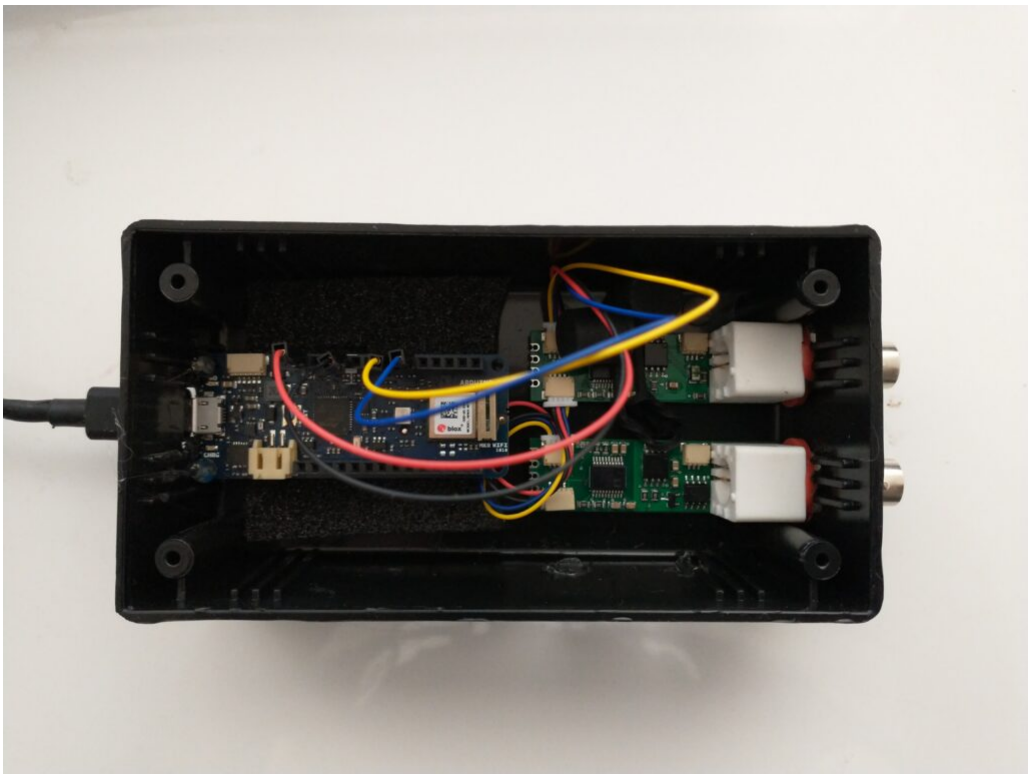
pronounced. These are both phenomena that are in-line with experimental observations and much better reflect how conductivity is supposed to change when different ions interact in solution.

The above equation provides us with a more satisfactory theoretical estimation of conductivity compared to the current HydroBuddy LMC model. The new model is able to implement correction factors on a per-ion basis and also changes the magnitude of these corrections depending on how concentrated the solutions are. This new model will be implemented to replace the current LMC model in HydroBuddy v1.9, which will be released in the near future. This should provide significantly more accurate estimates of conductivity for the preparation of hydroponic solutions.

Creating a pH/EC wireless sensing station for MyCodo using an Arduino MKR Wifi 1010

There are multiple open-source projects available online for the creation of pH/EC sensing stations for hydroponics. However, all of the ones I have found use a single Arduino or Raspberry Pi to perform the measurements and store any data, making them unsuitable for applications where more flexibility is needed. For example, a facility using multiple different reservoir tanks for nutrient storage might require multiple pH/EC sensing stations, and single-board wired setups would be unable to accommodate this without a lot of additional

development. In this post, I am going to show you a simple pH/EC sensing station I built with an Arduino MKR Wifi 1010 that can communicate with a MyCodo server using the MQTT protocol. Multiple sensing stations could be built and all of them can communicate with the same MyCodo server.



My Arduino MKR wifi 1010 based sensing station, using uFire pH and EC boards in a small project box.

This project makes use of the small pH/EC boards provided by uFire, which have a lower cost compared to those provided by companies like Atlas, but do have adequate electrical isolation to avoid problems in readings when multiple electrodes are put in the same solution. This is a substantial improvement over other low-cost boards where using multiple probes can cause heavy electrical noise and interference. In order to build this project you will require the following materials:

Note, some of the links below are amazon affiliate links. This means that I get a small commission if you purchase through these links at absolutely no extra cost to you. The links to other websites are not affiliate links.

1. Arduino MKR Wifi 1010
2. uFire pH probe
3. uFire EC probe
4. A rugged pH probe with a VNC connector
5. An rugged EC probe with a VNC connector
6. Two Qwiic-to-Qwiic connectors
7. One Qwiic-to-male connector
8. A project box to put everything inside (optional)
9. A micro USB cable

The code for the project is shown below:

```
#include <uFire_EC.h>
#include <uFire_pH.h>
#include <WiFiNINA.h>
#include <ArduinoMqttClient.h>

#define SECRET_SSID "ENTER WIFI SSID HERE"
#define SECRET_PASS "ENTER WIFI PASSWORD HERE"

//calibration solutions used
#define PH_HIGH_SOLUTION_PH 7.0
#define PH_LOW_SOLUTION_PH  4.0
#define EC_HIGH_SOLUTION_EC 10.0
#define EC_LOW_SOLUTION_EC  1.0
#define CALIBRATION_TEMP    20.0

// topics for the mqtt sensors
// Make sure all stations have different topics
#define EC_TOPIC       "EC1"
#define PH_TOPIC       "PH1"
#define CALIB_TOPIC    "CALIB1"
#define MQTT_BROKER    "ENTER MQTT SERVER IP HERE"
#define MQTT_PORT      1883

int status = WL_IDLE_STATUS;     // the Wifi radio's status
String message;

uFire_pH ph;
uFire_EC ec;
WiFiClient wifiClient;
```

```
MqttClient mqttClient(wifiClient);

void check_connection()
{
  if (!mqttClient.connected()) {
    WiFi.end();
    status = WiFi.begin(SECRET_SSID, SECRET_PASS);
    delay(10000);
    if (!mqttClient.connect(MQTT_BROKER, MQTT_PORT)) {
      Serial.print("MQTT connection failed! Error code = ");
      Serial.println(mqttClient.connectError());
      delay(100);
    }
    mqttClient.subscribe(CALIB_TOPIC);
  }
}

void setup()
{
  Serial.begin(9600);
  while (!Serial);

  // connect to wifi and mqtt broker
  check_connection();
  // coorectly initialize the uFire sensors
  // note the Wire.begin() statement is critical
  Wire.begin();
  ec.begin();
  ph.begin();
}

void loop()
{
  // mqtt keep alive
  mqttClient.poll();

  // read messages
  message = "";
  while (mqttClient.available()) {
      message += (char)mqttClient.read();
    }
```

```
  // execute calibration if requested
  Serial.println(message);
             if       (message       ==       "EC1_HIGH")
ec.calibrateProbeHigh(EC_HIGH_SOLUTION_EC, CALIBRATION_TEMP);
              if       (message       ==       "EC1_LOW")
ec.calibrateProbeLow(EC_LOW_SOLUTION_EC, CALIBRATION_TEMP);
             if       (message       ==       "PH1_HIGH")
ph.calibrateProbeHigh(PH_HIGH_SOLUTION_PH);
              if       (message       ==       "PH1_LOW")
ph.calibrateProbeLow(PH_LOW_SOLUTION_PH);

  // Measure EC
  ec.measureEC();
  Serial.println((String) "mS/cm: " + ec.mS);

  // Measure pH
  ph.measurepH();
  Serial.println((String) "pH: " + ph.pH);

  // Ensure the wifi and mqtt connections are alive
  check_connection();

  // post EC to MQTT server
  mqttClient.beginMessage(EC_TOPIC);
  mqttClient.print(ec.mS);
  mqttClient.endMessage();

  // post pH to MQTT server
  mqttClient.beginMessage(PH_TOPIC);
  mqttClient.print(ph.pH);
  mqttClient.endMessage();

  // ensure sensors are not probed too frequently
  delay(1000);

}
```

Once you get all the materials you should first assemble the components. Connect the pH and EC board together using the Qwiic-to-Qwiic connector, then use the Qwiic-to-male connector to hook up one of these boards to the Arduino (doesn’t matter

which one). Connect the black cable to ground, red cable to 5V, blue cable to SDA, and yellow cable to SCL. Set up your board according to the instructions in the Arduino MKR wifi 1010 getting started page, modify the code above to properly include information about your wifi network, calibration solutions, and MQTT server, then upload the code. The Arduino will connect to your Wifi and MQTT servers and automatically reconnect when there are connection issues.

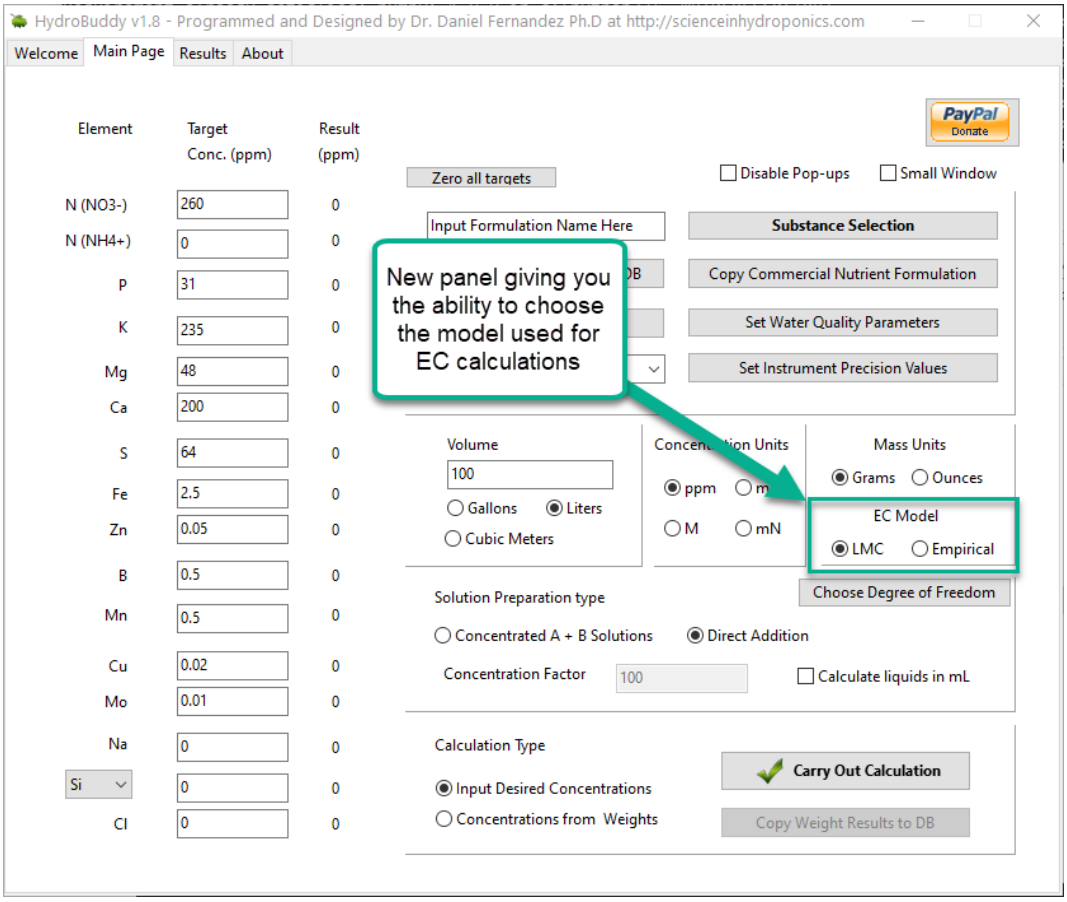
The above code will also post the readings of the pH and EC sensors to topics PH1 and EC1 respectively if you add an input in MyCodo to capture these readings you should be able to store them and take control actions using the MyCodo interface. Additionally, the Arduino code will respond to calibration requests published to the topic "CALIB1". For example, if you want to calibrate your EC sensor with a two-point calibration method with a standard solution with an EC of 10mS/cm, you would put the electrode in the calibration solution, then send the message "EC1_HIGH" to the CALIB1 topic and the Arduino will perform the task as requested. The code assumes you will want to do 2 point calibrations for both EC and pH, with the calibration events triggered by EC1_HIGH, EC1_LOW, PH1_HIGH, and PH1_LOW. Note that the definition of the EC and pH values of the calibration solutions should be changed to the solutions you will be using within the code. The high/low values in the code, as is, are 10mS/cm|1mS/cm for EC and 7|4 for pH.

A new conductivity model in

HydroBuddy

On my previous post you can read about how I ran experiments to develop a conductivity model using empirical data in order to improve our ability to predict EC values from the concentration of individual nutrients in a hydroponic nutrient solution. In this post I will now talk about how this was finally implemented in HydroBuddy, what form it took and what kind of result can be expected from it. The implementation discussed in this post has already been updated to the HydroBuddy github along with all the experimental data used to derive this empirical EC model.

Given the amount of data and the nature of the problem at hand, the easiest and most accurate way to build a model was to use a simple linear regression algorithm. As previously shown this model was able to give great results within the data, even when performing random training and testing splits. I have added a jupyter notebook to the github repository, along with all the data we measured in order to allow you to see how all the calculations were done, how the model was created and the sort of accuracy the model got within the set of experimental results. You can also play with this notebook to develop your own models or analyse the data any further if you wish. You can also try to reproduce our experiments and help verify our results. The linear model was translated into FreePascal and added to HydroBuddy although the program still retains the ability to estimate conductivity using the previously available LMC based model.



New hydrobuddy implementation now including the ability to choose between LMC and empirical EC models.

The fact that we were able to create a model to accurately determine conductivity within this experimental space does not mean that this model will work to magically determine the conductivity of any hydroponic formulation. These experiments were designed using five salts – calcium ammonium nitrate, ammonium sulfate, potassium sulfate, magnesium sulfate and monopotassium phosphate – which means that although our model is able to greatly describe conductivity in this space, the model is likely to run into trouble when attempting to describe a space that deviates too strongly from the one described above. This will be most evident whenever there are some cations or anions that are not present at all within these experiments. For example when silicates, chlorides or other such salts are used or when strong acids or bases are added to the solution.

Another important issue is the way these ions are paired. In our experimental process the concentration of Ca and N as

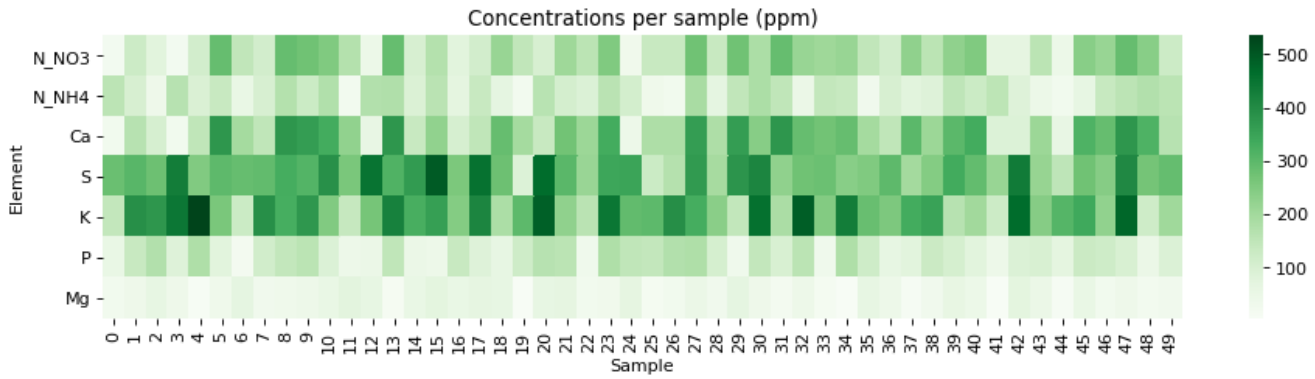
nitrate always increased at the same time, meaning that the linear model implicitly carries this assumption. A setup were magnesium nitrate or potassium nitrate are used as well, will contain deviations from the current model that it is likely not very well prepared to deal with. A similar problem might happen when salts such as ammonium monobasic phosphate are used, since our model only contained a single example of a phosphate salt (monopotassium phosphate). While it is not easy to predict how much accuracy will be lost in these cases, we do expect the model to be significantly more inaccurate as other salts are used.

Additionally, our experimental setup did not contain any corrections of pH values, so the conductivity values described include a pH drift related with the amount of acid contributed by the potassium monobasic phosphate, which was not neutralized by a base. This will also cause differences with conductivity, if the conductivity is measured after the pH of the solution is corrected to the proper range used within the hydroponic process. Although at the concentration values used in hydroponics this should not be a big issue, it is still something worth considering.

As I mentioned above, the model is already implemented within the github repository – if you want to compile the program yourself – but the binaries won't be updated to v1.8 until later this week. I look forward to your feedback about the model and hope it can help – at least some of you – to dramatically improve the estimations of conductivity of your hydroponic nutrient solutions.

Building a model to predict EC in hydroponic nutrient solutions

Electrical conductivity (EC) is one of the most useful parameters in the practical preparation of hydroponic nutrient solutions. This is because knowing the expected conductivity of a nutrient solution can allow you to prepare solutions without having to measure the total volume exactly, a parameter that is often hard to accurately determine in practice. Although determining the target conductivity is easy to do using small preparation volumes – which can be done accurately – it is often impractical to do so routinely, which is necessary if the actual composition of the nutrient solution is being changed as a function of time. Due to all the above, it is important to come up with accurate models to estimate the EC of nutrient solutions with only information about their mineral composition, without having to measure the value experimentally. In this post I am going to talk about how I created a model to do exactly this, taking advantage of multi-variable experimentation and simple modeling techniques.



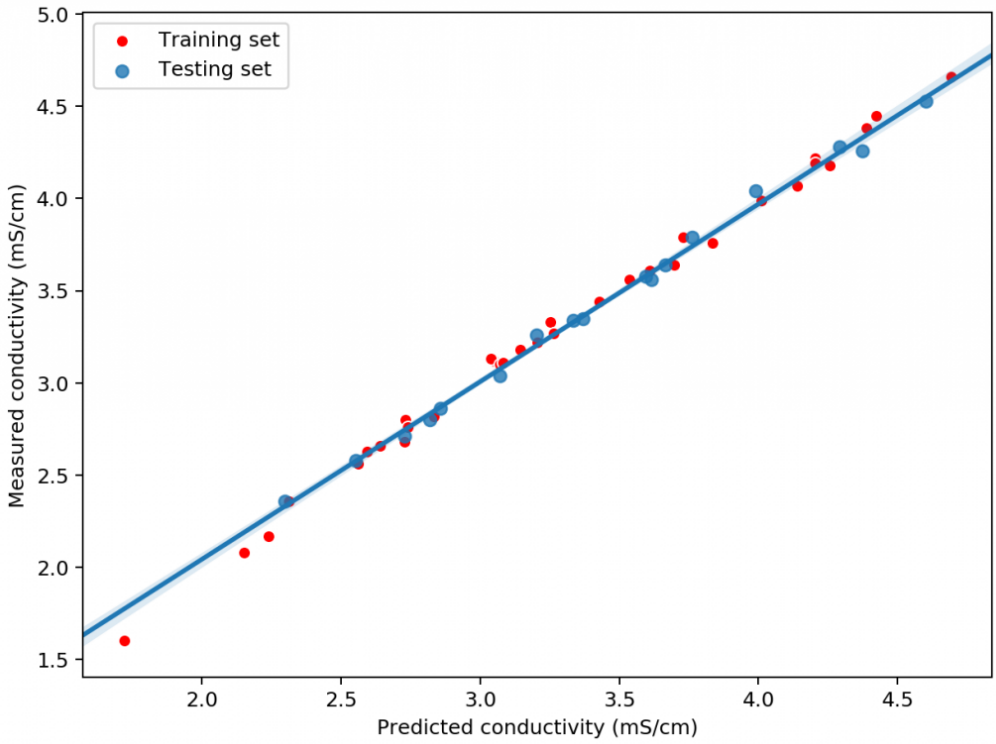
Mineral nutrient concentrations (ppm) of all the samples measured

The problem with conductivity modeling is that not all salts contribute the same to the conductivity of a nutrient solution. For example potassium sulfate can contribute

significantly more to conductivity per gram compared to a salt like monopotassium phosphate. Furthermore, the addition of some salts can affect the conductivity of others (see my previous post on conductivity modeling in Hydrobuddy for more details). In the regime we use in hydroponics, the determination of electrical conductivity using data from limiting molar conductivity can lead to very skewed results, which makes these estimations of little usage in practice.

To solve this issue, I designed an experiment where 50 different EC measurements were made for different hydroponic nutrient solutions within the range of concentrations of nutrients that are reasonably expected in hydroponic culture, with some values being above these in order to ensure that all values encountered in practice will be within the measured ranges. The image above shows you all the concentrations that were measured within the experiment. To prepare the solutions I used calcium ammonium nitrate, potassium sulfate, magnesium sulfate heptahydrate, monopotassium phosphate and ammonium sulfate. All of these were agricultural grade salts in order to reflect the same impurities expected in a normal hydroponic setup. Note that no heavy metal salts were used since their contribution to the EC of a hydroponic nutrient solution is negligible.

Concentrated solutions of all the salts were prepared in 250mL volumetric flasks using a +/-0.001g scale and aliquots of these solutions were drawn using 5mL plastic syringes (+/- 5%) in order to prepare final 250mL solutions using volumetric flasks. Conductivity measurements were done using an Apera EC60 conductivity meter that was previously calibrated using a 2 point calibration method. All the solutions were prepared using distilled water. The target concentrations for the solutions were determined using a pseudo random number generator in order to try to ensure a random distribution of samples within the concentration space of interest.

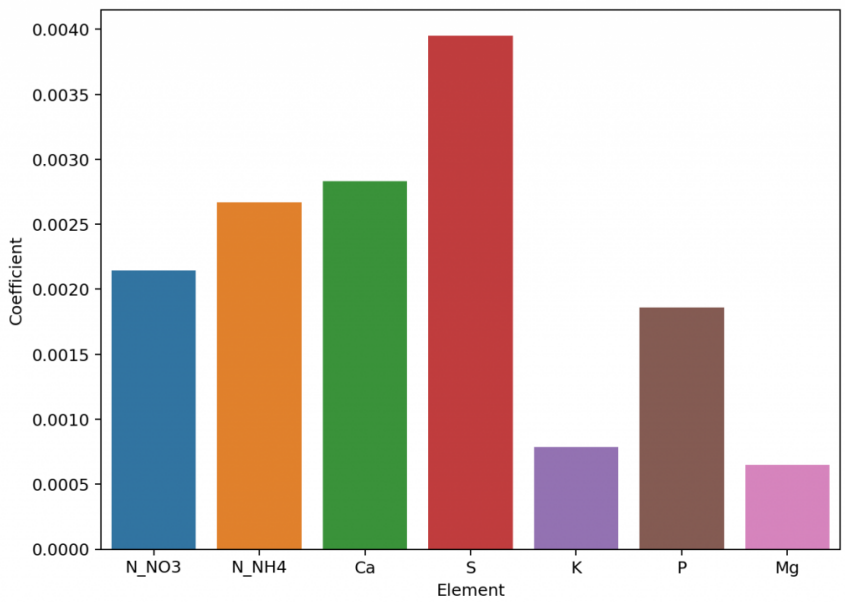


A sample modeling results for a random split with training (33 data points) and testing sets (17 data points)

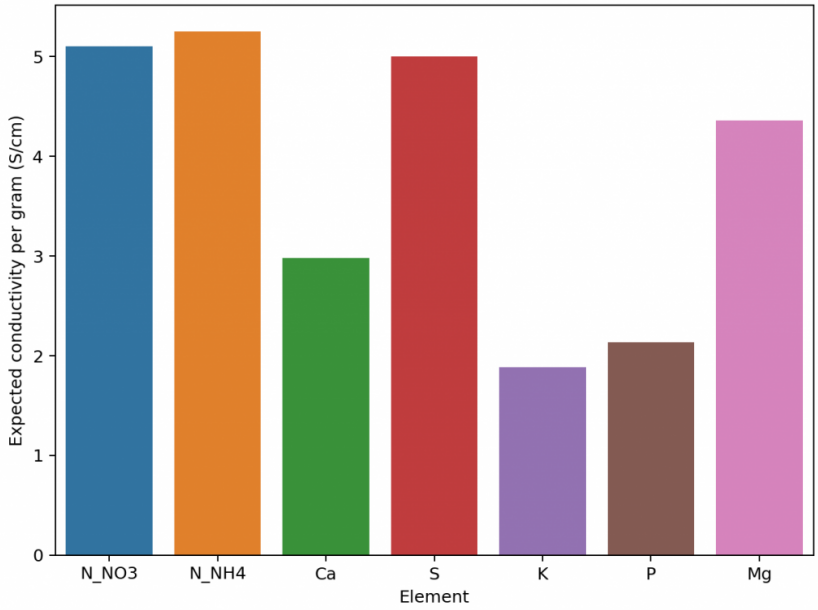
Using this data we constructed a linear model to attempt to predict conductivity. In order to evaluate the model we randomly split the results to get 33 data points used for model construction and 17 points left for model validation. Performing this process 100 times shows that the mean R2 of the model on the training set is 0.995 while the average on the training set is 0.994. This shows that the model is able to properly generalize the conductivity data in order to properly predict the conductivity of the solution across the space studied. **The mean absolute error in the testing set was 0.036 mS/cm. This shows the high certainty with which we can make conductivity predictions.**

Exploring the model coefficients can also show us how different the contributions of the different elements to the conductivity of the nutrient solution can actually be. These results are surprising if you compare them to the conductivity contributions per gram that are expected from the limiting molar conductivity values, which are the conductivity values the ions exhibit on their own under very high dilutions (this

is also the method used in HydroBuddy <=v1.65). We can clearly see here that in reality we are getting way more conductivity out of sulfate compared to the other elements and significantly less from magnesium. This means that at the makeup and concentration values used in hydroponics the Mg ions are not being able to contribute as much as they can when they are alone because their activity is being lowered by the other ions in solution, while the opposite case applies to sulfate.



Linear model coefficients for the different elements (proxy for their contribution to conductivity)



Expected conductivity values per gram using data from limiting

molar conductivity values (taken from here)

The above shows us why conductivity in hydroponics is so complicated, it shows how ions do not contribute equally to conductivity and how they behave very differently in real hydroponic solutions. Thankfully the above also shows how we can create a model using experimental data that is actually able to predict conductivity, since the relationships – although different than expected – are still highly predictable when enough experimental data is available. All the above experimentation took 4 hours to do – with the help of my lovely wife, who is also a chemist – and should allow me to add a very powerful model to predict hydroponic nutrient solution EC values to HydroBuddy.

All the above experimentation data will be open source and available in a github repository soon. We also hope to show you how all of this was done in a youtube video in the near future.

Why TDS is NOT equal to Total Dissolved Solids in hydroponics

Electrical conductivity is a very commonly used measurement in hydroponics, yet a very poorly understood one. I have written several posts about conductivity in the past (1,2,3) and today I want to talk about the use of the term "Total Dissolved Solids" and the poor usage of the unit "ppm" in order to express a measurement of electrical conductivity. In this article I will walk you through why this term exists in the first place and why its use in hydroponics is terribly

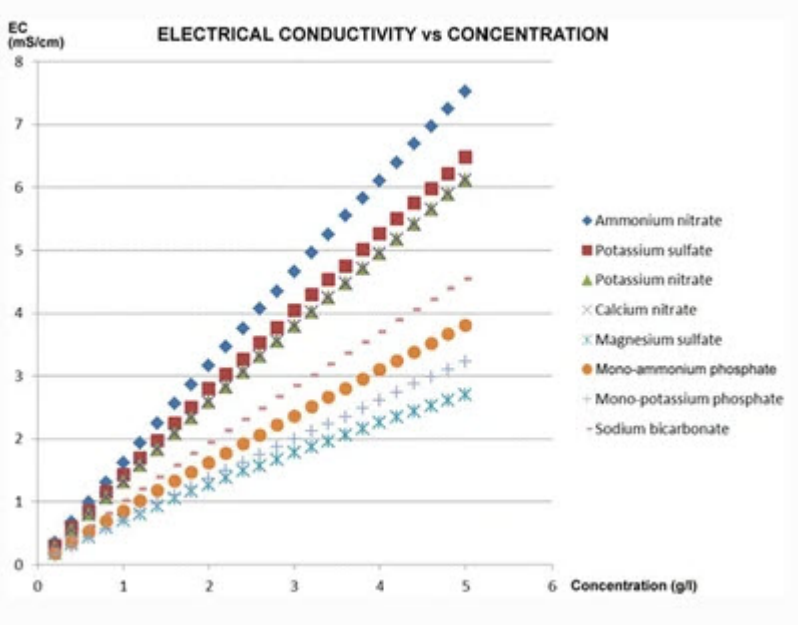
misleading for growers.



Conductivity as a function of NaCl concentration (taken from here)

Conductivity is just a measure of how easy it is for an electrical charge to go from one electrode of a certain area to another. It's generally expressed in mS/cm, which is a measurement of conductance (the opposite of resistance) and area (the area of the electrode). How in the world do we get from this to a measurement like "ppm", which measures the concentration of something in mg/L? What does a measurement of 500 ppm even mean? What is it that we are expressing a concentration of?

The answer lies in the practical uses of conductivity and a simplification to make the evaluation of water sources easier. Conductivity is generally linearly proportional to the amount of a pure salt dissolved in solution at low concentrations. For a pure salt like table salt (NaCl) the higher the concentration of the salt in solution the higher the conductivity (you can see this in the image above). People working on water quality realized that they generally dealt with similar salt combinations (Mg and Ca carbonates and possibly some Na and K chlorides) so they decided to use some standard salt mixtures (say KCl, NaCl or some mixture of Ca/Mg/K/Na salts) and then use conductivity as a proxy for the concentration of these things that are actually in solution. So the "ppm" that your EC meter reads is just the equivalent conductivity of some standard. A meter reading 500 ppm in conductivity is telling you "your solution has the same conductivity as a solution of the standard at 500 ppm". The "standard" can change – as mentioned before – which is why there are several different TDS scales. One meter might be telling you it's the same conductivity as a solution of KCl with that concentration, while another might be in NaCl.



Conductivity curves of different salts used in hydroponics (taken from this article)

The above is very useful when you're measuring things that tend to be similar but this becomes a complete nightmare when the composition of what you're measuring can change substantially. *In hydroponics you have a wide variety of different salts, all with very different conductivity values at different concentrations*. Look at the graph above, which shows the conductivity as a function of concentration for 8 different salts commonly used in hydroponic culture. If you prepare three solutions, one with 1000 ppm solution of potassium sulfate, another with 1000 ppm of monopotassium phosphate and another with 1000 ppm of ammonium nitrate and measure them with your conductivity meter they would *all* give very different results. The meter might be close to 0.95mS/cm for the monopotassium phosphate, but it might read almost 1.5 mS/cm for the potassium sulfate. Both solutions have 1000 ppm of "total dissolved solids" but the conductivity meter is telling you one has 500 ppm and the other almost 800 ppm, none of them even close. This is because "total dissolved solids", as used in water quality measurements, is a meaningless measurement in hydroponics as it relates to the actual ppm values of things dissolved.

This is the main reason why you should never compare the EC

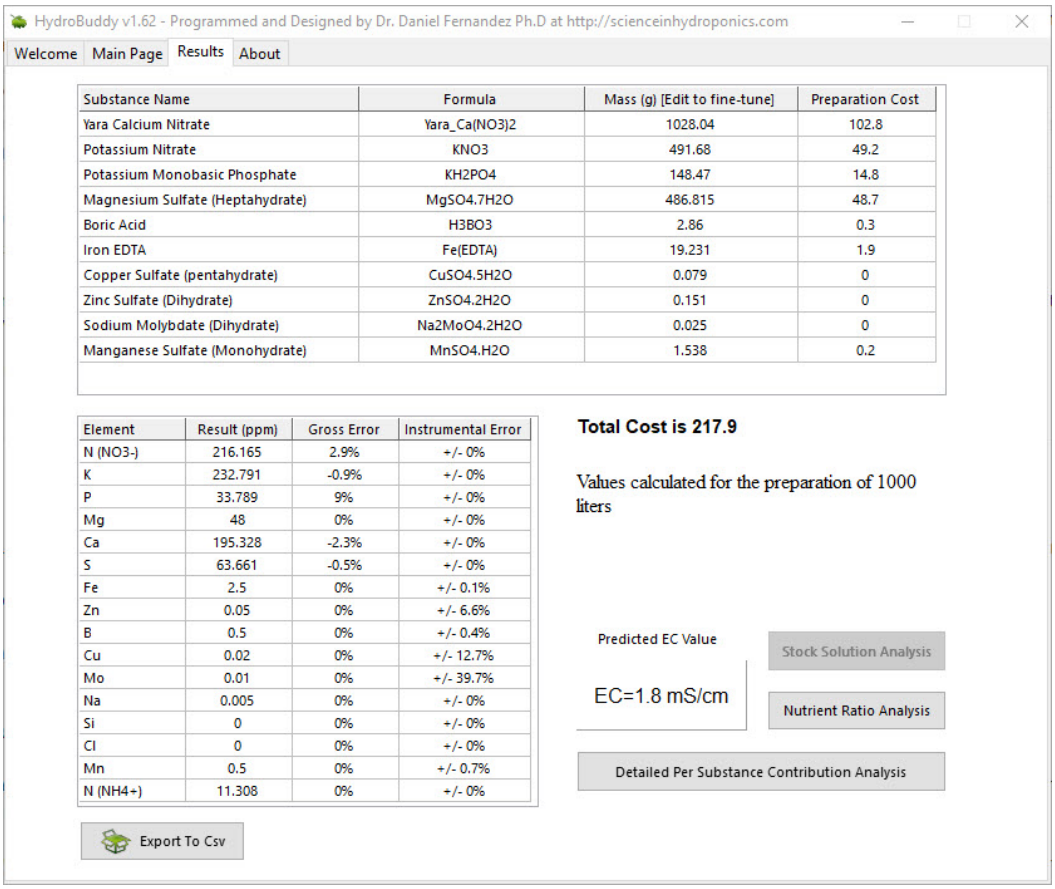
values of nutrients that contain different ratios of salts, because they are simply not the same. One nutrient might give you 100 ppm of potassium at some EC level, while another might give you 200 ppm. Thinking that having the same EC level means that both are at the same “strength” is a big mistake, since this is never going to be the case when two nutrient solutions are mixed with different ratios of nutrients. This is also why comparing vegetative and bloom formulation EC values is not correct. A solution in veg might contain a lot more of nitrates while a solution in bloom might contain more phosphates. As we saw above this might mean that a solution of the “same strength” might actually have a significantly lower measured EC value.

Since the TDS measurement is not telling you anything about “total dissolved solids” in hydroponics, you should avoid using it to avoid confusion. This is important since nutrient concentrations are usually expressed in ppm as well, ppm of actual nutrients dissolved in solutions. Instead use the normal conductivity measurements of your meter in conductance per area. You should also take care to only use EC values to talk about comparative strength when you’re talking about a formulation where the ratios of nutrients remain the same. If that’s not the case, then you should not talk in comparative terms between the two solutions as this might deviate a lot from reality.

My advice is to not think in EC terms to begin with, but to think about nutrient concentrations, prepare solutions that match the concentrations you want and then use the EC of those solutions as references to know whether they are prepared correctly or not. The conductivity should be a measurement used for confirmation but not as a guiding principle. For example the aim should be to “prepare a solution containing 150 ppm of N and an K:N ratio of 1.2” not to “prepare a solution with an EC of 1.2 mS/cm”.

Nutrient solution conductivity estimates in Hydrobuddy

People who use Hydrobuddy can be confused by its conductivity estimates, especially because its values can often mismatch the readings of conductivity meters in real life. This confusion can stem from a lack of understanding of how these values are calculated and the approximations and assumptions that are made in the process. In this post I want to talk about theoretically calculating conductivity, what the meters read and why Hydrobuddy's estimations can deviate from actual measurements.



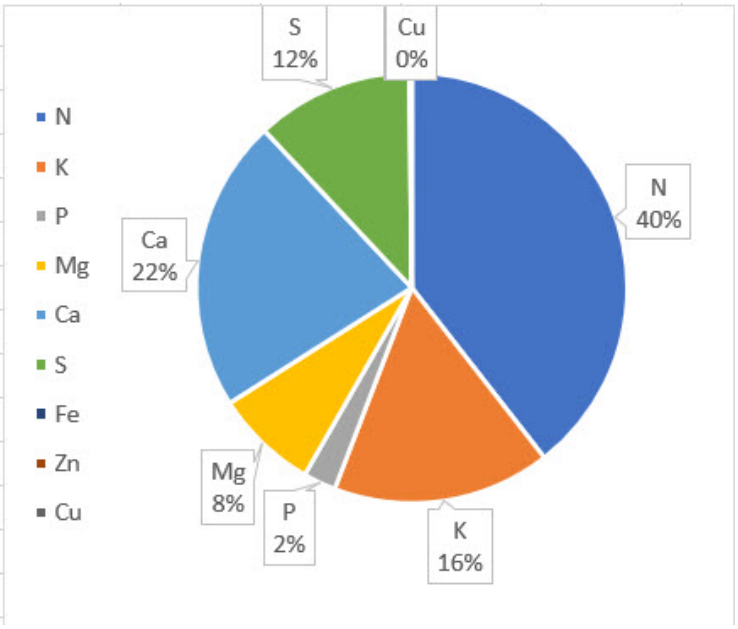
Standard Hoagland solution calculation using HydroBuddy with a

set of basic chemicals.

The images above show the use of HydroBuddy for the calculation of a standard Hoagland solution for a 1000L reservoir. The Hoagland solution's recipe is expressed as a series of elemental concentrations, all of them in parts per million (ppm) units. The results show that the final conductivity of this solution should be 1.8 mS/cm but in reality the conductivity of a freshly prepared full strength Hoagland solution will be closed to 2.5mS/cm. You will notice that HydroBuddy failed to properly calculate this value by an important margin, missing the mark by almost 30%. But how does HydroBuddy calculate this value in the first place?

Conductivity cannot be calculated by using the amount of dissolved solids in terms of mass because charges are transported per ion and not per gram of substance. To perform a conductivity calculation we first need to convert our elemental values to molar quantities and then associate these values with the limiting molar conductivity of each ion, because each ion can transport charge differently (you can find the values HydroBuddy uses in the table available in this article). This basically means we're finding out how many ions we have of each kind and multiplying that amount by the amount each ion can usually transport if it were by itself in solution. The sum is the first estimate in the calculation of conductivity.

	ppm	M	mS/cm
N	210	1.49E-02	1.06E+00
K	235	6.01E-03	4.42E-01
P	31	1.00E-03	6.61E-02
Mg	48	1.97E-03	2.09E-01
Ca	200	4.99E-03	5.94E-01
S	64	1.99E-03	3.18E-01
Fe	2.5	4.48E-05	4.84E-03
Zn	0.05	7.64E-07	8.07E-05
Cu	0.02	3.14E-07	3.37E-05
		Total	**2.70E+00**
		HB Guess	**1.8E+00**



Conductivity calculations carried out by HydroBuddy, also showing conductivity contributions per ion. This is done by converting ppm quantities to moles, then multiplying by limiting molar conductivity values here.

The image above shows the result of these calculations for an example with a perfectly prepared Hoagland solution. You can see that the estimate from limiting molar conductivity is initially 2.7 ms/cm – much closer to the expected 2.5 mS/cm – but then HydroBuddy makes an additional adjustment that lowers this down to 1.8 mS/cm. This is done because limiting molar conductivity values make the assumption of infinite dilution – what the ion conducts if it were all by itself in solution – but in reality the presence of other ions can decrease the actual conductivity things have in solution. HydroBuddy accounts for this very bluntly, by multiplying the result by 0.66, in effect assuming that the measured value of conductivity will be 66% of the value calculated from the limiting molar conductivity values. This is of course wrong in many cases, because the reduction in activity due to the presence of other ions is not as strong. However it can also be correct in many cases, primarily depending on the substances that are used to prepare the formulations and the ratios between the different nutrients.

In my experience HydroBuddy tends to heavily underestimate the

conductivity of solutions that receive most of their conductivity from nitrates, as this example, but it tends to do much better when there are large contributions from sulfate ions. When I first coded HydroBuddy all my experiments were being done with much more sulfate heavy solutions, so the correction parameter value I ended up using for the program ended up being a bad compromise for solutions that deviated significantly from this composition. With enough data it might be possible to come up with a more advanced solution to conductivity estimations in the future that can adjust for non-linear relationships in the conductivity and activity relationships of different ions in solution.

If your measured conductivity deviates from the conductivity calculated in HydroBuddy you should not worry about it, as HydroBuddy's values is meant to be only a rough estimate to give you an idea of what the conductivity might be like but, because of its simplicity, cannot provide a more accurate value at the moment. The most important thing is to ensure that all the salts, weights and volumes were adequately measured in order to arrive at the desired solution.

Creating a robust pH/EC monitor for hydroponics using Atlas probes and an Arduino

A few months ago I talked about how you could build a simple sensor station for your hydroponic projects using an arduino (see here). However this small project used the relatively cheap – but I have found not very robust – pH/EC probes and boards from gravity which makes it a poorer choice for a more

professional project aiming to constantly monitor the pH/EC of a production hydroponic setup. Today I am going to tell you how you can build a dedicated pH/EC monitor using the robust pH probes from Atlas, which also have several important advantages we will be discussing within this post. *I would also like to point out that Atlas is not paying me anything to write this post, I write just because of my experience using their probes.*

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The pH/EC probes from gravity have several problems when looking for a robust sensing setup. The first issue they have is that the probes are not rated for constant immersion, so they are damaged if you place them within solution the whole time which is probably what you want to do within a production hydroponic setup. The second issue is that the boards require cable connections to the Arduino which introduces a significant amount of noise that can causes problems with measurements. Due to poor isolation there can also be issues with the gravity boards when measuring EC/pH at the same time. To overcome these issues we can use probes and boards from atlas which have the advantage of having no cable connections to the Arduino – connections are through pins directly – plus the probes are rated for constant immersion and are much more robust. These are the things we would need to build this project:

- Arduino UNO R3 – 23.90 USD
- LCD 12864 screen shield – 24.05 USD
- Mini tentacle shield – 85.00 USD
- pH kit from Atlas – 149.15 USD
- EC kit from Atlas – 195.71 USD
- Arduino headers – 12.99 USD

As you notice this sensor project is much more expensive than the sensor station I had discussed before, with a price tag of around 490 USD (not including shipping). However when looking for a robust setup you definitely should favor the additional expense as this will likely be paid off with much longer service times.

When you get the pH/EC kits the first thing you want to do is change your EZO boards (the small circuit boards that come with them) to i2C mode so that you can use them with your mini tentacle shield. To do this follow the instructions here, follow the instructions in the “Manually switch between UART and I2C” section, use female jumpers to make this process easier. Note that you can use your LCD shield analogue 5V and ground pins when you need power within the process.

```
//Libraries
#include <U8glib.h>
#include <stdio.h>
#include <Wire.h>
#include <Arduino.h>

#define TOTAL_CIRCUITS 2

///---- variables for pH/EC tentacle shield ------- //

#define TOTAL_CIRCUITS 2

char sensordata[30];
byte sensor_bytes_received = 0;

byte code = 0;
byte in_char = 0;
int channel_ids[] = {99, 100} ;
// ------------------------------------------------ //

// EC values // CHANGE THESE PARAMETERS FOR EC PROBE CALIBRATION
#define EC_PARAM_A 0.00754256
```

```
//pH values // CHANGE THESE PARAMETERS FOR PH PROBE CALIBRATION
#define PH_PARAM_A 1.0
#define PH_PARAM_B 0.0

#define XCOL_SET 55
#define XCOL_SET2 65
#define XCOL_SET_UNITS 85

//--------------------------

U8GLIB_NHD_C12864 u8g(13, 11, 10, 9, 8);
float pH, EC;

//--------------------------

void draw() {
  u8g.setFont(u8g_font_04b_03);
  u8g.drawStr(0,11,"pH:");
  u8g.setPrintPos(XCOL_SET,11);
  u8g.print(pH);
  u8g.drawStr(0,21,"EC:");
  u8g.setPrintPos(XCOL_SET,21);
  u8g.print(EC);
  u8g.drawStr( XCOL_SET_UNITS,21,"mS/cm" );
}

void read_tentacle_shield(){

  for (int channel = 0; channel < TOTAL_CIRCUITS; channel++) {
    Wire.beginTransmission(channel_ids[channel]);
    Wire.write('r');
    Wire.endTransmission();
    delay(1000);

    sensor_bytes_received = 0;
    memset(sensordata, 0, sizeof(sensordata));

    Wire.requestFrom(channel_ids[channel], 48, 1);
    code = Wire.read();
```

```
    while (Wire.available()) {
      in_char = Wire.read();

      if (in_char == 0) {
        Wire.endTransmission();
        break;
      }
      else {
        sensordata[sensor_bytes_received] = in_char;
        sensor_bytes_received++;
      }
    }
    if (code == 1){
      if (channel == 0){
        pH = atof(sensordata);
        pH = pH*PH_PARAM_A + PH_PARAM_B;
      }
      if (channel == 1){
        EC = atof(sensordata);
        EC = EC*EC_PARAM_A;
      }
    }
  }
}

void setup()
{
    pinMode(13,OUTPUT);
    Serial.begin(9600);
    u8g.setContrast(0);
    u8g.setRot180();
}

void loop()
{

  digitalWrite(13, HIGH);
  delay(800);
  digitalWrite(13, LOW);
  read_tentacle_shield();
```

```
  u8g.firstPage();
    do  {
      draw();
    }
      while( u8g.nextPage() );
}
```

Once you have changed the EZO boards to i2C you can now plug everything into the arduino and upload the code into your arduino. Plug the EZO boards into the mini tentacle shield and then plug that shield into the arduino. You'll notice that the EZO boards make it impossible to plug the LCD screen directly on top – as the EZO circuits make the shield too tall – so you should use stackable headers to extend the connections so that you can plug the LCD screen on top without any problems. Make sure you download and install the U8glib library in your arduino IDE before uploading the code.

As with the previous code you'll notice there are variables called PH_PARAM_A, PH_PARAM_B and EC_PARAM_A within the beginning of the code that you should change in order to calibrate your probes. Follow the instructions about calibration I gave in the previous post in order to figure this out. Using the calibration solutions that come with your kits you'll be able to perform this calibration procedure. Whenever you want to calibrate your probes you should reset these variables to their original values, reupload the code and retake measurements.

Following this guide you will have a very robust sensor setup using very high quality probes. These probes are also coupled with a board that has no wire connections with the arduino, offering very high quality readings with very small amounts of noise. Additionally the LCD shield opens up the possibility to add more sensors to your station so that you can monitor, temperature, humidity, and carbon dioxide potentially from a single place.