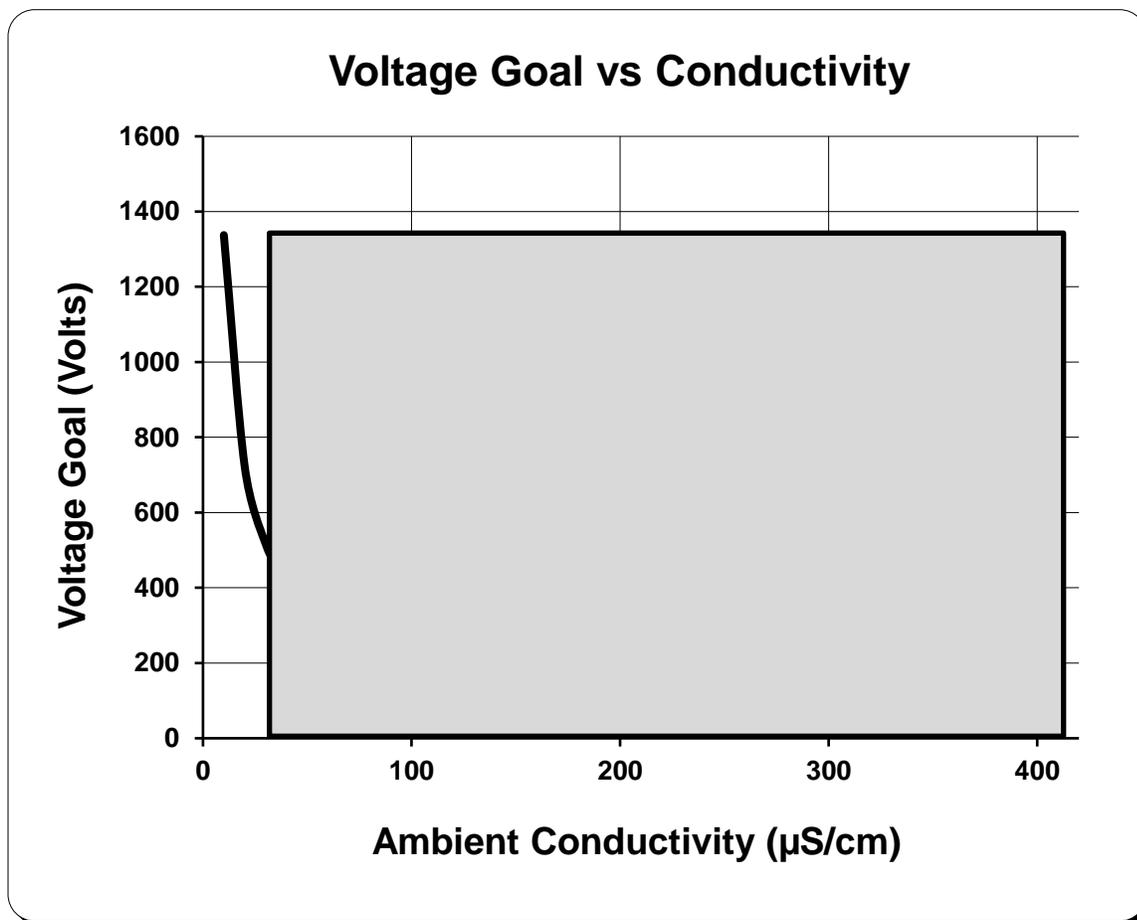


## Power Transfer Theory of Electrofishing, in a Nutshell

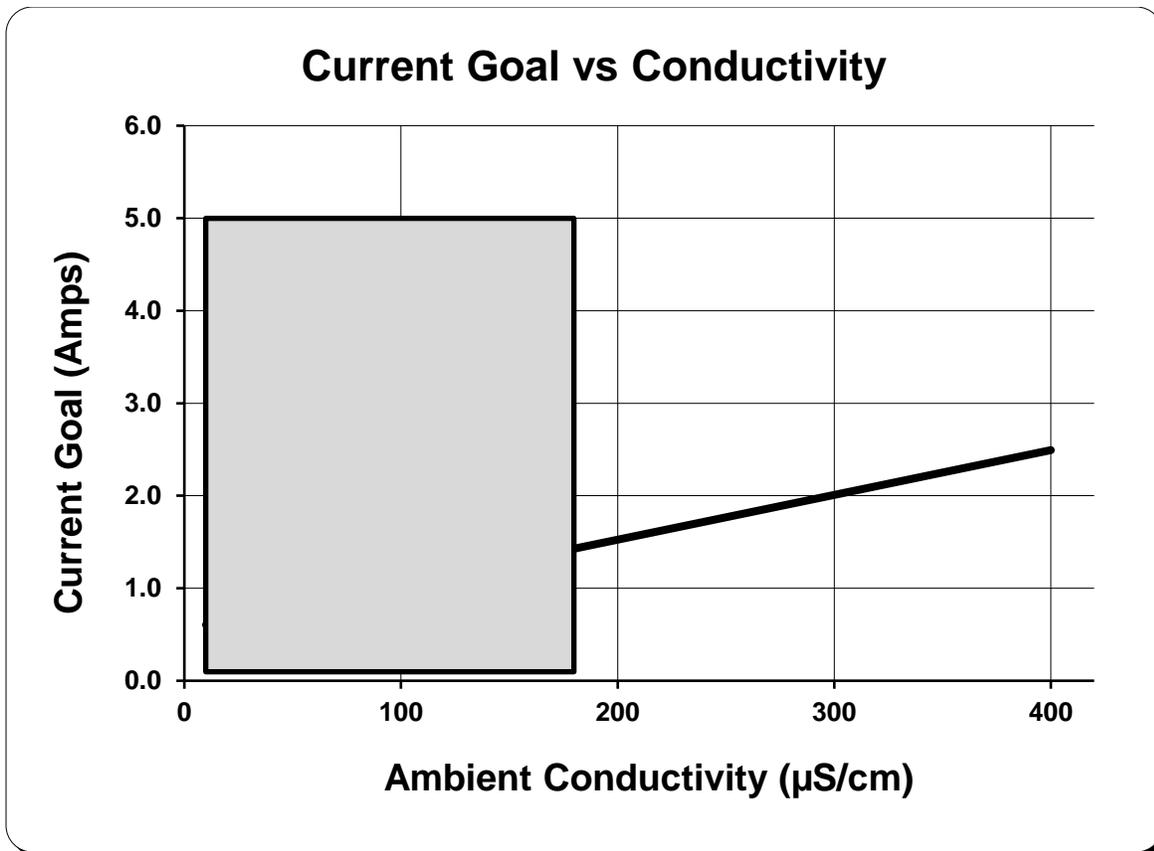
Fisheries biologists have known for a long time that many factors affect fishing success. The most important environmental factor is the conductivity of the water, i.e. its ability to conduct an electrical current due to the concentration of ions in the water. Water conductivity has been used as independent variables in multiple regression equations or as covariates to estimate catch per unit effort or some measure of capture efficiency. For decades, biologists made equipment adjustments to compensate for varying water conductivity in an ad hoc fashion without a guiding principle.

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Some fisheries biologists were convinced that voltage must be adjusted as one fishes in waters of varying conductivity. Others were equally convinced that it is the electrical current which must be changed. Each group was right, but neither group saw the whole picture.



The voltage-conductivity graph represents what the voltage group saw because they tended to sample in lower-conductivity waters. The line represents the voltage needed for successful fishing. They rightly concluded that voltage, not current, is the determining factor for fishing success in low-conductivity water.



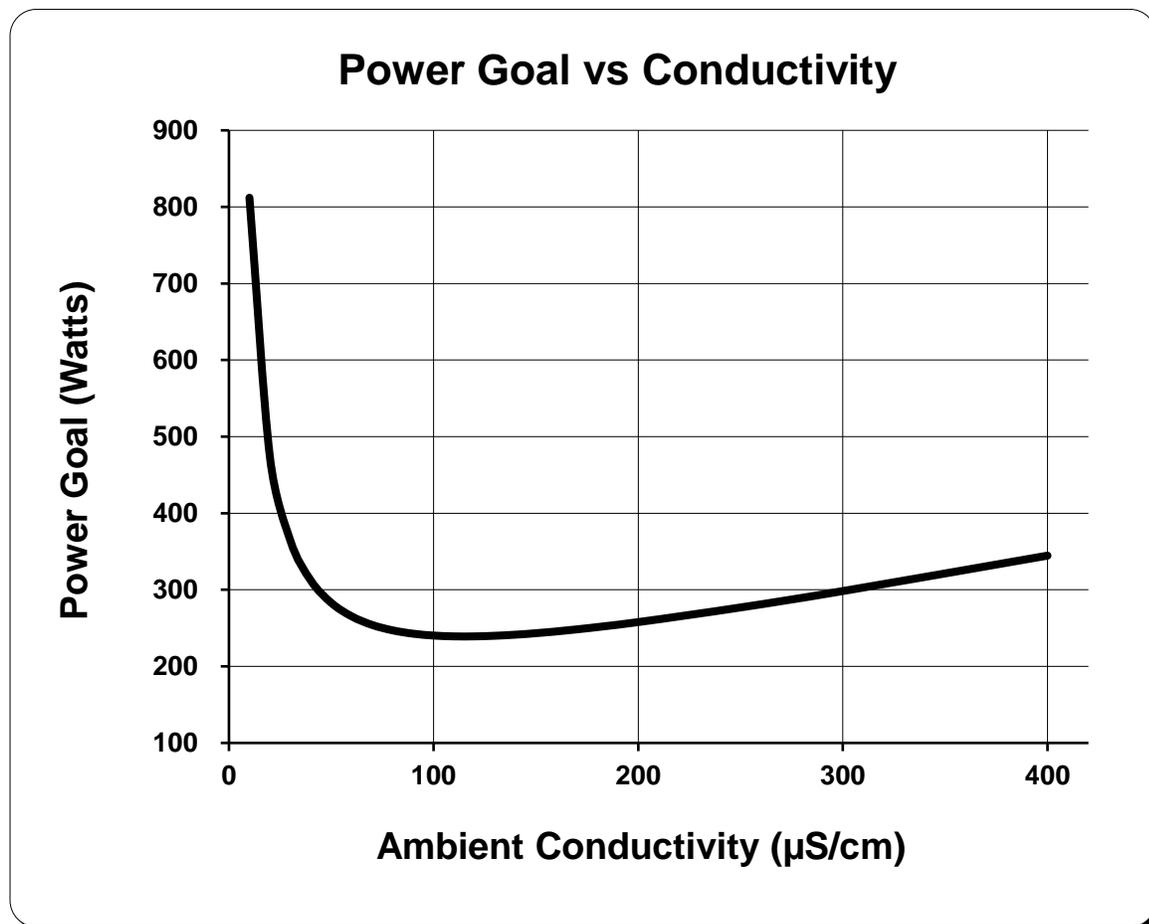
The current-conductivity graph represents what the current group saw because they tended to sample higher-conductivity waters. The line represents the voltage needed for successful fishing. They rightly concluded that current, not voltage, is the determining factor for fishing success in moderate to high-conductivity water.

Both had good reason, based upon their relative experiences, to conclude that they had the answer they needed to fish in waters of varying water conductivity. And each group could learn from the other, if they were willing. The situation called for a neutral person with a different perspective. Thomas Kuhn taught in his “The Structure of Scientific Revolutions” that scientific discovery is not a constant process over long periods of time. Rather, achievements generally occur rapidly when people with different backgrounds look at a situation or problem in a novel way. Kuhn defined the term “paradigms” as “universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners.” Frankly, the electrofishing community needed a paradigm to explain some of the variability in fishing success.

A. Lawrence (Larry) Kolz, an electrical engineer with an unusual background, was invited as a guest to answer electrical questions for an electrofishing course in 1980. He saw immediately the problem with papers which talked only about voltage or only about current. His thesis work was on microwave propagation in an ionized media, and he later worked on detecting signals of rockets reentering the earth’s atmosphere at hypersonic speed, thereby generating an ionized gas around them. That and other experiences with wildlife telemetry allowed him to recognize that electrofishing was a power

transfer problem that involved the interface between water and the fish. Larry became an instructor for the U.S. Fish and Wildlife electrofishing course. He met Dr. Jim Reynolds in 1984, and they began teaching the course together and continued so for many years. They taught the first such course that I took in 1985. Jim encouraged Larry to publish his theory (Kolz 1989), and they conducted the research to demonstrate the validity of the theory (Kolz and Reynolds 1989). Randy Burkhardt took the course and convinced a multi-state group sampling fish in the upper Mississippi River to adopt the concept of power standardization in 1991, and the result was reduced catch variation at no additional cost (Burkhardt and Gutreuter 1995). Dr. Steve Miranda at Mississippi State University conducted a more extensive study which proved the viability of the power transfer theory (Miranda and Dolan 2003).

Okay, enough of the history, now back to the concept. Electrical power is the product of voltage and current; in physics, power is a measure of work (moving objects). Larry's studies and experience provided the key that it was power instead of either voltage or current alone.



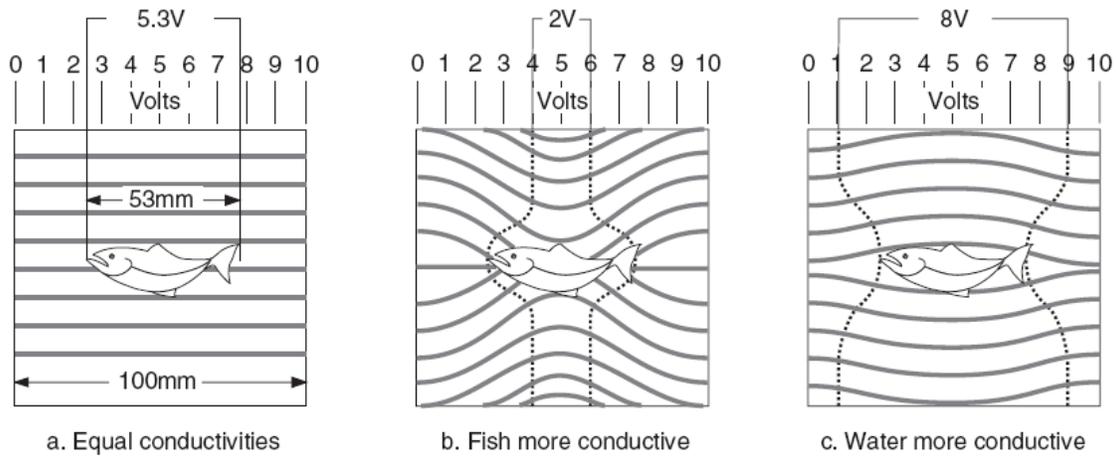
The concept or paradigm is standardizing by power. At very low conductivity, voltage is the driving force controlling power. At higher conductivity, current is the factor most controlling power. Standardizing by power does not mean using the same applied voltage, current or power across a wide conductivity range. In fact, just the opposite is true. Standardizing by power means to adjust power settings based on

water conductivity so that the catchability remains the same. We want to adjust power so that conductivity is taken out of the equation. Let's develop more of the theory to explain this.

Larry explained his theory of power transfer in two ways, circuits and fields (Kolz 1989). Using a simple circuit with a fixed resistor and a variable resistor, he showed that the maximum transfer of power from one resistor to the other occurs when the resistances of the two resistors are equal. Think of the one resistor as the water and the other as the fish. The other way in which he explained the concept was based on wave (field) theory in which electricity flows in three-dimensional space and thus is not restricted to wires and electrical components. Further, he quantified the relative power transferred to the fish as a function of the ratio between the conductivity of the water and the fish. Prior estimates of fish conductivity were based upon sticking probes in fish or by grinding a fish and measuring its resistance. Larry coined a term, effective fish conductivity, which was a biological term based upon the **behavior** of fish in an electrical field. The responses could be twitch, taxis, forced swimming, narcosis, tetany or even death.

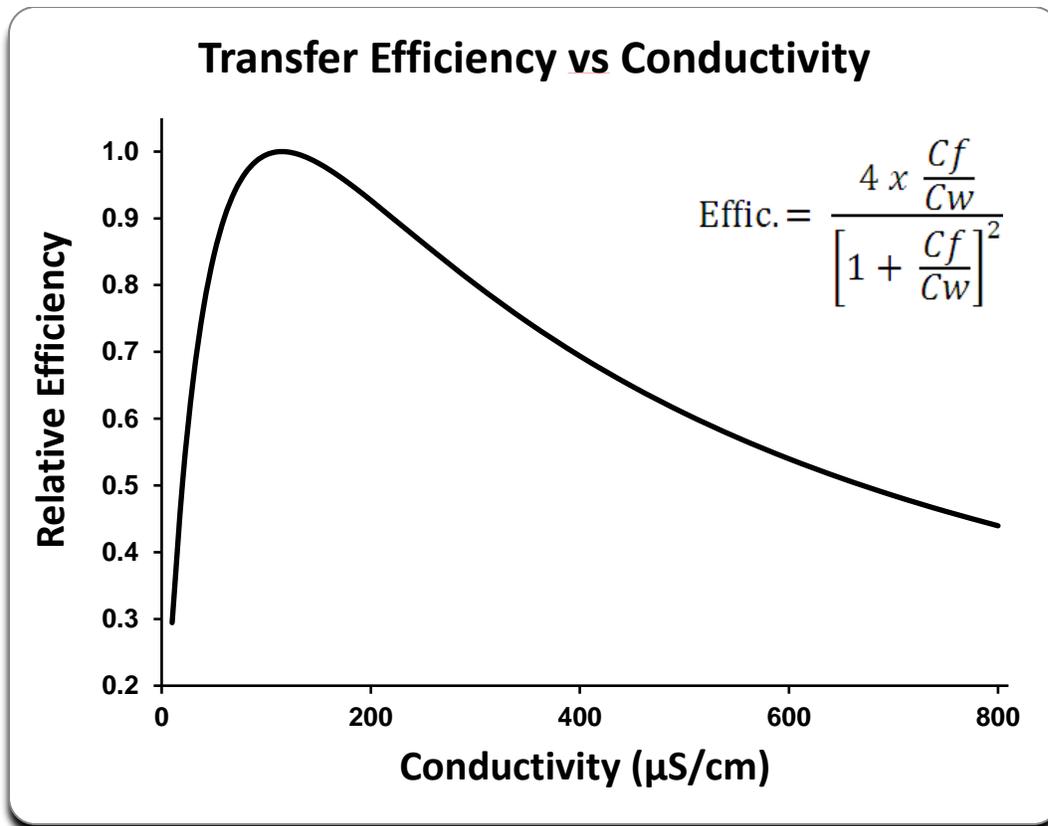
Water conductivity obviously varies depending upon the ionic concentration of the water. What about fish conductivity? The thought is that effective fish conductivity is relatively constant, regardless of the water conductivity. Fishes employ various physiological processes (pumping salts either into or out through their gills, excreting salts in their feces or not, producing a mildly or very dilute urine) to maintain a constant internal ionic balance. According to Bond's "Biology of Fishes" the osmotic concentration of typical freshwater fish blood is about 265 to 325 mOsm per kg. Seawater is 1000 mOsm per kg and fresh water can be less than 5 mOsm per kg. Several studies have shown that fish conductivity ranges from less than 50 to 175  $\mu\text{S}/\text{cm}$ , but more research is needed. The American Fisheries Society has adopted 115  $\mu\text{S}/\text{cm}$  as a standard value for fish conductivity (Miranda 2009). The point is that effective fish conductivity is basically constant, we think, whereas water conductivity can vary tremendously.

So how does water conductivity affect the voltage, current and power to which a fish is subjected?



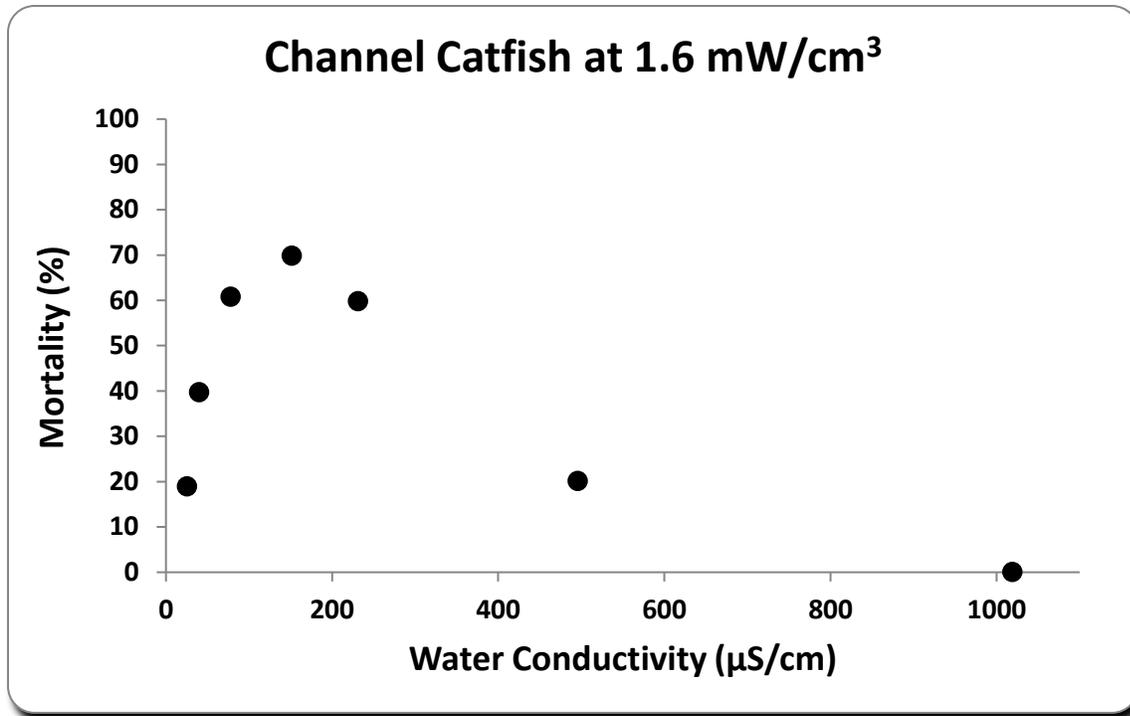
**Figure 11. Electric field patterns caused by fish.**

This graph from the Smith-Root, Inc. GPP manual describes the situations when fish and water have equal conductivity, when the fish is more conductive, and when water is more conductive. With equal conductivity, the fish does not disrupt the electrical field. The current flows through the fish the same as it would through the water. In very low conductivity water, i.e. where the fish is more conductive, the current takes the path of less resistance, in this case through the fish. However, lines (actually surfaces) of equal voltage (or electrical potential) must occur at right angles to the current lines, so less voltage goes into the fish. In contrast, in highly conductive water, the current again follows the path of less resistance, in this case around the less conductive fish. However, more voltage enters the fish. The change in voltage should offset the change in current so that the power transfer from the water to the fish is constant, right? Well, no. The maximum transfer of power (the ability to do work) occurs when the water and the fish are equally conductive; in this case voltage and current are at their maximums relative to each other, so their product (power) is also at maximum.

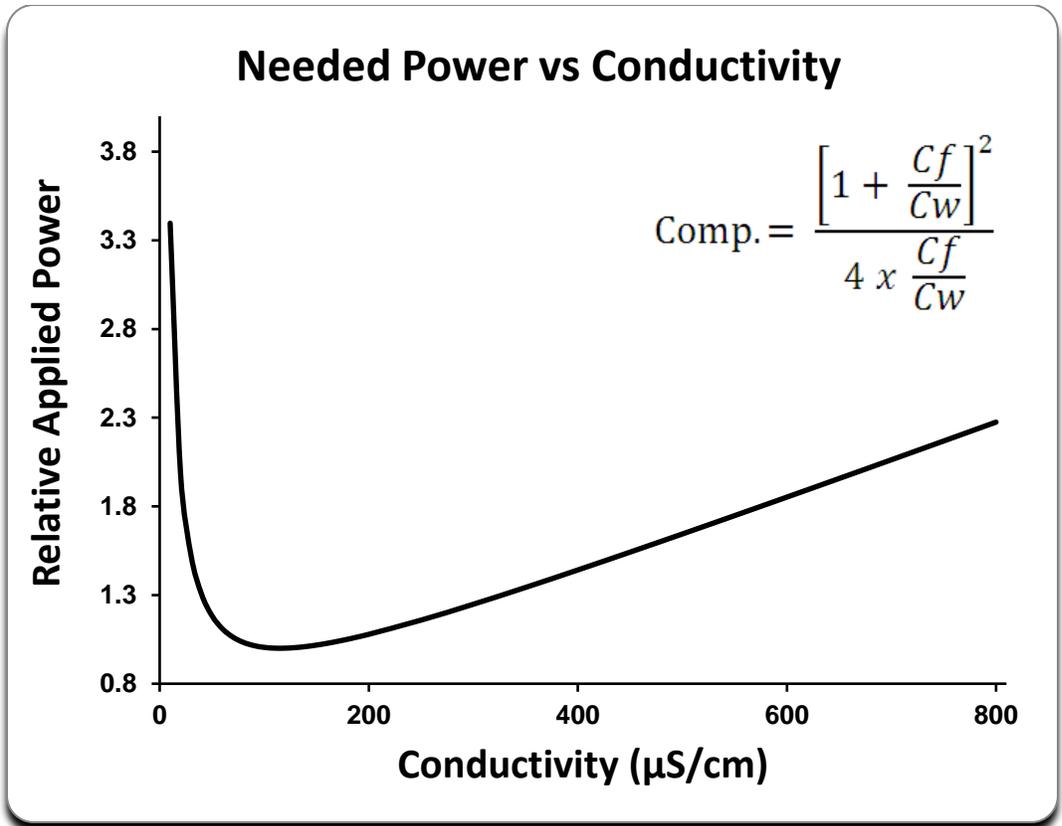


Here is the graph of the power transfer efficiency from water to fish as a function of water conductivity. The peak occurs at the effective fish conductivity ( $C_f$ ) and declines at higher and lower water conductivity ( $C_w$ ); both are measured in  $\mu\text{S/cm}$ .

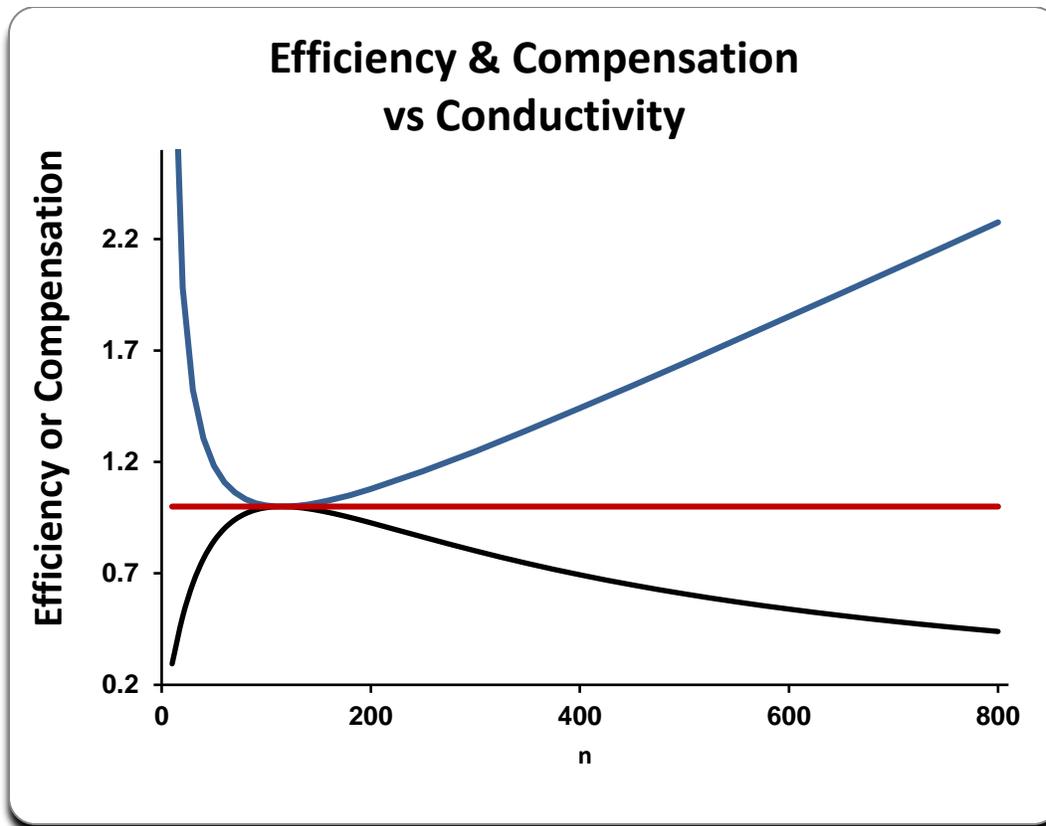
Think of this power efficiency as capture efficiency if the same power is applied for any conductivity situation. For example, based on the above graph, at a water conductivity of  $700 \mu\text{S/cm}$ , the efficiency of electrical power transfer to the fish is a little less than half of the efficiency at match, when  $C_f = C_w$ . How does this work in practice? Let's say that some study has determined the best capture efficiency in a given area using some electrical waveform and sampling methodology at match is 40%. If you used the same power setting at  $700 \mu\text{S/cm}$  as you did at match, then the capture efficiency would presumably be slightly less than 20%. That difference could have a profound effect on the conclusions from your study or survey. As you can see, standardizing by power does not mean applying a constant power regardless of conductivity. It means that you must adjust the applied power based on the water conductivity. So how do we do that? We must compensate for the inefficiency of the mismatch between fish and water conductivity by taking the inverse of the formula above. But first, let me show you some actual data from a study in which the applied power was maintained across a wide range of water conductivity.



Henry and Grizzle (2006) applied a constant power density (1.6 mW/cm<sup>3</sup>) to produce mortality in small (34-43 mm TL) channel catfish. Again, think of this as an efficiency curve. When the applied power was constant, the mortality peaked at some intermediate level -- the effective fish conductivity -- near 150 µS/cm.

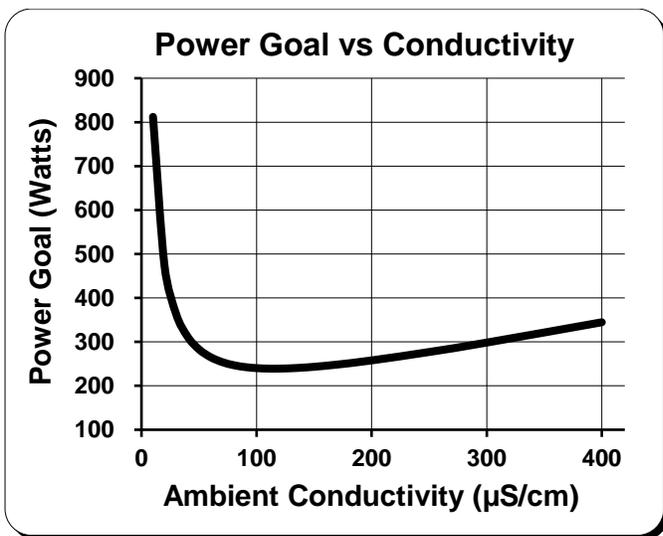
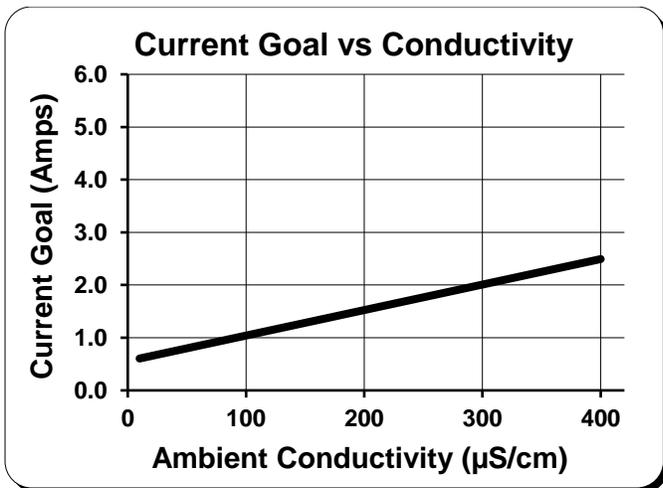
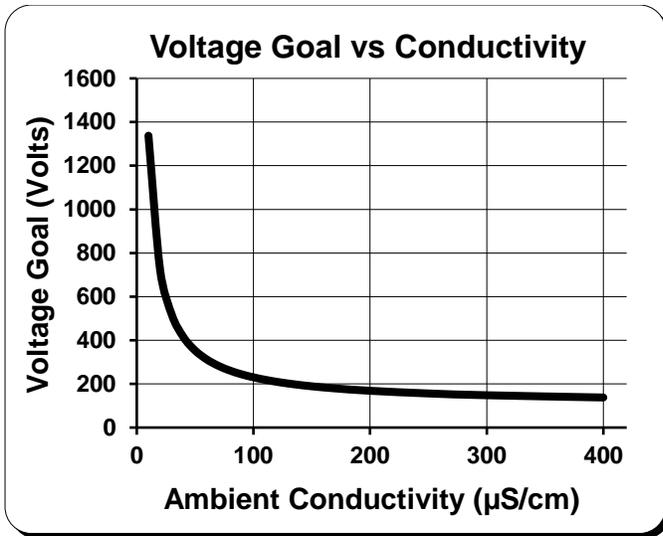


The power compensation curve is the relative applied power to compensate for the reduced power transfer efficiency when there is a mismatch between fish and water conductivity. Think of this as a relative power goal curve. The formula for the compensation curve is simply the reciprocal of the efficiency curve formula.



Here are both curves at once. Because there is inefficiency in power transfer from water to fish at other than matched conductivity, we must compensate by adding more power in those situations. The desired outcome is the red line which indicates a constant amount of power is transferred into the fish to produce the same capture-prone response, regardless of water conductivity.

By using the power compensation formula, we effectively remove the influence of conductivity from our electrofishing catch variability. It allows us to use the same size effective fishing zone or “electrical net” in any water conductivity up to the capability of our electrofishing gear, all else being equal. And a big part of “all else” is using the same electrical waveform in terms of frequency and pulse width or duty cycle, if those terms are applicable for the waveform used. Thus, standardizing by power requires independent controls for voltage, frequency and pulse width or duty cycle when using pulsed direct current. Also required for standardizing by power is using the same electrode arrangement and immersion depth. We calculate the electrode resistance as if in 100  $\mu\text{S}/\text{cm}$  water conductivity. That resistance value is termed the R100 value, and it must remain basically constant in order to properly standardize by power. One can standardize by power using voltage, current or power as the measure of interest, but let’s leave that for another blog.



To conclude and summarize, let me refer you to the three small graphs above. They all are goals to produce the same power transfer efficiency and the same capture efficiency across a wide range of water conductivity, all else being equal. As you can see, the efficiency driver in low conductivity is voltage whereas in higher conductivity it is current. The more complete answer is that it is power in both cases and throughout the continuum of water conductivity. Fishing with a constant applied power is not standardizing by power. I hope you understand and appreciate that now. Standardizing by power means adjusting applied power so that the power which enters the fish is the same, regardless of water conductivity.

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