

# Numerical Simulations of Seawater Electro-Fishing Systems

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## 1. Introduction

In the last decades, several surveys and research works have reported a decrease in pelagic fish resources in the Mediterranean sea, with the exception of the Adriatic sea. In fact, in this area, an overall decrease of stocks of fish species was reported as opposed to the simultaneous increase in others (Picinetti 2008). Fishing methods that use attractive elements of fish such as light and the electric current are used in many parts of the world. In this regard, the attraction of light, which exploits the phototropism of certain fish species is widely used, for instance, by the famous Japanese method for squid catching or electro-fishing techniques of bluefish in use throughout the Mediterranean. Also in freshwater lakes and rivers is very common to use electro-fishers to attract and capture fish. Regarding the electrical fishing in salt water, various experiments have been carried out to develop this new technique (Kolz,1993; Kurk,1971,1972; Roth et al., 2006). These studies were mainly carried out in the United States, France and Soviet Union (Blabcheton,1971; Diner & Le Men, 1971; Kolz, 1993; Van Harreveld, 1938). The basic elements that must be taken in consideration for the personnel who, for the first time, is preparing to use a sea electric attraction system are, first and foremost, the safety of operators and possible damage to fish. To understand these effects, it is necessary to know some basic principles of electrical circuits and the chemical-physical characteristics of water and fish subjected to different types of current. Regarding the former, it is important the knowledge of circuit features such as the power and characteristics of an electric generator, the current type, shape and use of electrodes (anode and cathode). The application of electric fields in non homogeneous systems consisting of fish and salt water is far more difficult than in freshwater conditions. This point is of fundamental importance and its understatement, in fact, may impair or reduce the efficiency of electrical fishing. Electric fishing is based on the principle of introducing an electric potential gradient in the water body, between one or more cathodes and one anode. The perception of this potential gradient by fish is function of their position towards electrodes and of their conductivity in respect to water's, as well as of temperature, size and species. The potential gradient produces different effects on fishes depending on the intensity and type of current used. Those effects are known and described since the end of 1800 (Van Harreveld, 1938). Currents used in electro-fishing can be continuous (DC), alternate (AC) or pulsed (PDC), depending on environmental characteristics

(conductivity, temperature) and fish to be sampled (species, size). The three current types (DC, AC, PDC) produce different effects. Only DC and PDC cause a galvanotaxis reaction, as an active swim towards the anode. With AC this phenomenon is not possible due to the continuous changing in polarity of the electrodes. Fundamental limit to the application of electric fishing in sea water is given by the high conductivity of salted water, that being much greater than animal tissues causes the current to flow around the fish instead of passing through it. In high conductive water, PDC is the mainly used current form, because of the lower power demand, at parity of result, compared to DC (Le Men, 1980; Beaumont et al., 2002), and also causes galvanotaxis in fish (Kurc et al., 1971). Fish in fact swims towards the anode under the effect of the muscle contraction given by each electric impulse (electrotaxis) until narcosis occurs (tetanus) (Beaumont et al., 2002).

## 2. Electro-fishing theory

### 2.1 Definition of an electric field

Materials consist of particles characterized by positive electric charges (protons) and negative (electrons), while others have neutral charge (neutrons). In various materials, in particular in metals, electrical charges have the ability to move. In reality, there is not a real movement of electrons, but a transfer of energy through collisions between electrons. The movement of charges, which occurs at a given time, is defined as movement of electric current (I) and is measured in amperes (A). The relationship between the aforementioned variables is as follows:

$$I=Q/t \quad (1)$$

where:

Q=charge in coulombs

I = electrical current in amperes

t = time in seconds.

Table 1 shows the basic terms, definitions and units of measurement of variables used in circuit theory and electric fields.

Term	Symbol	Unit
Electric charge	Q	coulomb
Voltage energy	V	volt
Current load/time	I	ampere
Electric resistance	R	ohm
Energy power/time	P	watts
Energy power*time	W	watt/hour
Resistivity fraction x distance	p	ohm/cm
Conductivity	1/P	μS/cm
Voltage gradient variation		e volts/
Current density		J amp/cm <sup>2</sup>
Power density		D watt/cm <sup>3</sup>

Table 1. Terms, symbols and unit used in the current field theory

The electric current is made up of a flow of charges which tend to restore a state of neutrality between two electrically charged bodies. If the two bodies become neutral, the current ceases immediately to flow (because there is no more a force of attraction between the two bodies). The circulation of electric current is higher in materials that have a large amount of free electrons as conductors. In this way, the electric current flows from a region with high negative charges to one with positive charges. The electric current ( $I$ ) is measured with the ammeter. The voltage ( $V$ ) is defined as the potential difference between two points of the electrical circuit and is measured with a voltmeter. With a voltage  $V$  and a current density  $I$ , the power  $P$  can easily be calculated as  $P = V \times I$ . The electric circuits can be classified into two main types: circuit in series or parallel. In the series circuits, all components (generator, switch and the transformer) form a single path. Instead, the circuits in parallel are divided into branches. If two different charged electrodes are immersed in a liquid, several lines of force are created between the two poles. Along these lines of force flows the electrical current. These lines of force coincide with the current lines (Fig.1).

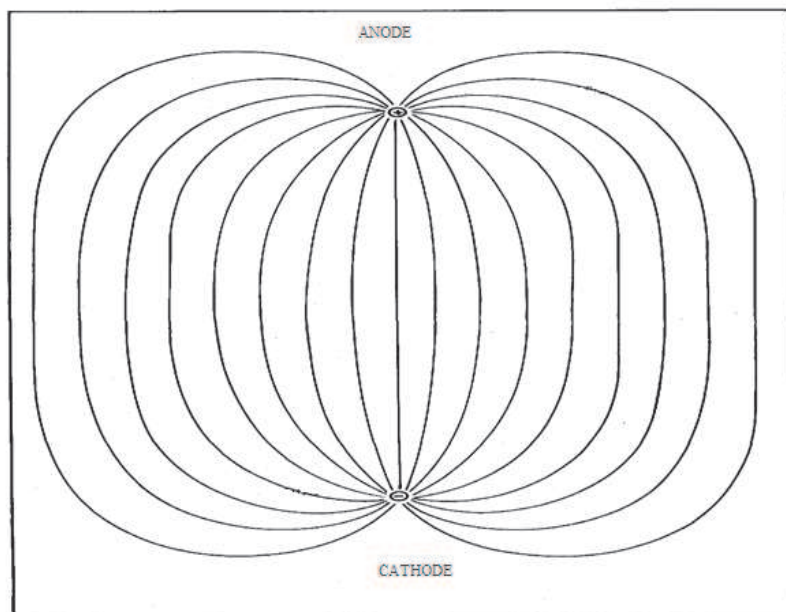


Fig. 1. Force lines are formed between the anode (positive) and cathode (negative) immersed in a liquid

Now, let's take an example of a potential difference of 400 V between the two poles of the field. This potential difference decreases gradually starting from the anode (+) going to the cathode (-) to finally reach the value of 0 volts at the cathode. Consequently, we can see that on the same force line, voltage values vary according to the position. We can also get lines that have the same voltage values. These lines are called equipotential lines (Fig.2).

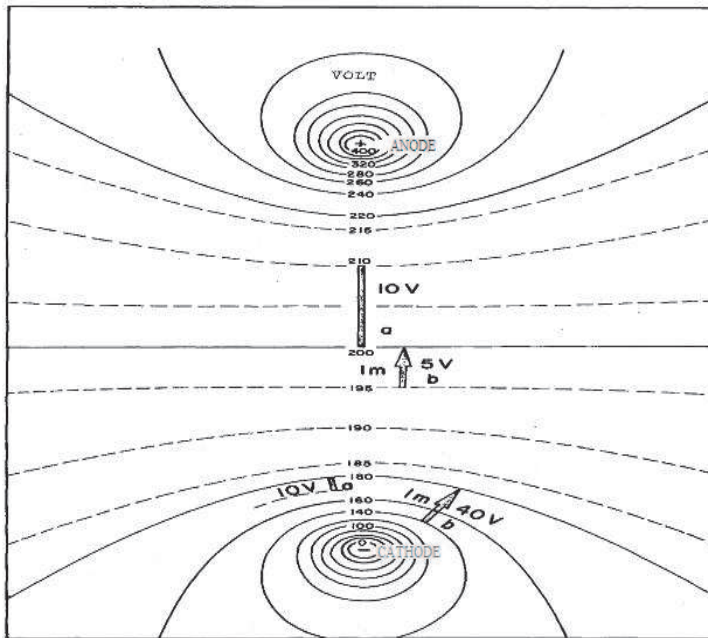


Fig. 2. The equipotential lines are obtained by bringing together points of equal voltage  
The figure obtained resembles a map in which lines mark the same altitude.

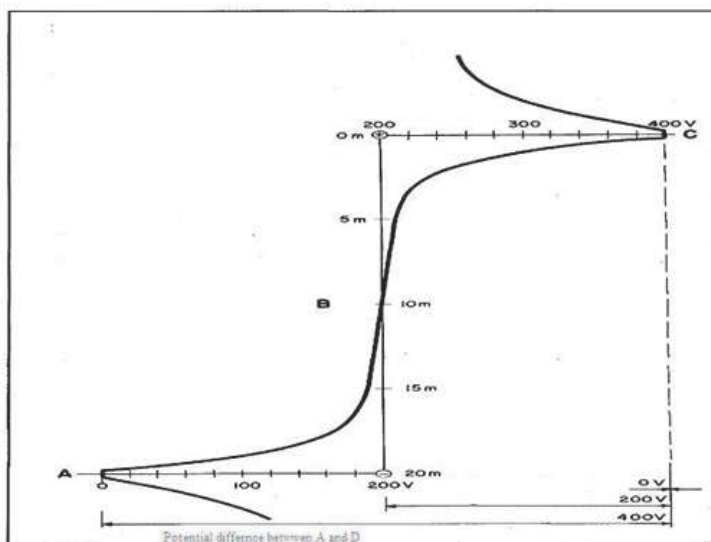


Fig. 3. Voltage curve between the anode (+) and cathode (-) located at a distance of 20 m apart

Potential differences are measured along a line of force (Fig. 3) . The greatest potential difference is obtained at the two electrodes A and C. Approaching the cathode, voltage decreases. For example at point B, midway between the two poles, voltage difference is 200 V. There is a progressive decrease until it reaches the value 0 at the cathode itself. This means that an object placed in an electric field is subjected to a potential difference. This potential difference varies depending on the location of the electric field where the object is placed and is greater in the vicinity of one of the two poles. Inside an electrical conductor, the movement of electrons is slowed down from their original path when the moving electrons collide with others. This phenomenon is called electrical resistance (R). The electrical resistance varies depending on the conductor. In practice, the electrical resistance results in a reduction of the current flow and a loss of energy. The electrical resistance increases in relation to the length of the conductor and decreases with higher cross-section values. If R is the total resistance of a conductor, the formula to determine the value will be:

$$R = \rho l / s \quad (2)$$

where:

R = electrical resistance in ohms

l = length of conductor in m

s = section in mm<sup>2</sup> conductor

$\rho$  = coefficient of electrical resistivity

The ratio voltage / current intensity measured in an electrical circuit has a constant value. In fact, being the resistance equal, the change in current intensity is directly proportional to the voltage. This relationship is explained by the second law of Ohm:

$$R = V / I \quad (3)$$

$$I = V / R \quad (4)$$

where:

R = electrical resistance in ohms

V = voltage in volts

I = electric current in amperes

Conductivity is reciprocal of resistance. The conductivity is measured in siemens (S). The conductivity varies for each material. Once known essential elements regarding electrical power and circuits is possible to build a system for electrical fishing.

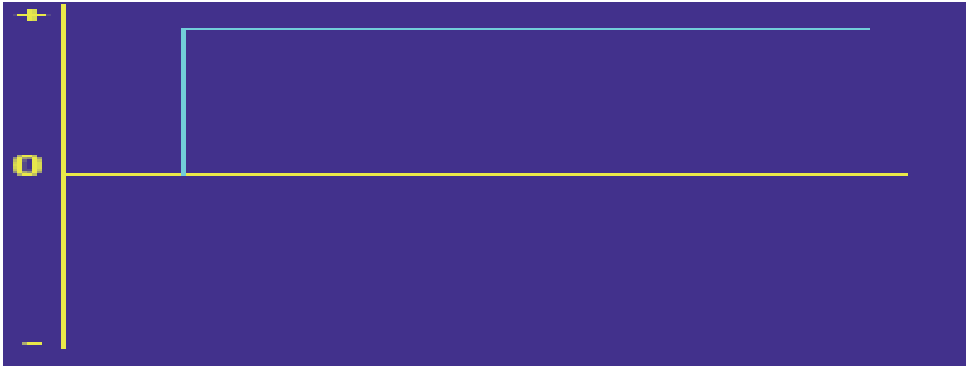
## 2.2 Types of current waves

The current is a continuous movement of electricity between two points on a conductor that are at different potential. The different types of electrical current produce different electrical shapes or wave forms.

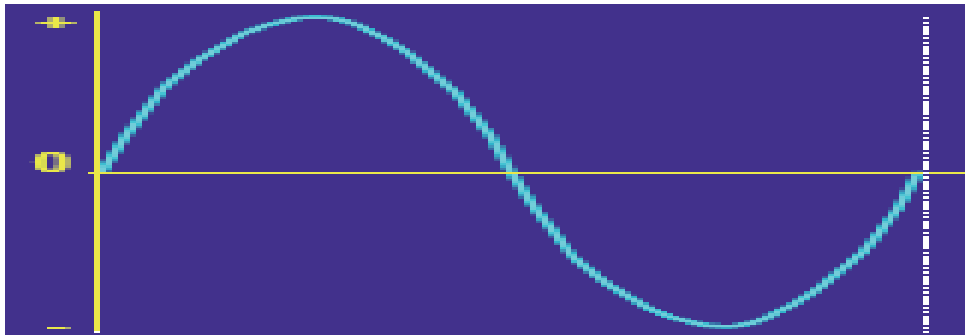
The three most important type of electric currents are:

- Direct Current (DC)
- Alternating Current (AC)
- Pulsed Direct Current (PDC)

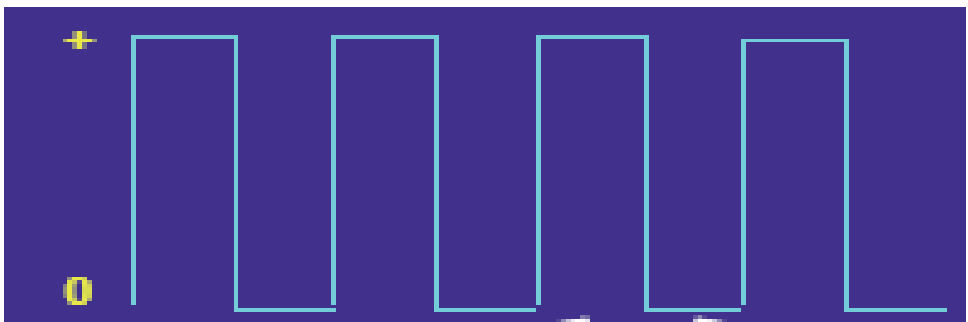
Direct current produces a unidirectional, constant electrical current. DC is a current of equal intensity with a smooth continuous flow that occurs from pole to pole. Strength and direction remain constant.



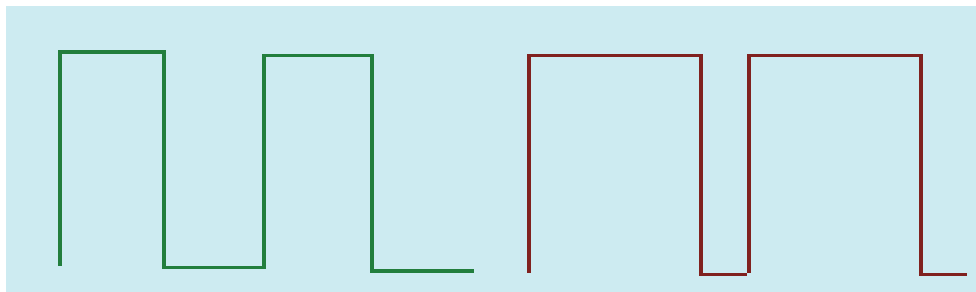
Alternating Current (AC) is an electrical current in which the direction of current reverses a number of times per second. Alternating current produces a wave form that consists of a sequence of positive and negative waves that are equal, usually sinusoidal, and follow each other alternately at regular time intervals. An alternating current is a current that changes strength and direction of propagation with a time constant. For example, a period lasts 1/50 of a second. Frequency is the number of periods per second. The unit of frequency is the hertz (Hz).



The Pulsed direct Current (PDC) is, in the simplest case, a direct interrupted current. This current flows in the form of pulses.



A period (duty cycle), in this instance comprises the pulse duration and pause.



### 2.3 Electrical fishing systems

Electro-fishing is the use of electricity to capture fish. The essential components of an electrical circuit are:

- The generator. The generator produces electricity. It is usually classified as a voltage source or current source. Conventional circuits are generally used for generating power.
- Conductors. Conductors are used to carry electric current from the generator to the electrodes.
- The transformer. The transformers allow to convert electrical energy into another form of energy (mechanical, thermal, etc.).

The electricity is generated by the generator whereby a high voltage potential is applied between two or more electrodes that are placed in the water. In the case of sea water, the voltage potential is created using a pulsed direct current which produces a unidirectional electrical current composed of a sequence of cyclic impulses. Sometimes you can have more than one cathode and anode. In a fishing system, with a single anode and a cathode, lifting them up from the water opens the circuit. The same is not true in a systems with multiple anodes and cathodes. Being arranged in parallel, their lifting from the water does not break the circuit and therefore does not terminate the action of fishing, at least until then the water is applied to the cathode or anode. However, even if they are applied more anodes, the circuit is opened by lifting the cathode from the water. In the systems for electrical fishing, water and fish are a component of the circuit. The basic requirement of electrical fishing equipment is to transfer energy from water to fish. The resistance of the fish is generally different from that of water. The difference between water resistance and resistance of fish can reduce the energy transmitted and thus the capture efficiency of the equipment. Thus, difficulties encountered in the use of electrical fishing are due mainly by transfer of adequate amounts of energy from the generator to the fish. Most systems are equipped with instruments for measuring the voltage (V) and current intensity (A). Characteristics of the current can be easily changed. In particular, for the PDC, it is possible to change the number of pulses and the pulse width. In electrical circuits there are two types resistances: the resistance inside the system and the load resistance. The maximum efficiency of the system is reached when the internal resistance is equal to the current load. An increase in resistance, causes a loss of power and an increase in tension. The maximum power transfer occurs when the current load is equal to 1, and this happens, as mentioned earlier, when the current load equals the internal resistance. The internal resistance is formed by the cathode, while a variable part, is composed by fish and some water. When the conductivity of the water and fish are the same, all the applied power will be transferred to the fish. The conductivity of sea water varies with the temperature and salinity (Fig. 4). The conductivity of water is a

very important factor that has already been introduced in the first part. We can define the specific conductivity of water as the conductivity of a cube of water of 1 cm side. This depends on the specific conductivity of dissolved materials and water temperature. Water is dissociated into its chemical components formed by ions ( $\text{OH}^-$  and  $\text{H}^+$  ions produced from  $\text{H}_2\text{O}$  molecule). These particles by their charge allow the transmission of the current. In addition, the higher the salt content of water, the greater the ion content and therefore the greater the conductivity. Water temperature also affects its conductivity. In fact, under conditions of high temperature, ions increase their mobility and decline with a lower temperature. The specific conductivity decrease of 2.5% per degree ( $1^\circ\text{C}$ ) lowering the temperature. The specific conductivity is measured by the conductometric. We have already seen that the specific conductivity is measured in microseconds / cm (microsiemens per cm). The specific resistance and specific conductivity are calculated using the relationship:  $1\text{ Ohm} \times \text{cm} = 1.000.000/\mu\text{S}/\text{cm}$ .

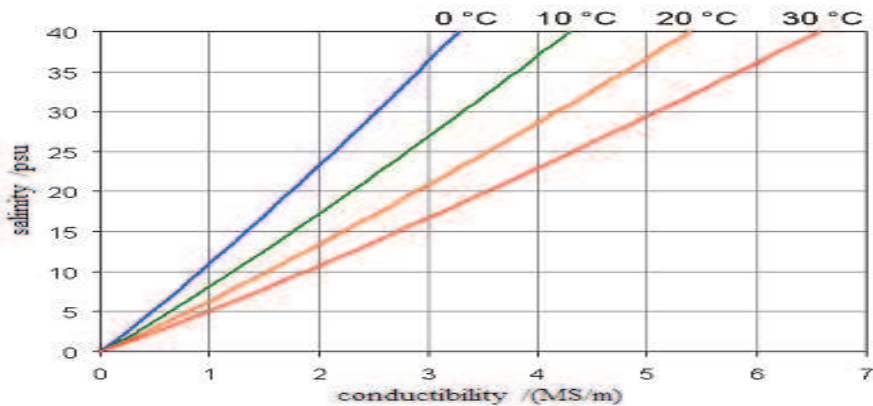


Fig. 4. Effects of salinity and temperature on salt water conductivity

In order to optimize the electro-fishing system in salt water, we should know in advance the average conductivity values of water and fish and water temperature of the area of interest. Figure 5, the horizontal axis indicates the ratio water/ fish conductivity and the vertical axis the percentage of the maximum transfer of power.

The maximum value (100%) is obtained when the ratio water conductivity/fish conductivity is equal to 1. While the conductivity of water is easily determined, this is not the case for fish and therefore, for all practical purposes, it is assumed that the latter is equal to  $115\ \mu\text{S}/\text{cm}$  ( $0.0115\ \text{S}/\text{m}$ ), as recommended by Miranda and Dolan (2003). The choice of this value, although not exact for all species, is essential for the standardization of electrical fishing. In practice, in waters with low conductivity, there is a decrease in the current voltage (volts), while in waters with high conductivity, there is a reduction in the current density (amperes). The standardization of electrical fishing require precise measurements of the electric field. These can be made using some instruments such as oscilloscopes or meters. In the absence of such instruments, the biologist should observe the behavior of fish, identifying the most appropriate adjustment of the power and pulse. Physical characteristics of the electric field change not only as a function of the current, but also in relation of the shape, size, position, distance and orientation of the electrodes. In all environments and conditions, the goal is



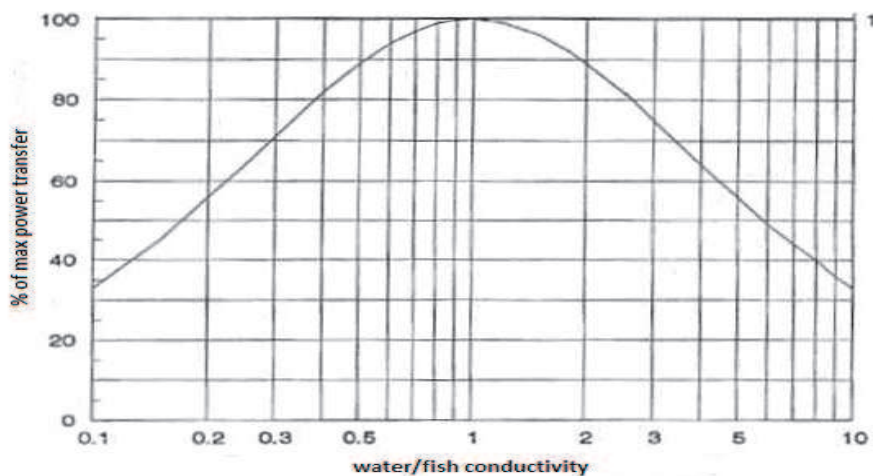


Fig. 5. Effect of fish and water conductivities on maximum power transfer

always the same: to bring the fish to the surface in the vicinity of the operators. In general, the cathode must have an area equal to or greater than the anode, thus avoiding power dissipation at the cathode. Another element that is very important but often overlooked, is the shape of the electrodes. In particular, attention should be paid to the size of the anode which should be of a diameter as large as possible to avoid causing damage to the fish. The increased diameter results in an increase in the size of the electric field which decreases the current intensity in the vicinity of the anode itself. Therefore, these solutions are recommended especially in waters with high conductivity, which require the use of small anode surface to prevent overloading of electrical generators. The anode can have different shapes, and usually the ideal shape is a sphere that ensures a uniform dispersion of energy. However, that solution would be impractical for weight, size and strength. Therefore, a more practical device consists of a chain consisting of 2 cm rings. Reducing the distance between the anode and cathode may be important to increasing the strength of the field. In this case, we need to prevent the contact of the two electrodes in order to avoid damage to the electrical generator. The electrodes are the link between the power generator and water and must, therefore, be located in such a way to allow the unit to operate under optimum conditions. The proportions of the size of the anode and cathode can be changed from 1: 4 to 1: 10. The efficacy is greatest when the electrodes are opposite each other on the side of their larger surface area. Several studies have shown that it is above or close the electrical circuit that the nervous system and muscle of the fish is stimulated.

#### 2.4 Effects of electricity on fish

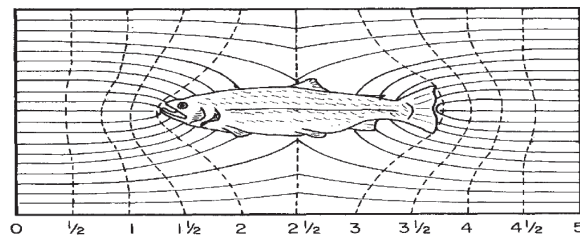
The two variables that can be modified using the PDC system are the pulse duration or amplitude (typically 5 msec) and the number of pulses per unit time (frequency: number of pulses per second or Hertz). The frequency typically used is 50/60 Hertz. Given the variability of the pulse, this current has a maximum voltage and an average intensity. To catch fish, both variables are important, although the intensity of the peaks may assume primary importance. Fish are attracted to the anode (positive galvanotaxis) probably

because the front of the brain seems to carry negative charges. It should be noted, moreover, even if they have the same nervous system, not all species respond similarly to electric fishing and also in the same species, the answer change depending on the size. Larger fish tend to be more vulnerable because of the current pulses intersect both axis cephalo-caudal and along the dorsal-ventral. From this point of view, it is worth noting that short-term treatments reduce the mortality or damage of the skeletal system. Instead, for smaller fish, and in general for all fish, any damage can be caused by the duration and frequency of pulses. These phenomena can be amplified by the special structure of fish skeletal muscle. In particular, it is important the percentage of muscle mass relative to total body mass. Another element that regulates the response of fish to electric applications is the magnitude and nature of the scales. Large and thick flakes, reduce the catchability, by contrast, the small scales are increased. Electrical fishing involves a complex system with a series of interactions between the electric field, water and fish. In fact, the study of electrophysiological responses of fish is based almost exclusively on laboratory experiments performed under controlled conditions. In fact, these experiments are only a part of the real complex natural situations. In this part, the basic reactions of fish in the electric field are discussed.

The typical reactions of fish to electric current are as follows:

- Electro-taxis: forced swimming towards the anode
- Electro-narcosis: muscle relaxation or stunning (fish swims)
- Tetanus: muscle stiffness, immobilization

The PDC causes reactions in the fish which are similar to those produced by a constant current, but, in the case of PDC, effects depend on the frequency (the number of pulses per unit time). The first reaction of fish is spasms and convulsions whose intensity depends on the number of electrical impulses. The second reaction (electro-taxis) depends on the shape of the pulses. During the third reaction (electronarcosis), the swimming motion decreases abruptly and the fish is immobilized. The ultimate goal of a well-conducted electrical fishing is the achievement of electro-taxis, i.e. the stage (or situation), where the fish is oriented toward the anode and swim actively to the electrode. It is also evident that it is important the achievement of the third stage in which the fish can not swim actively. The electric current density is the basic element that influence the reactions of fish. The current density at which the fish is exposed depends mainly on fish body size and its structure of epidermis. Using an electrical fishing equipments in marine waters, we can find that the specific resistance of fish body is smaller than that of water. As illustrated in figure 6, all the lines of force are directed toward the body of the fish. As a consequence of the lower resistance offered by fish compared with the aquatic environment, the electric force lines are concentrated in the body of fish.

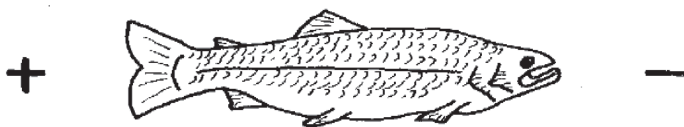


It 's possible to define a minimum value (threshold) for the desired reaction. The current density is measured in  $A/m^2$  (amperes per square meter) or  $\mu A/mm^2$  (microamperes per square millimeter). By definition, this is the intensity of current flowing through a unit surface perpendicular to the lines of force of the electric field. This current density required to obtain a specific reaction in the fish is fairly constant and characteristic for each species of fish. By means of laboratory experiments, current density values have been determined for a given species and a given length of fish. This value is the potential difference between the head and tail of the fish. This value is required to activate the physiological reactions of fish. In summary, to obtain a certain reaction, if the length of the body increases, the density of current required decreases being constant the potential difference of the body. In other words, the potential difference of the body necessary to obtain electro-taxis will be reached more rapidly in larger specimens. Furthermore, fish exposed to a potential difference below a threshold value are not attracted and they can escape. Extensive research shows that the application of electrical fishing made as the right criteria is not harmful to fish. Only by applying inappropriate techniques such as voltage too high and for long periods will create serious drawbacks. The physiological reactions of fish to an electric field can be divided into:

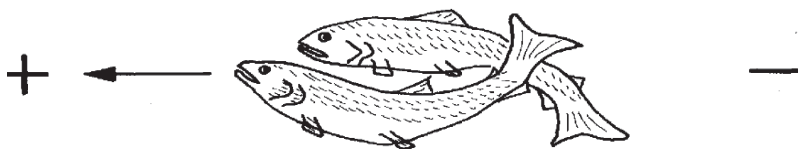
- involuntary reaction
- voluntary reaction

The involuntary reaction consists of the first movement or contraction of the fish body. The curvature (bending) of the body is followed immediately by a voluntary backlash in the opposite direction. At this point we have three possible effects on the orientation and movement of fish.

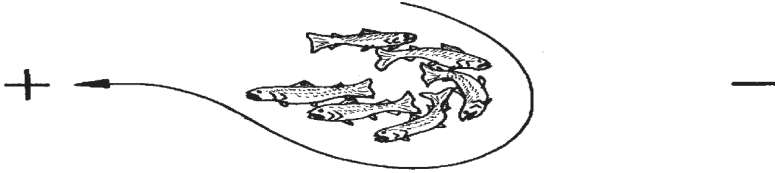
1) a fish is swimming oriented with the head towards the cathode



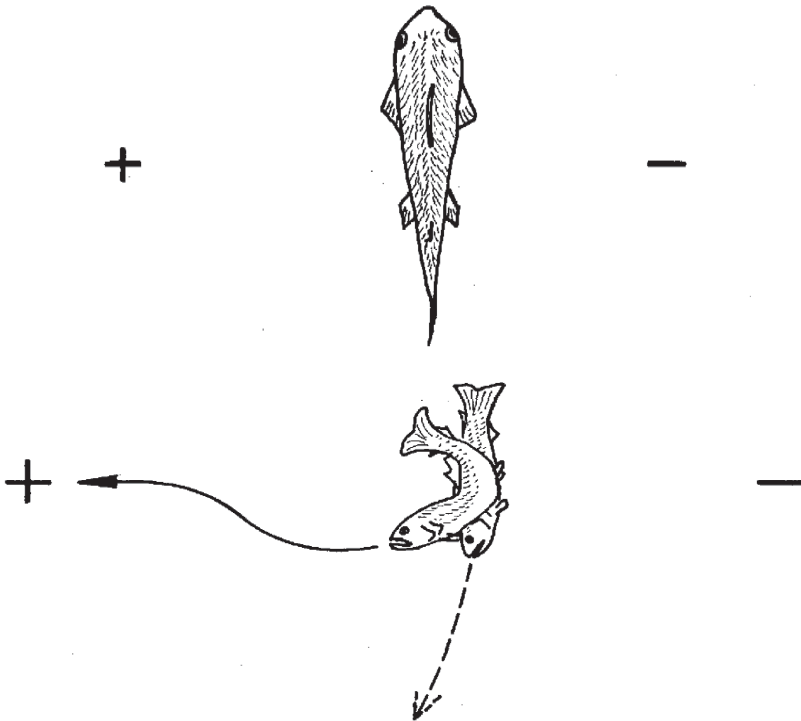
but after some time, the fish is no longer able to swim. When fish is showing cramps, it stops swimming and voluntary movement is transformed into spasms toward the anode [involuntary reaction].



2) one fish is swimming oriented with the head towards the cathode. The fish shows firstly a spasm and than it makes an half run toward the anode. Note that the reasons for this "half-turn towards the anode are not yet fully understood. After the change of orientation towards the anode, fish fall back into the dynamics of the first effect.



3) The fish is placed perpendicular to the force lines of the current field [position across]. After anodic curve and the new orientation, fish fall back into the dynamics of the first effect.



### 3. Numerical simulations of electro-fishing systems

Generally, data simulation includes all methods that can reproduce the processes of a system in a theoretical fashion. Numerical simulation is the kind of simulation that uses numerical methods to quantitatively represent the evolution of a physical system. It pays much attention to the physical content of the simulation and emphasizes the goal that, from the numerical results of the simulation, knowledge of background processes and physical understanding of the simulation region can be obtained. In practice, numerical simulation uses the values that can best represent the real environment. In the specific, a numerical simulation was used to set up an electro-fishing system to be used in the open sea environment. Subsequently, a laboratory trial was carried out to obtain real electric field

values in a confined environment (tank) to validate the theoretical simulation values. The tank trials reproduced the open sea conditions at different distances from the electrodes for a given geometry of electrodes and voltage. Electric field simulations were obtained through a bi-dimensional campistic model of stationary conduction in a non homogenous electric system (fish swimming in sea water). This model can calculate the current density distribution and electric field pattern both in the fish and in water for a given electrode geometry. The numerical model is based on a discrete formulation of the electro-magnetic field equations in stationary conduction conditions and is a module of a software named GAME (Geometric Approach for Maxwell Equations) (Specogna & Trevisan, 2005; Specogna & Trevisan, 2006; Codecasa et al., 2007). It requires to discretize the domain of interest (made up of fish in marine water) in a couple of reticules one dual of the other. Subsequently, the physical quantities were univocally associated to the geometric nodes of the two complexes. In this way, the geometric aspects at a discrete level are evidenced and the physical laws are directly translated into an algebraic shape without having to discretize equations to the partial derivatives. Coupling then the approximated equations (Ohm's law in the specific case) in a discrete shape, it is possible to write scattered algebraic systems of great dimensions that once resolved supply the solution of the field problem. Such approach is alternative to the classic methodologies such the finite elements, finite differences or side elements and it can be used to study this physical problem in which the mediums are non homogeneous. The model gives output values for the following parameters: electrode current (A), fish head-tail potential difference (V), mean electric field inside the fish (from the mean of discrete portions constituting the fish, V/m) and in the surrounding water (from the mean of values of discrete portions of water near the fish, V/m), values relative to arbitrary sampling points (electric field  $E$ , V/m and current density A/m<sup>2</sup>). For the Gulf of Trieste (Northern Adriatic Sea), monthly recorded mean values for salinity range from 32.29 to 38.12 psu and for temperature from 6.60 to 24.20°C (Stravisi, 1983). A range of 30 - 40 psu for salinity and of 6 - 25°C for temperature has therefore been considered. On the basis of known relationship between salinity, temperature and conductivity in sea water, at depth 0 m, the considered values of salinity and temperature correspond to the range 2.99 - 5.97 S/m of water conductivity (Stravisi, 1983). Therefore, numerical simulations have been conducted at water conductivity of 3.0, 4.0, 5.0 and 6.0 S/m.

### 3.1 Numerical simulations of fish in an open sea

The transversal section of the electrodes geometry in sea water (Fig.7) is given by a circular electrode ( $D = 1$  m) symmetric to a couple of cathodes far  $A=10$  m from each other and with width 2 m. The anode and cathode are supplied with  $V_1$  and  $V_2$  potentials, respectively. Being the model a stationary conduction bi-dimensional system, its depth is unitary (1 m). The electric field for the described geometry was numerically simulated. The electric field was described in five points ( $d_1, d_2, d_3, d_4, d_5$ ), which are respectively 2.5, 2.7, 3.2, 4.7, 8.4 m far from the centre of anode and cathode. The electric field intensity which is required to achieve an electro-taxis response at a given distance from electrodes and water conductivity were obtained from bibliographic data (threshold values of 10 V/m for electric field (Beaumont et al., 2002); water conductivity of 3.5 S/m (Beaumont et al., 2002, Le Men, 1980); 40  $\mu$ A/mm<sup>2</sup> for current density (Beaumont et al, 2002)). The required power of the system was calculated from those values. In the specific, the power transfer theory (PTT) as defined by Kolz (1989) and validated by Miranda & Dolan (2003) for pulsed direct current was calculated as:

$$P_f = \frac{P_w}{M_{ep}} \quad (5)$$

$$M_{ep} = \frac{\left(1 + \frac{C_f}{C_w}\right)^2}{4 \cdot \frac{C_f}{C_w}} \quad (6)$$

where  $P_w$  is the power applied to water and  $P_f$  is the power transferred to fish ( $\mu\text{W}/\text{cm}^3$ );  $C_f$  and  $C_w$  are the conductivity of fish ( $\mu\text{S}/\text{cm}$ ) and water, respectively.

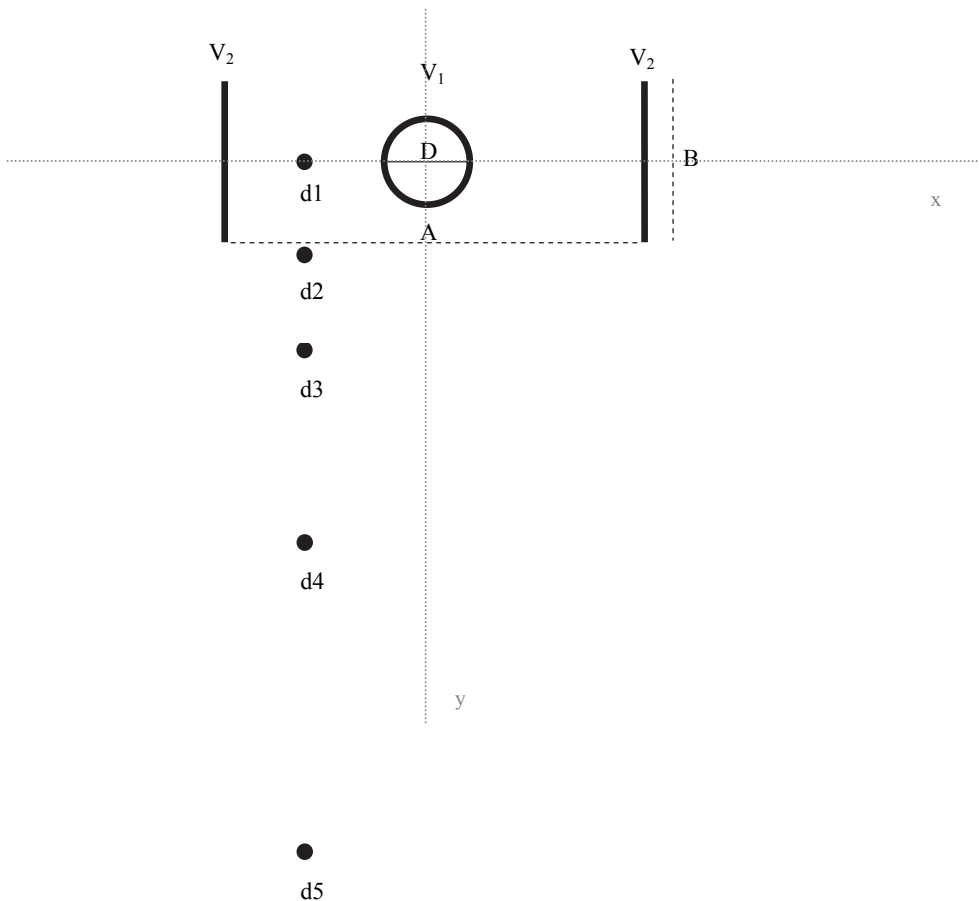


Fig. 7. Transversal section of electrodes in open sea. Dimensions are defined by parameters A, B, D.  $d1-d5$  are the sampling points in which the electric field has been described.

$$P_w = C_w \left( \frac{V}{D} \right)^2 \tag{7}$$

where  $V$  is the voltage at the electrodes and  $D$  the distance (cm) between electrodes. The  $PTT$  has been defined and validated for a uniform electric field, generated by parallel plate electrodes in a tank (Kolz, 1989; Miranda & Dolan, 2003). fish conductivity value was of  $115 \mu\text{S/cm}$  ( $0.0115 \text{ S/m}$ ), as recommended by Miranda and Dolan (2003). Using this value to calculate  $M_{cp}$ , we obtained the smallest error of estimate. Power density was calculated using the peak voltage (Beaumont et al., 2002; Kolz, 1989) obtaining the maximum power density. Miranda and Dolan (2003) reported a minimum threshold value for power transferred to the fish necessary for narcosis, obtained with  $PDC$  at  $60 \text{ Hz}$ , that corresponds to  $P_f=15 \mu\text{W/cm}^3$ . So, considering this power density and assuming  $C_f=115 \mu\text{S/cm}$ , the required  $P_w$  is given by:

$$P_w = P_f \cdot M_{cp} \tag{8}$$

The required voltage is obtained from (3), using  $D=500 \text{ cm}$  and with electrodes described earlier. Simulations have been carried out without fish using four water conductivity values (3,4,5,6 S/m). The same simulations have been repeated in presence of fish: single and in a group (30 fish). Fish had a length of  $10 \text{ cm}$  (single fish and group) and  $30 \text{ cm}$  (single fish), respectively. Single fish were positioned in the five sampling points (d1-d5) and in the case of a group of fish, the barycentre of the group was centred on the sampling point. The effect of water conductivity and fish length on the electric field variables were tested using one way ANOVA and Tukey’s test as a *post-hoc* test. A group of fish of 30 individuals was used. Levene’s test and normality of residuals were carried out to check the ANOVA assumptions. Data analysis was carried out using the statistical package SPSS 14.0. Equipotential surfaces areas were obtained using the software ImageJ and Matlab from the output files of the *G.A.M.E fish* software. Applying the  $PPT$  equations, a constant voltage value of about  $90 \text{ V}$  was obtained. This effect can be explained because  $P_w/C_w$  is a constant and is itself multiplied for a constant ( $D^2$ ). Using several values of water conductivity, voltage values at the electrodes resulted almost constant (Fig. 8).

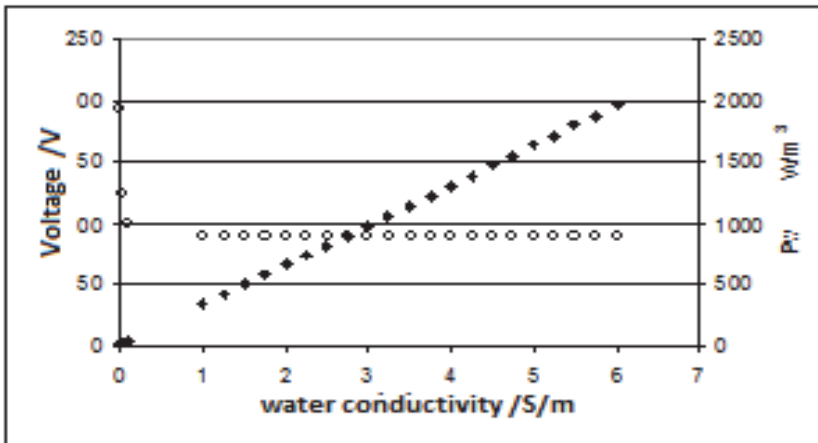


Fig. 8. Voltage (white) and  $P_w$  (black) for increasing water conductivity values

Using 90 V voltage at the electrodes, for a water conductivity ranging between 3 and 6 S/m, the electric field intensity values ranged between 15.14 V/m and 1.48 V/m at the *d1* and *d5* positions. The intensity of the field is function of distance but not of the water conductivity (table 1). On the other hand, electric density at the electrodes increased at higher water

power kW	Tension V	Current at electrodes A	Water conductivity S/m	point	Distance from anode m	V/m	A/m <sup>2</sup>	Mean V
51.75	90	574.99	3	1	2.5	15.14	45.44	37.77
				2	2.7	13.28	39.83	36.55
				3	3.2	9.43	28.3	33.13
				4	4.7	4.44	13.32	27
				5	8.4	1.48	4.43	19.41
69.00	90	766.65	4	1	2.5	15.14	60.58	37.77
				2	2.7	13.28	53.1	36.55
				3	3.2	9.43	37.73	33.13
				4	4.7	4.44	17.76	27
				5	8.4	1.48	5.91	19.41
86.25	90	958.32	5	1	2.5	15.14	75.73	37.77
				2	2.7	13.28	66.38	36.55
				3	3.2	9.43	47.16	33.13
				4	4.7	4.44	22.2	27
				5	8.4	1.48	7.39	19.41
103.50	90	1149.98	6	1	2.5	15.14	90.87	37.77
				2	2.7	13.28	79.65	36.55
				3	3.2	9.43	56.59	33.13
				4	4.7	4.44	26.64	27
				5	8.4	1.48	8.87	19.41

Table 1. Results of numerical simulations of fish and open sea using 90 V at the electrodes (water conductivity between 3.0 and 6.0 S/m in points *d1-d5*)



conductivities. The required power ranged from about 52 kW to 103 kW for 3 - 6 S/m conductivity values (applying 90 V voltage). Assuming a threshold of 10 V/m, the electric field gradient values obtained from the model are suitable to produce electro-taxis until point 3, that is a distance of almost 3 m from the centre of the anode. Fig. 9 shows the distribution of equipotential areas respect to the electrodes. An area of 28.9 m<sup>2</sup> shows values greater than 9.6 V/m.

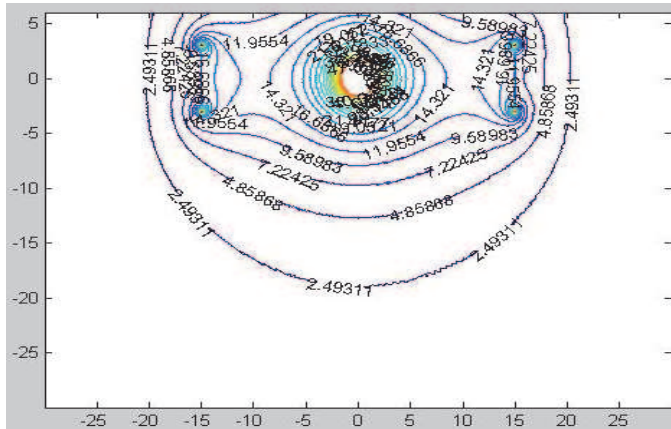


Fig. 9. Electric field distribution and equipotential areas obtained supplying 90 V to the electrodes in open sea

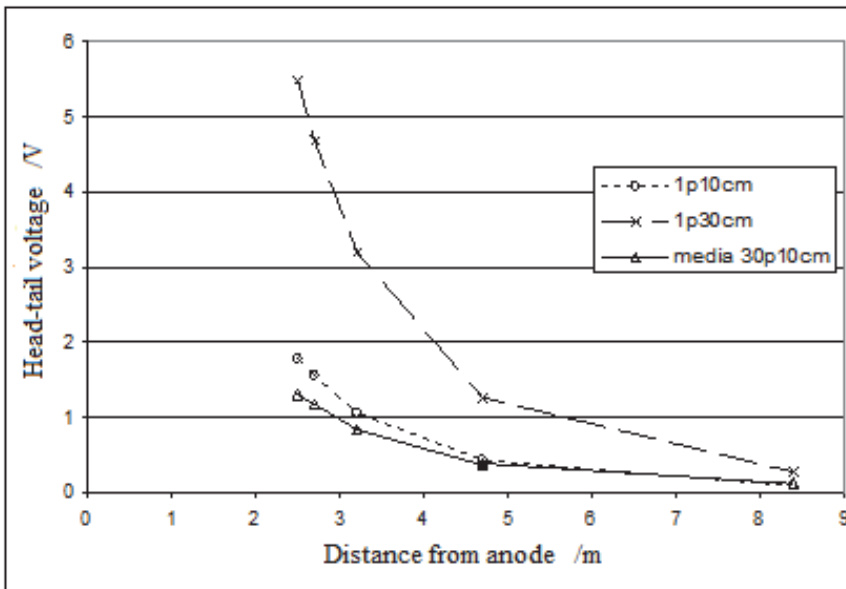


Fig. 10. Head-tail potential difference in fish

Water conductivity had no significant effect on fish parameters: head-tail potential difference, mean, maximum and minimum field inside and outside the fish, for no fish configuration (1 fish 10 cm and 1 fish 30 cm:  $P=1,000$ ;  $F_{3,19}=0,000$ ;  $N=20$ ; 30 fish 10 cm:  $P=1,00$ ;  $F_{3,599}=0,0$ ;  $N=600$ ). The head-tail potential difference and the field outside the fish decreased with distance (Fig. 10 and 11). This is due to the fact that the electric field is not uniform and its effects are reduced closer to the cathode. Table 2 shows the results of the simulations in open sea in presence of fish. While the mean current field external to the fish is similar using different fish configurations, the internal mean field is greater considering fish groups, with values that are more than double respect to single fish. The mean field inside the fish is greater than the field in the water surrounding the fish (table 2). Fish dimensions do not have a significant effect on the mean field inside the fish ( $F_{2,59}=0.24$ ,  $P=0.787$ ;  $N=60$ ). Correlation between mean external and internal field in the fish is positive and significant ( $R=0,81$ ;  $P=0.000$ ;  $N=640$ ). The relationship between the mean field inside fish and in the water is not linear (Fig. 12).

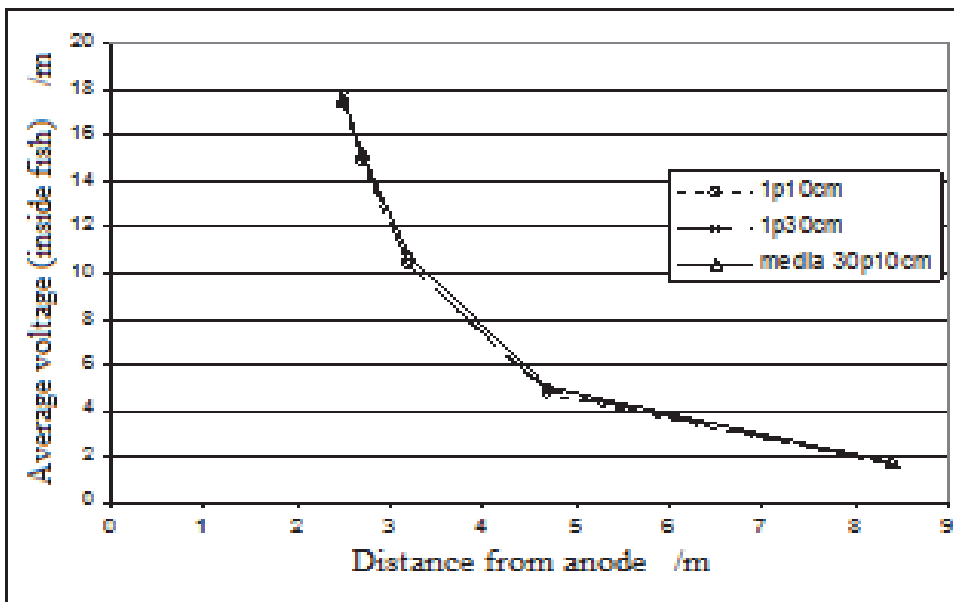


Fig. 11. Mean electric field in the water surrounding the fish

Mean field inside the fish decreased with distance; in the case of single fish (10 and 30 cm) maximum values were obtained 3 m far from the anode (Fig. 12).

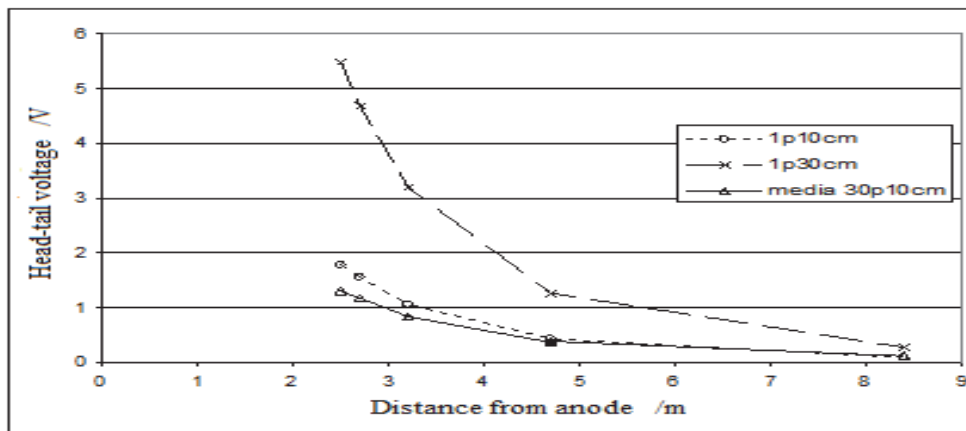


Fig. 12. Mean electric field inside the fish

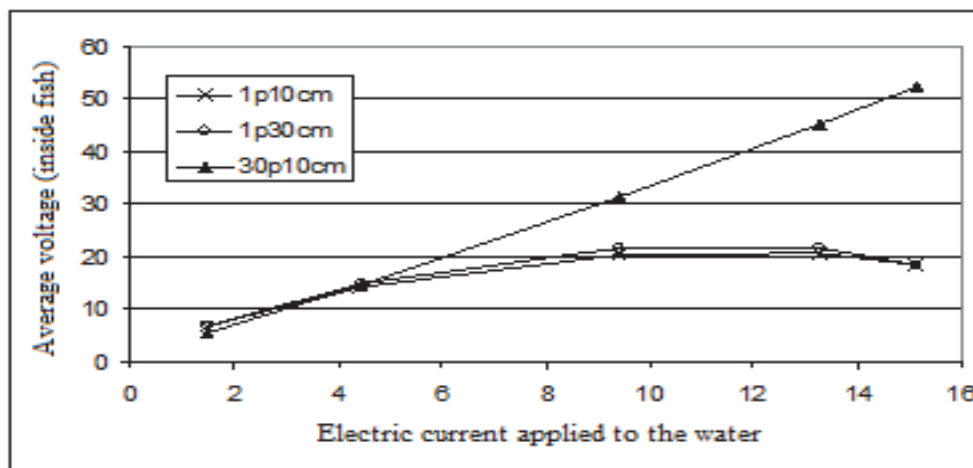


Fig. 13. Mean electric field inside the fish (without fish; water conductivity of 5S/m)

The mean electric field of the water (closed to the fish) increased compared to the same conditions but without fish.

Total n. fish	dim fish (cm)	point	dist from anode (m)	cond water (S/m)	Current at electrodes (A)	power kW	ddp V	$E_{\text{man int}}$ V/m	$E_{\text{max int}}$ V/m	$E_{\text{min int}}$ V/m	$E_{\text{max ext}}$ V/m	$E_{\text{min ext}}$ V/m	$E_{\text{mean ext}}$ V/m
1	10	d1	2.5	3	574.98	51.7	1.78	18.25	19.66	11.43	19.63	13.62	17.39
				6	1149.97	103.5	1.78	18.26	19.68	11.41	19.65	13.61	17.39
		d2	2.7	3	574.98	51.7	1.54	20.43	24.47	14.00	21.65	3.69	14.91
				6	1149.96	103.5	1.54	20.50	24.60	14.10	21.72	3.59	14.92
		d3	3.2	3	574.97	51.7	1.06	20.23	28.22	17.05	19.16	1.31	10.36
				6	1149.94	103.5	1.06	20.35	28.51	17.13	19.25	1.30	10.36
		d4	4.7	3	575.00	51.8	0.42	14.17	18.45	11.80	12.09	0.34	4.75
				6	1150.01	103.5	0.43	14.27	18.62	11.88	12.18	0.34	4.76
		d5	8.4	3	574.99	51.7	0.09	6.63	8.85	5.79	5.17	0.17	1.67
				6	1149.97	103.5	0.09	6.68	8.93	5.83	5.22	0.15	1.68
1	30	d1	2.5	3	574.84	51.7	5.48	18.48	20.15	16.03	20.09	14.96	17.76
				6	1149.68	103.5	5.49	18.49	20.16	16.03	20.10	14.96	17.76
		d2	2.7	3	574.86	51.7	4.67	21.51	23.60	19.24	22.80	4.07	15.15
				6	1149.73	103.5	4.68	21.59	23.72	19.31	22.89	3.98	15.16
		d3	3.2	3	574.90	51.7	3.18	21.52	24.42	19.68	21.76	1.32	10.39
				6	1149.80	103.5	3.18	21.65	24.59	19.78	21.88	1.25	10.39
		d4	4.7	3	574.97	51.7	1.25	14.81	16.96	13.21	13.70	0.34	4.85
				6	1149.94	103.5	1.25	14.92	17.10	13.30	13.79	0.30	4.86
		d5	8.4	3	574.95	51.7	0.26	6.72	7.93	5.92	5.51	0.16	1.67
				6	1149.90	103.5	0.26	6.77	8.00	5.96	5.55	0.15	1.68
30	10	d1	2.5	3	573.57	51.6	1.31	51.92	77.30	40.13	42.66	2.78	17.52
				6	1147.13	103.2	1.31	52.28	78.04	40.36	42.99	2.69	17.57
		d2	2.7	3	573.97	51.7	1.18	45.04	63.02	35.09	37.65	1.95	15.20
				6	1147.92	103.3	1.18	45.36	63.60	35.30	37.93	1.88	15.25
		d3	3.2	3	574.49	51.7	0.82	30.98	46.92	23.72	25.85	1.62	10.80
				6	1148.97	103.4	0.83	31.19	47.37	23.85	26.04	1.56	10.83
		d4	4.7	3	574.88	51.7	0.37	14.35	20.80	10.90	12.01	0.89	5.05
				6	1149.77	103.5	0.37	14.45	20.99	10.96	12.10	0.86	5.06
		d5	8.4	3	574.97	51.7	0.12	5.38	7.87	4.19	4.40	0.23	1.75
				6	1149.93	103.5	0.12	5.42	7.94	4.21	4.44	0.22	1.75

Table 2. Numerical simulations in open sea (water conductivity 3-6 S/m) in presence of fish. For fish in group mean values are shown ( $N=30$ ). The impressed voltage is 90 V.

### 3.2 Numerical simulations of fish in a tank

Numerical simulations in a controlled environment have been carried out considering an experimental tank of 2.5 m x 0.7 m; h max 0.6 m. Plate electrodes are positioned on the short sides of the tank and are supplied with a  $V_1$  and  $V_2$  potential, respectively. The dimensions of the electrodes, which are identical and parallel, are 0.6 m x 0.6 m. This configuration permits to obtain a uniform electric field (Holliman and Reynolds, 2002). The same fish configurations used before were also used in the tank simulations (single fish of 10 cm and 30 cm and group of 30 fish of 10 cm). The orientation of fish in the group is the same as in open sea simulation. Single fish are centred in the tank, parallel to the electric field; for the group, the barycentre corresponds to the centre of the tank (Fig. 14).

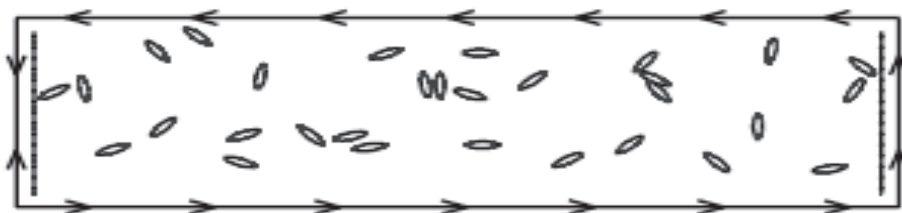


Fig. 14. Lay out of the group of 30 fish in the tank. The two electrodes, supplied with  $V_1$  and  $V_2$  potentials, are parallel and placed at the short sides of the tank.

Tank simulations have been carried out with the same values of V/m obtained from open sea simulations in the five sampling points  $d_1$ - $d_5$ . Only values greater than 5 V/m have been considered, which correspond to about half the minimum field intensity required to achieve electro-taxis in sea fish (Le Men, 1980). Water conductivity values were the same as in the open sea simulations: 3.0, 4.0, 5.0, and 6.0 S/m. In the tank simulations, the voltage used at the electrodes was similar to the values obtained in the open sea simulations in the points  $d_1$ - $d_3$ . Similarly to the open sea simulations, the work carried out for tanks, showed that the mean current field inside the fish was greater than the field in the water surrounding the fish. Furthermore, fish in groups showed values inside the body greater and more than double respect to single fish. Results of simulations of electric fields for fish reared in a tank are presented in Table 3. In these simulations, a specific voltage was applied at the electrodes to produce voltage gradients which were identical to those obtained in simulations of open sea conditions without fish. As for the open sea, the mean current density inside fish was greater compared to the water close to the fish and for groups of fish compared to single fish. Using a voltage similar to the values obtained in open sea in the points  $d_1$ - $d_3$ , the mean electric field inside the fish resulted different between tank and open sea simulations (table 4). In the tank, the electric field inside the fish increased linearly. By contrast, in open sea, the electric field is not uniform and it varies in the three considered sampling points ( $d_1$ - $d_3$ ). This determines a non linear pattern of the mean field inside the fish compared to the field in the water without fish. The difference between tank and open sea values is higher for the mean field inside the fish but negligible for the field in

the water surrounding the fish. Table 5 shows the difference between tank and sea. For single fish, the difference between tank and sea increases for higher field intensities and for fish groups. In each case, electric field mean module inside the fish was always lower in the tank than in open sea. The required power, expressed as the applied voltage at the electrodes is listed in table 5. These values represent the maximum instantaneous required power. Using *PDC* the effective required power, in the time unit, depends on the impulse length and frequency. Therefore, using for example a *PDC* with 60 Hz frequency and 6 msec impulses (duty cycle 36%), the mean required power/sec corresponds to the 36% of the maximum instantaneous power. In practice, in this case, the required power is reduced from 103 kW to less than 40 kW (table 5).

E water V/m	Applied voltage V	Total n. fish	length m	conduc water S/m	current A	ddp V	$E_{mean\ int}$ V/m	$E_{max\ int}$ V/m	$E_{min\ int}$ V/m	$E_{max\_ext}$ V/m	$E_{min\_ext}$ V/m	$E_{mean\_ext}$ V/m		
15.1	36.24	1	0.10	3	19.10	1.76	18.05	19.81	11.27	19.72	12.19	17.11		
				6	38.20	1.76	18.06	19.83	11.25	19.73	12.17	17.11		
			0.29	3	18.89	5.34	18.25	19.70	15.82	19.69	12.99	17.40		
				6	37.79	5.34	18.26	19.72	15.82	19.70	12.99	17.41		
		30	0.10	3	17.59	1.18	44.29	62.19	31.86	38.24	2.40	15.62		
				6	35.15	1.18	44.56	62.72	32.02	38.50	2.32	15.66		
		13.3	31.92	1	0.10	3	16.82	1.55	15.90	17.45	9.93	17.37	10.73	15.07
						6	33.65	1.55	15.90	17.46	9.91	17.38	10.72	15.07
0.29	3				16.64	4.70	16.07	17.35	13.94	17.34	11.44	15.33		
	6				33.28	4.70	16.08	17.36	13.94	17.35	11.44	15.33		
30	0.10			3	15.49	1.04	39.01	54.78	28.06	33.68	2.12	13.76		
				6	30.96	1.04	39.25	55.24	28.20	33.91	2.04	13.79		
9.4	22.56			1	0.10	3	11.89	1.09	11.24	12.33	7.02	12.28	7.59	10.65
						6	23.78	1.09	11.24	12.34	7.01	12.28	7.58	10.65
		0.29	3		11.76	3.32	11.36	12.27	9.85	12.26	8.08	10.83		
			6		23.53	3.33	11.36	12.27	9.85	12.26	8.08	10.84		
		30	0.10	3	10.95	0.74	27.57	38.71	19.84	23.80	1.50	9.72		
				6	21.88	0.74	27.74	39.04	19.93	23.97	1.44	9.75		

Table 3. Numerical simulations of a tank using different fish configurations. E water (first column) is the current field obtained in points *d1-d3* in the open sea simulation without fish

			ddp	E <sub>med int</sub> V/m	E <sub>med est</sub> V/m	% Δ int	% Δ est	
Field in water point d1	15,1V/m	1fish 10cm	tank	1,76	18,06	17,11	0,20	0,28
			sea	1,78	18,26	17,39		
	1fish 30cm	tank	5,34	18,26	17,41	0,23	0,35	
		sea	5,48	18,49	17,76			
	30fish 10cm	tank	1,18	44,51	15,65	7,70	1,91	
		sea	1,31	52,21	17,56			
Field in water point d2	13,3V/m	1fish 10cm	tank	1,55	15,90	15,07	4,59	-0,15
			sea	1,54	20,49	14,92		
	1fish 30cm	tank	4,70	16,08	15,33	5,49	-0,17	
		sea	4,67	21,57	15,16			
	30fish 10cm	tank	1,04	39,20	13,78	6,09	1,46	
		sea	1,18	45,29	15,24			
Field in water point d3	9,4V/m	1fish 10cm	tank	1,09	11,24	10,65	9,08	-0,29
			sea	1,06	20,32	10,36		
	1fish 30cm	tank	3,33	11,36	10,84	10,27	-0,45	
		sea	3,18	21,63	10,39			
	30fish 10cm	tank	0,74	27,71	9,74	3,44	1,08	
		sea	0,83	31,15	10,82			

Table 4. Summary comparison values obtained from open sea and tank simulation, for the same field intensity. Only values for water conductivity of 5 S/m are shown. In the last columns, the difference between sea and tank field (internal and external to the fish) values, in percentage on sea values, are reported

Water conductivity S/m	Peak power kW	Mean power at 36% duty cycle kW
3	51.7	18.6
4	69.0	24.8
5	86.2	31.0
6	103.5	37.3

Table 5. Maximum (peak) and mean power required in an open sea electro-fishing system at different water conductivity values (voltage of 90 V and 36% duty cycle)

#### 4. Field testing of electro-fishing systems

The effectiveness of the electro-fishing is affected by several factors as type of current, voltage applied, electrode shape, water conductivity and temperature, distance of fish, size and fish species. The number of pulses per second (pulse frequency) and the time (pulse width) have different effects on different species of fish. In a PDC field, fish body flexes with each pulse, and returns to normal situation. Flexing and

straightening movements of fish towards the anode, called electro-taxis. Modern equipments allow complete control over the electrofisher output. These methods of synthesizing waveforms makes it possible to produce virtually any waveform, so it can be selected one that is safest for the fish. It allows to create narrow pulses to achieve the same results as wide ones. An electric field in water can be considered to have three separate areas. The outer peripheral area is a weak field to which the fish is indifferent to. The next area, closer to the electrodes, has a stronger electrical field, but not enough to stun the fish. In this area, the involuntary swimming action will occur and the fish will swim towards the anode. The innermost area has the strongest electrical field, and fish within that area are immobilized. When electro-fishing starts, fish are usually hiding up to three meters away, so high power is required to attract them out of hiding. Fish close to the anode receive a very high head-to-tail voltage. Most fish injuries occur within half a meter from the anode. This is called the zone of potential fish injury. We can minimize the injury by reducing the time the electricity is turned on. The duty-cycle is the percent of on-time. It is a product of the pulse width and the pulse frequency. The duty-cycle can be lowered in three ways: by reducing the pulse width, by reducing the pulse frequency, or by using gated bursts, where the power is off for a period between each burst of pulses. Fish close to an anode with a low duty-cycle are far less likely to be injured than with a high duty-cycle. The way in which voltage and current distribute around electrofisher electrodes is complex. Note that the current density and voltage gradient are highest near the electrodes. The dimensions of the electrodes are very important in determining the voltage distribution around electro-fisher electrodes. The cathode dimension is considered to be infinite. Field testing has confirmed that the mean electric field simulated inside the fish is greater than the nominal field in the water, with a significant effect of orientation of the fish towards the electric field. To collect fish by electrical means we must create an electrified zone of sufficient amplitude to stun fish. The responses of fish to electric fields in water are dependent on the field's intensity. Field intensity can be described by any of three interrelated quantities: voltage gradient, current density or power density. Field intensity is greatest next to the electrodes and decreases to barely perceptible levels as distance from the electrodes increases, even in the area directly between anode and cathode when they are sufficiently separated. Electrofishing fields are nearly always heterogeneous, with field intensity highest at the electrode surface and decreasing geometrically from that surface to barely perceptible levels a few meters away. The outer boundary for each response zone represents the minimum in-water field intensity or threshold for that response. The specific values for these thresholds vary with water conductivity and temperature, electric-field waveform and frequency, and the pertinent electrical and physiological characteristics of the fish, which, considered as a whole, define its effective conductivity. Electrofishing tends to be size selective, larger fish being more vulnerable to capture, has long been established (Reynolds 1996). Larger fish are also more likely to be injured by electrofishing than smaller ones of the same species. Sharber et al. (1994) demonstrated a curvilinear relationship between pulse frequency and injury rate; frequencies of 60 Hz and higher were more damaging than lower frequencies. This relationship has been confirmed repeatedly (McMichael 1993, Dalbey et al. 1996, Ainslie et al. 1998). The likelihood of tetany (forced muscle contraction) also increases with pulse frequency, lending credence to the idea that tetany tends to induce injury. Pulse frequency

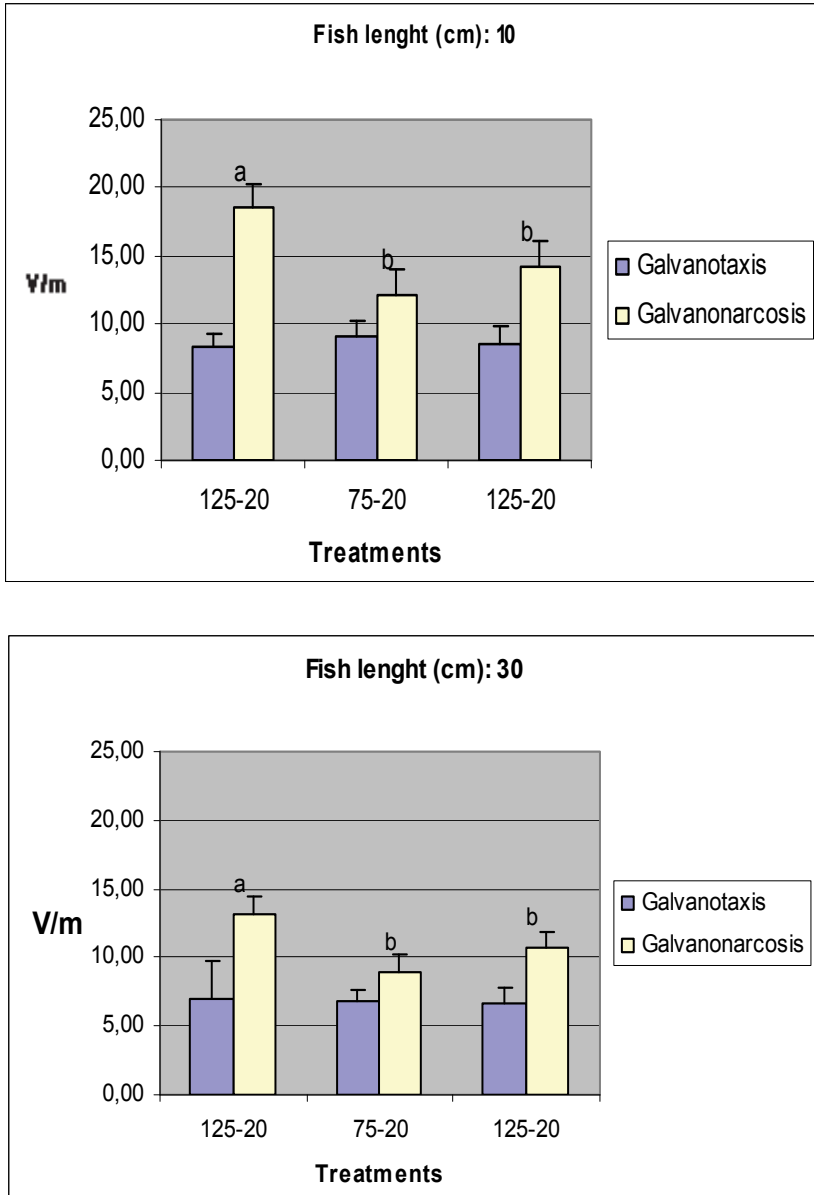


can often be manipulated on manufactured equipment, In general, operators should reduce pulse frequency to the range of 15-30 Hz, while trying to maintain acceptable catch rate, if injury rate has to be significantly reduced. Pulse duration is related to duty cycle. At a given peak voltage or amplitude, changing pulse duration will change the average voltage (area under the waveform curve), meaning that the fish is subjected to more electrical energy. It is possible that longer pulse duration (e.g., 6-8 ms) contributes more to added stress than injury, compared to shorter pulse duration (e.g., 2-4 ms). Experimental results of sea bass after exposure to electro-fishing in laboratory tanks are presented in Figure 15 and 16. These figures illustrate differences in sea bass fish (two sizes: 10 and 30 cm) in terms of electro-taxis and tetanus threshold values after electrical exposure. Tetanus threshold values decreased significantly ( $P < 0.05$ ) for higher frequencies in both sizes while electro-taxis was not influenced by the electrical exposure. It is worth noting that, these values decreased with the fish size. All fish were immobilized during the electrical exposure. However, after 5 minutes, they recovered the opercular movements and swimming ability.

Results of electro-fishing exposure (frequency: 25-75-125 Hz; duty cycle: 5-20-40%) on carcass quality characteristics are reported in Table 6, Fig.15 -16. No effects on carcass quality characteristics were identified for any of the fish exposed to the experimental treatments. Fish were inspected for hemorrhages in the skin, external damage, internal haemorrhaging, blood spotting and damage of the spines. No differences were found after electro-fishing on other carcass quality characteristics (QIM, colour, shear force, rigor mortis).

	<i>Treatments</i>									Rse df 18
	25-5	25-20	25-40	75-5	75-20	75-40	125-5	125-20	125-40	
pH	6.4	6.1	6.4	6.1	6.4	6.2	6.1	6.2	6.3	0.19
Colour:										
L*	34.8	36.4	35.5	36.5	36.1	36.1	35.5	35.8	36.0	2.65
a*	-1.9	-1.6	-1.7	-2.7	-1.5	-1.5	-1.5	-2.5	-1.8	0.16
b*	6.0	7.6	6.3	5.4	5.1	5.1	6.4	6.1	6.5	1.74
Croma	6.3	7.8	7.3	6.7	5.3	5.3	6.6	6	6.7	1.63
Hue angle	107.3	102.2	109.6	107.4	106.9	106.9	105.1	109.8	106.2	15.98
Cooking yield (%)	98.76	98.00	97.96	98.62	99.02	98.93	97.66	97.78	98.10	0.96
Maximum force (N)	9.0	8.5	8.7	9.2	8.3	7.5	8.5	8.9	9.0	4.34
Total amount of work (J)	0.125	0.095	0.122	0.104	0.090	0.088	0.103	0.100	0.101	0.0001

Table 6. Results of electro-fishing exposure on carcass quality characteristics of sea bass



a, b < P<0.05

Fig. 15. 16. Electric-induced electro-taxis and tetanus of sea bass after electro-fishing exposure (frequency:25-75-125 Hz; duty cycle: 20)

## 5. Conclusions

The main problem in sea water electro-fishing is the high electric current demand in the equipment, brought about by the very high ionic concentration of salt water. The solution of this problem is to reduce the current demand as much as possible by using pulsed direct current, the pulses being as small as possible. For example, if pulse duration is reduced to 1 or 2 milliseconds, and pulse frequency is kept below 30 hertz (pulses per second), this will allow the operator to increase the amplitude, or height, of the pulses with the voltage control. Fish generally respond best when the peak voltage is higher and the average voltage (area under each pulse curve) is lower. If the fish don't respond, then average voltage is increased (i.e., pulse frequency and/or pulse duration) is increased until they do respond. It is usually better to increase frequency first, followed by duration. Ultimately, if none of this may work, the power source (generator) is may be inadequate. In this case, one can experiment with smaller electrodes (reduced surface area) to further reduce the demand for current. The numerical simulations of a non homogeneous electric field (fish and water) permit to estimate the current gradient in the open sea and to evaluate the attraction capacity of fish using an electro-fishing device. An area of about 30 m<sup>2</sup> suitable for electro-taxis is estimated for a voltage of 90 V on a circular anode and two linear cathodes which are 5 m far from the centre of the anode. Tank simulations are, instead, carried out in a uniform electric field, generated by two parallel linear electrodes. The convenience of using an uniform field is given by the need of finding threshold values of current field which are independent from the position of the fish in the tank. Numerical simulations allow to compare the electric field in the water and inside fish. The current field inside fish is resulted smaller in a tank compared to the open sea. This means that, in practice, in the open sea situation, the efficacy of an electro-fishing system is stronger, in terms of attraction area. Numerical simulations carried out using a group of 30 fish, both in open sea and in the tank, showed the presence of a "group effect", increasing the electric field intensity in the water around each fish. In this situation, each single fish has a greater current field compared to a fish group.

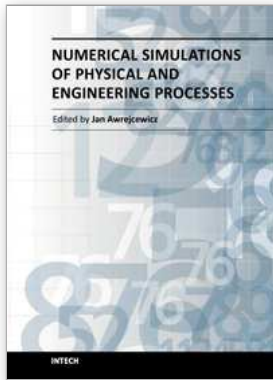
## 6. Acknowledgement

This study was funded by the Region Friuli Venezia Giulia, Innovation Projects 2010.

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## **Numerical Simulations of Physical and Engineering Processes**

Edited by Prof. Jan Awrejcewicz

ISBN 978-953-307-620-1

Hard cover, 594 pages

**Publisher** InTech

**Published online** 26, September, 2011

**Published in print edition** September, 2011

Numerical Simulations of Physical and Engineering Process is an edited book divided into two parts. Part I devoted to Physical Processes contains 14 chapters, whereas Part II titled Engineering Processes has 13 contributions. The book handles the recent research devoted to numerical simulations of physical and engineering systems. It can be treated as a bridge linking various numerical approaches of two closely inter-related branches of science, i.e. physics and engineering. Since the numerical simulations play a key role in both theoretical and application oriented research, professional reference books are highly needed by pure research scientists, applied mathematicians, engineers as well post-graduate students. In other words, it is expected that the book will serve as an effective tool in training the mentioned groups of researchers and beyond.

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