



Numerical simulation of electro-fishing in seawater

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ABSTRACT

We evaluated the feasibility of an electro-fishing system using numerical simulations for laboratory tanks and the open sea. A non-homogeneous bi-dimensional electric-field model for water and fish based on discrete formulation of electro-magnetic field equations was developed using GAME (geometric approach for Maxwell equations) software. Current densities ($\mu\text{A}/\text{cm}^2$) and voltage differences (V/m) were calculated for a fixed shape and spatial geometry of electrodes (one circular anode central to two symmetric linear cathodes 10 m distant from each other). Voltage gradients inside the fish and close to the body (head-tail potential difference and mean, maximum and minimum field modules) were determined. Tank and open sea environments were numerically described for single fish 10 cm or 30 cm long and for groups of 30 fish 10 cm long. In the open sea, a tension of 90 V at the electrodes and a water conductivity of 5 S/m resulted in an area of fish attraction (voltage gradient >10 V/m) of about 30 m². Fish in the open sea and in groups had greater internal voltage differences than did fish in tanks and single fish.

Key words: Electro-fishing, Seawater, Electric field simulation.

RIASSUNTO

SIMULAZIONI NUMERICHE DI UN CAMPO ELETTRICO PER L'ELETTROPESCA IN MARE

L'obiettivo della presente ricerca era la messa a punto di un modello di simulazione di un sistema di pesca elettrica da testare prima in laboratorio e poi in mare aperto.

Le simulazioni del campo elettrico sono state realizzate mediante un modello campistico bi-dimensionale che considera un sistema disomogeneo costituito da pesci che nuotano in acqua marina. Tale modello consente di calcolare l'intensità della corrente agli elettrodi e la differenza di potenziale elettrico (la differenza di potenziale testa-coda, media, minimo e massimo del campo elettrico, V/m) sia nei pesci che nell'acqua marina per una data geometria e distribuzione spaziale degli elettrodi. Le simulazioni del campo elettrico sono state ottenute mediante un software denominato GAME (Geometric Approach for Maxwell Equations).

In mare aperto, una disposizione a triangolo degli elettrodi (anodo circolare e una distanza di 10 m tra i catodi) è risultata più efficace rispetto a quella lineare. Le simulazioni del campo elettrico sono state realizzate per le vasche e l'ambiente marino utilizzando dei pesci singoli (1 pesce di 10 e 30 cm) e gruppi (30 pesci di 10). In mare aperto, applicando agli elettrodi una tensione pari a 90 V e con una conducibilità di

5 S/m, la superficie che risulta idonea all'attrazione dei pesci (differenza di potenziale >10 V/m) è risultata pari a circa 30 m². La differenza di potenziale all'interno del pesce è risultata maggiore in mare aperto rispetto ai valori misurati nelle vasche e nei singoli pesci.

Parole chiave: Pesca elettrica, Acqua marina, Simulazione campo elettrico.

Introduction

Electric fishing is a widely used tool to monitor freshwater species without harmful effects (Bohlin *et al.*, 1989). The principle of electric fishing is based on the introduction of an electric potential gradient in the water between one or more cathodes and one anode. The effects of the potential gradient on fish is a function of the orientation of the fish relative to the electrodes, fish size and species, water conductivity and temperature and intensity and type of current (Van Harreveld, 1938; Kolz, 1993). Continuous current (DC), alternating current (AC) or pulsed current (PDC) are used, depending on environmental conditions (conductivity and temperature) and the fish to be sampled (species and size). The various types of current differ in their effects on fish. Only DC and PDC induce galvanotaxis in fish, i.e., active movement of fish towards the anode. The fish swims towards the anode because of muscle contractions induced by the electric impulses (electrotaxis) until tetanus occurs (Beaumont *et al.*, 2002). Previous authors have suggested that the application of electric fishing to the open sea environment is limited by the high conductivity of seawater, which is much greater than that of animal tissues. Consequently, PDC is preferred for highly conductive water because of a lower power demand than DC (Kurk, 1971; Le Men, 1980; Beaumont *et al.*, 2002). PDC waveforms are characterized by voltage amplitude, frequency (pulse pattern per second), pulse width (period in which current flows during each pulse) and duty cycle (percentage of time in which current flows during each pulse).

The aim of this study was to evaluate the feasibility of electric fishing in the open sea by using numerical simulations. This method could improve the efficacy and selectivity of fishing, which currently involves light attraction and net capture. With electric fishing, fish are attracted using an electric field (electrotaxis) and an aspiration pump is substituted for a net (Blancheteau, 1971; Diner and Le Men, 1971; Kurk, 1971, 1972; Le Men, 1980).

Material and methods

Electric field simulations were conducted using a bi-dimensional, non-homogenous electric system for fish in seawater, which was developed specifically for this purpose. The model calculates the head-tail potential difference of fish and the mean electric field in both fish and water for a given electrode geometry. The model is based on discrete formulation of electro-magnetic field equations under stationary conduction conditions and is part of a more complex software program called GAME (geometric approach for Maxwell equations) (Specogna and Trevisan, 2005; Trevisan and Kettunen, 2006; Codecasa *et al.*, 2007). The domain of interest (fish in seawater) consisted of a couple of reticles and physical quantities univocally associated with the geometric parts of the two complexes. Thus, geometric aspects are evident at a discrete level and physical laws are directly translated into algebraic shapes. By coupling the approximated constituent equations (Ohm's law in this case) in a discrete shape, it is possible to develop scattered algebraic systems of great dimen-

sions, which supply the solution to the field problem when resolved. This approach is an alternative to classic methodologies involving finite elements, finite differences or side elements and is useful for studying physical environments consisting of a non-homogeneous medium.

The output values of the model are: electrode current density (I), $\mu\text{A}/\text{cm}^2$; fish head-tail voltage gradient, V/m ; mean voltage gradient (E) inside the fish (from the mean of discrete portions of the fish, V/m) and in the surrounding water (from the mean of discrete portions of water close to the fish, V/m) and values for arbitrary sam-

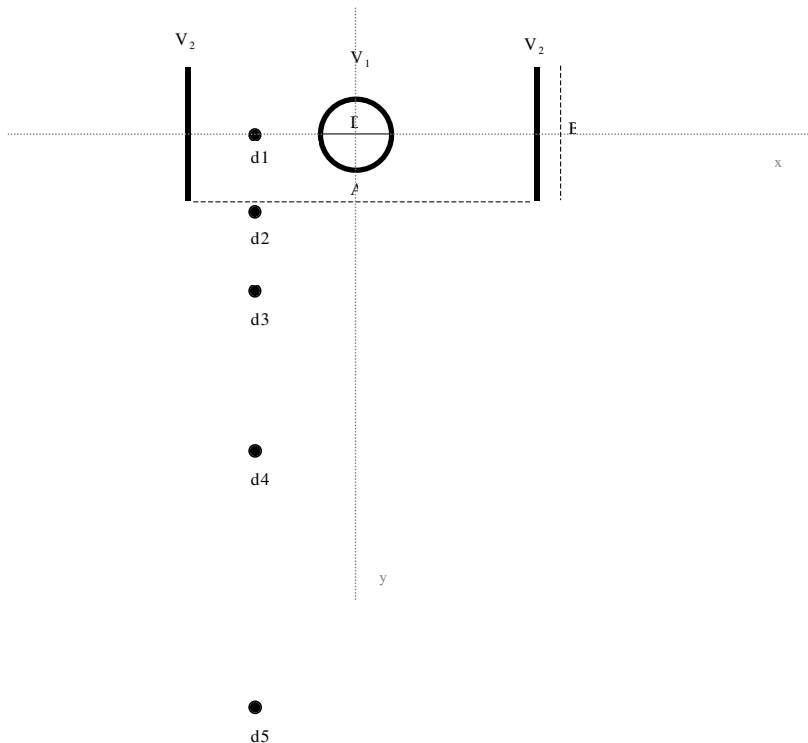
pling points (mean voltage gradient (E), V/m and current density (J), A/m^2).

In the Gulf of Trieste (Northern Adriatic Sea), mean monthly salinity ranges from 32.29 to 38.12 psu and the temperature ranges from 6.60 to 24.20°C (Stravisi, 1983). In this study, we used ranges of 30-40 psu for salinity and 6-25°C for temperature. Numerical simulations were carried out for water conductivities of 3.0, 4.0, 5.0 and 6.0 S/m.

Simulation of open sea conditions

Crosswise sections of the electrodes are depicted in Figure 1. The circular electrode (diameter (D)=1 m) was symmetric to a cou-

Figure 1. Crosswise sections of electrodes in open sea. The depth of the model is 1 m. d1-d5 are the sites of the electric field described in the paper. The figure is out of scale.



ple of cathodes (distance between cathodes (A)=10 m and with (B)=2 m). The anode and the cathodes were assigned potentials V_1 and V_2 , respectively. As the model is a stationary conduction bi-dimensional model, its depth is unitary (1 m). Voltage gradients and current densities of defined systems were numerically simulated. The electric field was described for five points ($d1, d2, d3, d4$ and $d5$) 2.5 m, 2.7 m, 3.2 m, 4.7 m and 8.4 m, respectively, from the midpoint between the anode and the nearest cathode.

Power density (P_w) for pulsed direct current, as defined by Kolz (1989) and validated by Miranda and Dolan (2003), was calculated as follows:

$$P_f = \frac{P_w}{M_{cp}} \tag{1}$$

$$M_{cp} = \frac{\left(1 + \frac{C_f}{C_w}\right)^2}{4 \cdot \frac{C_f}{C_w}} \tag{2}$$

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

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

where P_w is the power applied to water ($\mu\text{W}/\text{cm}^3$), P_f is the power transferred to the fish ($\mu\text{W}/\text{cm}^3$), C_f is the conductivity of fish ($\mu\text{S}/\text{cm}$), C_w is the conductivity of water ($\mu\text{S}/\text{cm}$), V is the voltage at the electrodes (V) and D is the distance between electrodes (cm).

A value of 115 $\mu\text{S}/\text{cm}$ (0.0115 S/m) was adopted for fish conductivity, as recommended by Miranda and Dolan (2003), to minimize the error associated with estimates of M_{cp} . Power density was calculated

from peak voltage (Kolz and Reynolds, 1989; Beaumont *et al.*, 2002). According to Miranda and Dolan (2003), the minimum threshold value necessary to induce tetanus (P_f) is 15 $\mu\text{W}/\text{cm}^3$ at 60 Hz.

Simulations were carried out for conditions involving no fish, single fish 10 cm or 30 cm in length and groups of 30 fish 10 cm in length (Figure 2). Single fish were positioned at five sites ($d1-d5$) and groups of fishes were positioned so that the centre of the group corresponded with the sampling point.

Tank simulations

Simulations were carried out for tanks measuring 2.5 m \times 0.7 m \times 0.6 m. Electrodes were positioned on both short sides of the tank and were supplied with voltage potentials of V_1 and V_2 , respectively. The electrodes were identical (0.6 m \times 0.6 m) and were placed parallel to each other, which induces a uniform electric field (Holliman and Reynolds, 2002). The configurations for fish and voltage gradients used for open sea simulations were also used for tank simulations (Figure 3). We only considered voltage differences greater than 5 V/m, which is about half the minimum field intensity required to achieve electro taxis in saltwater fish (Le Men, 1980).

Figure 2. Distribution of the group of 30 fish in the tank. The two electrodes, supplied with V_1 and V_2 potential, are parallel and placed at the short sides of the tank.

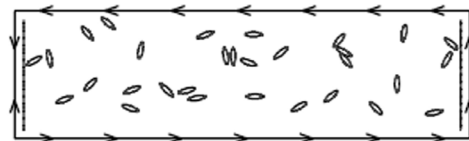
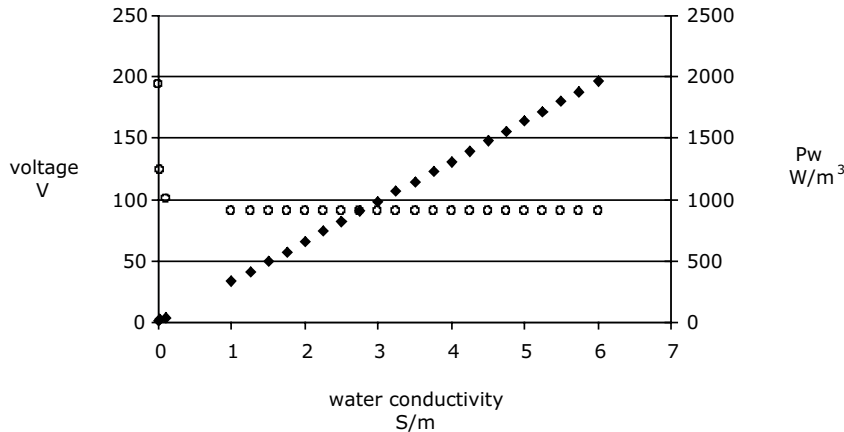


Figure 3. Pattern of the voltage gradient (white) and Pw (black) for increasing values of water conductivity.



Data analysis

Variations in electric field variables were analysed using a one-way ANOVA with Tukey's test as a *post hoc* test. Mean, minimum and maximum voltage gradients (V/m) in fish and water were compared between the open sea and tank systems. ANOVA assumptions were validated using Levene's test and normality of residuals. Data analysis was conducted using SPSS 9.0 (1999) software. Surface analysis of data from the output files of the GAME software was carried out using ImageJ and MATLAB software.

Results and discussion

Estimation of the waterpower (Pw) requirement under open sea conditions

Application of the equations proposed by Kolz (1989) revealed an almost constant voltage requirement of about 90 V when water conductivity was increased (Figure 3).

Simulation of an electric field in the open sea

The results of the numerical simulations are presented in Table 1. Electric field intensity was 15.14–1.48 V/m at a voltage of 90 V

at the electrodes, a water conductivity of 3–6 S/m and distances *d1–d5*. Voltage gradient was a function of distance and was not affected by water conductivity. On the other hand, the current at the electrodes and the current density increased as water conductivity increased. At a voltage gradient threshold value of 10 V/m, fish had to be at maximum 3 m from the centre of the anode for electro taxis to be effective. Figure 4 shows the distribution of 90 V isopotential areas in the open sea. An area of 28.9 m² with values greater than 9.6 V/m is evident.

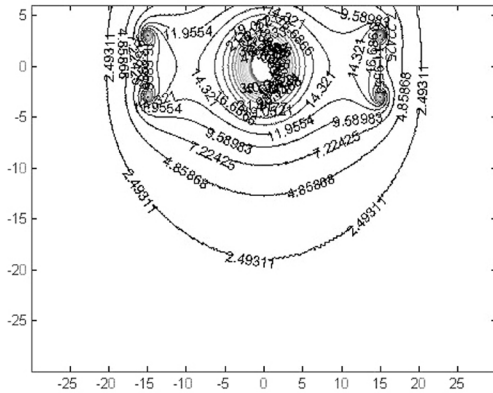
Simulation of the effect of an electric field on fish in the open sea

The results of simulations for single fish 10 cm or 30 cm long and a group of fish 10 cm long in the open sea are shown in Table 2. Whereas mean external current density was similar for these three instances, the mean internal current density for the group of fish was more than double that for single fish. Water conductivity did not significantly affect fish parameters: head–tail voltage gradient, mean, maximum and minimum current density inside and outside the fish

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

Power (kW)	Tension (V)	Current at electrodes (A)	Water conductivity (S/m)	Site	Distance from anode (m)	Voltage gradient (V/m)	Current density (A/m ²)	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

Figure 4. Electric field distribution and iso-potential areas obtained supplying 90 V to the electrodes in the open sea.



(one fish 10 cm or 30 cm long: $F_{3,19} = 0.000$; $df = 19$; $P = 1.000$; 30 fish 10 cm long: $F_{3,599} = 0.000$; $df = 599$; $P = 1.00$). The head-tail voltage gradient and the current density inside and outside the fish decreased with distance (Figures 5, 6 and 7). The maximum current density for single fish and groups of fish was about 3 m from the anode (Figure 7). In all cases, mean current density was greater inside the fish than in the water close to the fish (Table 2). Fish size did not affect mean current density inside the fish ($F_{2,59} = 0.24$, $df = 59$; $P = 0.787$) but groups of fish had higher mean current densities compared with single fish ($F_{2,19} = 4.932$, $df = 19$;

Table 2. Results of the numerical simulations in open sea using single fish and group mean values (n=30).

Number of fish	Length of fish (cm)	Site	Distance from anode (m)	Water conductivity (S/m)	Current at electrodes (A)	Power (kW)	Head /tail gradient (V)	$E_{\text{mean int}}$ (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
		d2	2.7	6	1149.97	103.5	1.78	18.26	19.68	11.41	19.65	13.61	17.39
		d3	3.2	6	1149.96	103.5	1.54	20.43	24.47	14.00	21.65	3.69	14.91
		d4	4.7	3	574.97	51.7	1.54	20.50	24.60	14.10	21.72	3.59	14.92
		d5	8.4	6	1149.94	103.5	1.06	20.23	28.22	17.05	19.16	1.31	10.36
1	30	d1	2.5	3	575.00	51.8	0.42	14.17	18.45	11.80	12.09	0.34	4.75
		d2	2.7	6	1150.01	103.5	0.43	14.27	18.62	11.88	12.18	0.34	4.76
		d3	3.2	3	574.99	51.7	0.09	6.63	8.85	5.79	5.17	0.17	1.67
		d4	4.7	6	1149.97	103.5	0.09	6.68	8.93	5.83	5.22	0.15	1.68
		d5	8.4	3	574.84	51.7	5.48	18.48	20.15	16.03	20.09	14.96	17.76
30	10	d1	2.5	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
		d3	3.2	6	1149.73	103.5	4.68	21.59	23.72	19.31	22.89	3.98	15.16
		d4	4.7	3	574.90	51.7	3.18	21.52	24.42	19.68	21.76	1.32	10.39
		d5	8.4	6	1149.80	103.5	3.18	21.65	24.59	19.78	21.88	1.25	10.39
30	10	d1	2.5	3	574.97	51.7	1.25	14.81	16.96	13.21	13.70	0.34	4.85
		d2	2.7	6	1149.94	103.5	1.25	14.92	17.10	13.30	13.79	0.30	4.86
		d3	3.2	3	574.95	51.7	0.26	6.72	7.93	5.92	5.51	0.16	1.67
		d4	4.7	6	1149.90	103.5	0.26	6.77	8.00	5.96	5.55	0.15	1.68
		d5	8.4	3	573.57	51.6	1.31	51.92	77.30	40.13	42.66	2.78	17.52
30	10	d1	2.5	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
		d3	3.2	6	1147.92	103.3	1.18	45.36	63.60	35.30	37.93	1.88	15.25
		d4	4.7	3	574.49	51.7	0.82	30.98	46.92	23.72	25.85	1.62	10.80
		d5	8.4	6	1148.97	103.4	0.83	31.19	47.37	23.85	26.04	1.56	10.83
30	10	d1	2.5	3	574.88	51.7	0.37	14.35	20.80	10.90	12.01	0.89	5.05
		d2	2.7	6	1149.77	103.5	0.37	14.45	20.99	10.96	12.10	0.86	5.06
		d3	3.2	3	574.97	51.7	0.12	5.38	7.87	4.19	4.40	0.23	1.75
		d4	4.7	6	1149.93	103.5	0.12	5.42	7.94	4.21	4.44	0.22	1.75
		d5	8.4	3	574.97	51.7	0.12	5.38	7.87	4.19	4.40	0.23	1.75

Figure 5. Head-tail voltage gradient in fish.

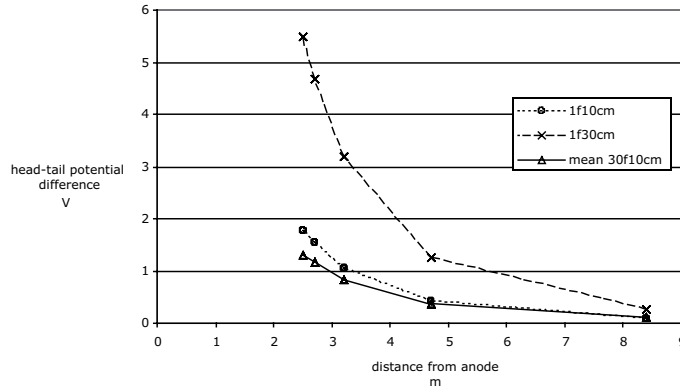


Figure 6. Mean electric field in the water closed to the fish.

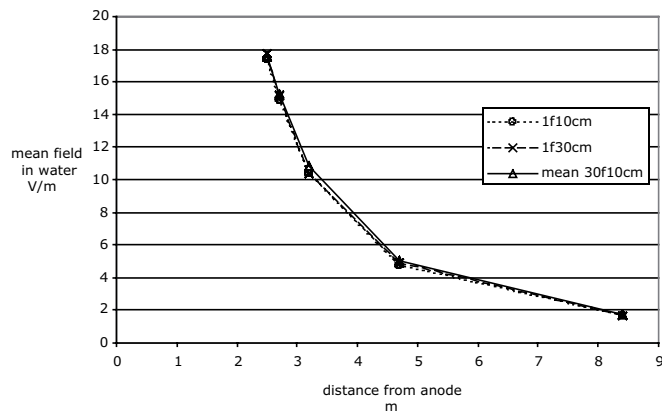
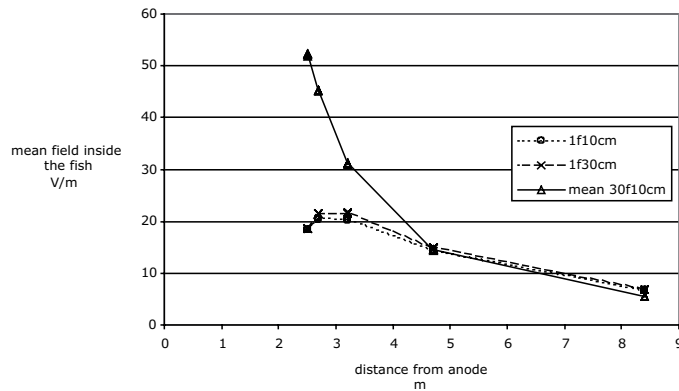


Figure 7. Mean electric field inside the fish.



$P=0.039$). The mean external and internal current densities in the fish were positively correlated ($R=0.81$; $P=0.000$; $N=640$). The relationship between mean current density inside the fish and in water in the absence of fish was non-linear (Figure 8). The current density in the water was lower with fish than without fish.

Simulation of electric current density in fish in a tank

The 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 identical to those at points *d1-d3* in simulations of open sea conditions without fish. As for the open sea, the mean current density inside the tank fish was greater than that in the water close to the fish and internal voltage differences for groups of fish were greater those of single fish.

Comparison between open sea and tank simulations

Table 4 shows differences between simulations for open sea and tank conditions. Only values obtained at 5 S/m conductivity

were considered. In the tank, the voltage gradient inside the fish increased linearly with that of the water because of the uniform field. As the field is not uniform in the open sea, the voltage gradient inside the fish differed between sampling points *d1-d3*. Thus, the mean voltage gradient inside the fish was non-linear. Comparison of tank and open sea simulations revealed a higher mean voltage gradient inside the fish than in the water close to the fish. For single fish, the difference between tank and open sea conditions increased as the water voltage gradient decreased; for groups of fish, the difference between tank and open sea conditions increased as the water voltage gradient increased. The mean electric field inside fish was generally less for fish in the tank than for those in the open sea.

Power required under open sea conditions

The maximum instantaneous power required at the electrodes under open sea conditions is represented in Table 5. In a *PDC* system, the effective mean power required per unit time depends on the impulse length and frequency. For example, in a *PDC* sys-

Figure 8. Comparison between voltage gradient values (E) measured inside a single fish (30 cm) in a tank and in the open sea.

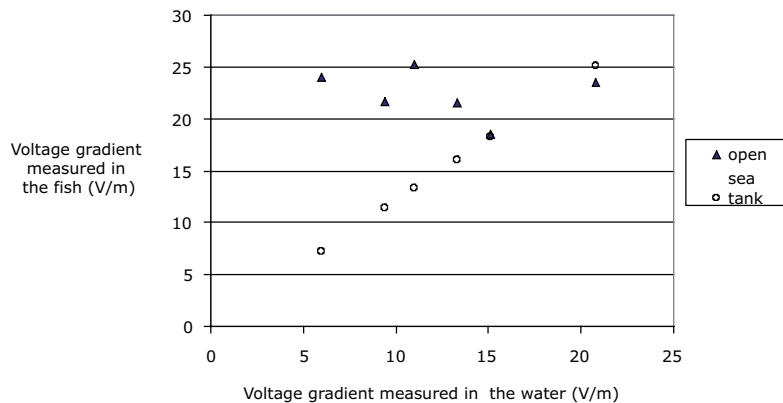


Table 3. Numerical simulations in a tank using different fish configurations. Values of first column (E water) were obtained from the open sea simulations without fish.

E water (V/m)	Applied voltage (V)	Number of fish	Length (m)	Water Conductivity (S/m)	Current (A)	Head /tail gradient ddp (V)	E_{int}^{mean} (V/m)	$E_{max, int}$ (V/m)	$E_{min, int}$ (V/m)	$E_{max, ext}$ (V/m)	$E_{min, ext}$ (V/m)	E_{ext}^{mean} (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
			0.30	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
			0.30	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
			0.30	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 4. Summary of simulations obtained in the open sea and in a tank with a water conductivity of 5 S/m.

			Head/tail gradient ddp	$E_{\text{mean int}}$ (V/m)	$E_{\text{mean ext}}$ (V/m)	E int tank/ E int sea (%)	E ext tank/ E ext sea (%)	
Field in water, Site d1	15.1 V/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, Site d2	13.3 V/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, Site d3	9.4 V/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 5. Maximum and mean power required in open sea, at different water conductivities (voltage of 90 V and 36% of duty cycle).

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

tem with a frequency of 60 Hz, 6 ms impulses and a duty cycle of 36%, the power required per second corresponds to 36% of the maximum instantaneous power.

Conclusions

These numerical simulations enabled us to estimate the voltage gradient of a non-homogeneous electric field in seawater and to evaluate the attractive capability of an electro-fishing device. With voltage of 90 V for a circular anode and two linear cathodes 5 m from the centre of the anode, the area of effective electrotaxis was estimated to be about 30 m². Simulations under tank conditions were carried out using a uniform electric field generated by two parallel linear electrodes. These uniform field simula-

tions were used to determine electric field thresholds that were independent of the position of the fish in the tank. The numerical simulations were used to compare the electric field in the water with that inside fish. The results of the simulations showed that the voltage gradient inside fish was less in tanks than in the open sea. Simulation of a group of 30 fish revealed a group effect under open sea and tank conditions. At a practical level, this effect may be important for improving the attraction efficacy of the system.

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