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Fjords in southern Chile have an extraordinary potential for energy extraction, due to the local amplification of the offshore tidal signal as it enters interior waters. In Chacao Channel, tidal currents may reach peak velocities of about 4 m/s during spring tide, being reduced at neap tide to about 1 m/s. The deterministic nature of the tidal cycle enables the prediction of the energy source, which is a great advantage from the planning perspective. In this article we show the application of the hydrodynamic model Mike21 HD (DHI, 2007) to estimate the energy generation and the physical impacts on the flow due to a tidal current farm in this channel. In our model we adopt the actuator disc theory for hydraulic turbines to obtain the drag coefficient (Polagye, 2009) and the total force on each turbine is estimated using Morison's equation (Morison *et al*, 1950). This force is included in the non-linear shallow water wave equations as a loss of momentum to obtain the extracted energy by an array of Seagen turbines (Fraenkel, 2007).

TIDAL CURRENTS

The power available from a tidal flow P is given by

$$P = 1/2 \rho A_2 u_0^{\,3},$$

where ρ is the fluid density; u_0 is the current speed and A_2 is the cross-sectional area of the rotor used to intercept the flow. This relationship shows how sensitive the power is to velocity and implies that accurate flow estimations are required to predict the energy output from turbines.

TURBINE MODEL

The extracted power on turbines is estimated from the theory by Garret & Cummins (2007) and Polagye (2009), from which a system of seven equations derived from balances of mass, momentum and energy is solved. This system includes the effects of confinement of the free surface and channel walls which together enhance the adjacent free-stream for a water turbine, leading to increased mixing losses (as compared to a wind turbine).

These system of equations contain known values such as the upstream current speed u_0 and depth h_0, and parameters such as the obstruction ratio $\varepsilon = A_2/(bh_0)$, the channel width b, the turbine diameter and the parameter $\alpha = u_3/u_0$, implicitly linked to the turbine performance. The unknown parameters are the speeds (u_2, u_3, u_4, u_5), depths (h_3 y h_5) and the section flux A_4 (Figure 1).

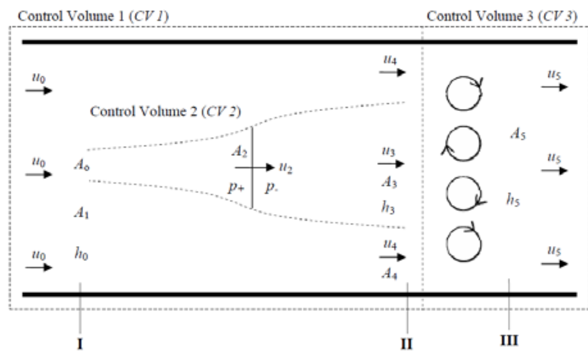

Figure 1: Schematic of actuator disc theory applied to hydrokinetic turbines, top view (Polagye, 2009).

From the system of equations we obtain the drag coefficient.

$$C_d = \left(u_4/u_0\right)^2 - \alpha^2,$$

which is used in the Morison formula (Morison *et al*, 1950) to account for the drag force on each turbine

$$F_T = 1/2\, C_d\, \rho\, A_2\, u_0^2.$$

Using the model outputs of drag force (F_T) and current speed crossing turbine (u_2), we estimate the extracted power P_E. Finally we estimate the output power P_0 as

$$P_o = \eta P_E = \eta F_T u_2,$$

where η is the combined efficiency of the electrical conversion (transmission and generation) obtained from the proposed models by Johnson (2006).

APPLICATION TO CHACAO CHANNEL

We applied this methodology to quantify tidal energy and hydrodynamic impacts caused by a turbine farm in Chacao Channel, Chile. We considered *i)* a non-project scenario and *ii)* a large scale farm of 461 SeaGen, of size comparable to large dams and thermal plants of 550-700 MW of installed power currently operating in Chile.

i) Non-project scenario

To compute the speed of currents we used the hydrodynamic model Mike21 HD (DHI, 2007), a two dimensional model based on the non-linear shallow water wave equations solved on a flexible mesh. The model was calibrated without the effect of turbines, using 4 tide records and 3 speed records obtained from ADCP's during one month. Figure 2 shows a window of the calibration of surface elevation in Carelmapu bay and current speeds in Roca Remolinos, which have a correlation of 96% and 80% respectively. Attractive sites were selected in regions where mean flow velocities exceeded 2 [m/s], with depths between 25 and 50 [m] extending over a wide area to permit the installation of the array of turbines (Fraenkel, 2002). These sites are sufficiently far from navigation routes, close to the shore-based grid connection and do not overlap with other uses, particularly fisheries. We selected 4 locations for further analysis: Carelmapu, Caulín, Roca Remolinos and Bajo Seluian. Figure 3 shows the maximum speeds in the numerical domain and Table 1 includes the speeds and power density at each site.

Parameter	1 Carelmapu	2 Caulín	3 Remolinos	4 Seluian
Mean current [m/s]	1.99	2.56	2.85	2.45
Maximum current [m/s]	4.73	4.90	5.91	5.45
Mean power density [kW/m^2]	7.62	13.99	20.31	13.58
Maximum power density [kW/m^2]	52.8	59.0	103.3	80.9

Table 1: Power parameters in attractive locations.

i) Project scenario

The effect of the turbines was included as a loss in the momentum equations. Figure 4 shows the area covered by the array of 461 Seagens, each one composed by two turbines of 16 [m] in diameter. To estimate the power extracted by the turbines (P_E), we adopted two levels of performance: α = 0.69 for the existing turbines and α = 0.63 for improved devices which will become available in the future (Polagye, 2009). The total energy output and the capacity factor of the farm are presented in Table 2.

Parameter	α = 0.69	α = 0.63
Monthly mean power per unit [MW]	0.264	0.221
Total monthly mean power [MW]	121.8	101.7
Rated power of Seagen [MW] (2 turbines per device)	1.5[(1)]	1.2
Mean Capacity Factor	17.5%	18.4%

Table 1: Power parameters. (1) Deduced with future value of α (Polagye, 2010) and the same rated speed of 2.4 [m/s].

Figure 4 shows the exceedence probability of the output power P_0 at selected locations. Though Carelmapu (1) shows the worst performance, it was selected for detailed analysis as it provides a suitable bathymetry to fit a large-scale farm.

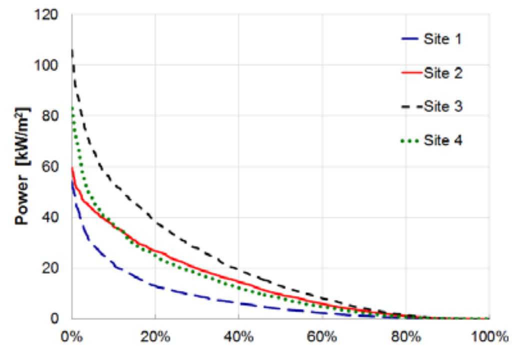

Figure 4: Extracted power at selected locations.

Figure 5 shows the variation of speed as a percentage of the undisturbed flow (non-project scenario). A 16% decrease in speed within the farm and a 17% increase outside the boundaries is observed.

CONCLUSIONS

The proposed farm in Chacao Channel would provide a monthly average between 102 and 122 MW, with a low capacity factor of 18%. The reduction in the flow speed within its boundaries is considered acceptable but the 17% increase in velocity in the northern boundary, raise concerns on the effects on navigation routes near Carelmapu bay (Figure 5). The deficient overall performance of the plant suggests other locations and turbine configurations should be tested, as smaller-scale farms may become attractive in more energetic sites. Tidal currents in Chacao channel are particularly modified by other factors such as winds and surface waves; all effects which should be assessed in the future. The proper assessment should also be complemented with cost-benefit analysis.

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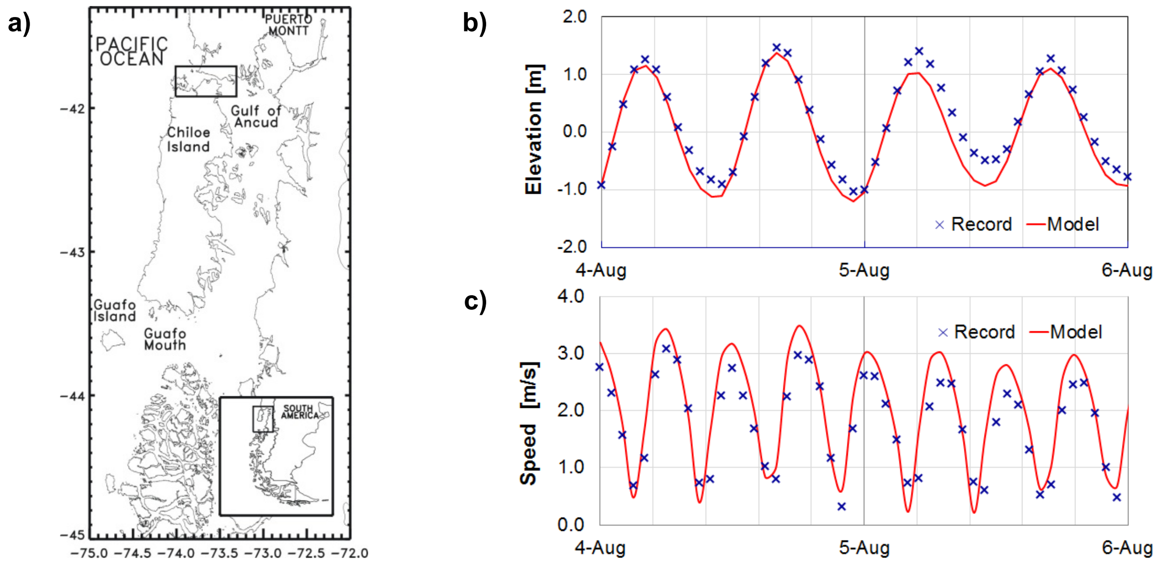

Figure 2: **a)** Canal Chacao and the fjord area in southern Chile. **b)** Calibration of surface elevation in Carelmapu tide gauge (◇ in Figure 3). The semidiurnal tide regime is clearly observed. **c)** Calibration of current speed in Roca Remolinos ADCP current meter (□ in Figure 3).

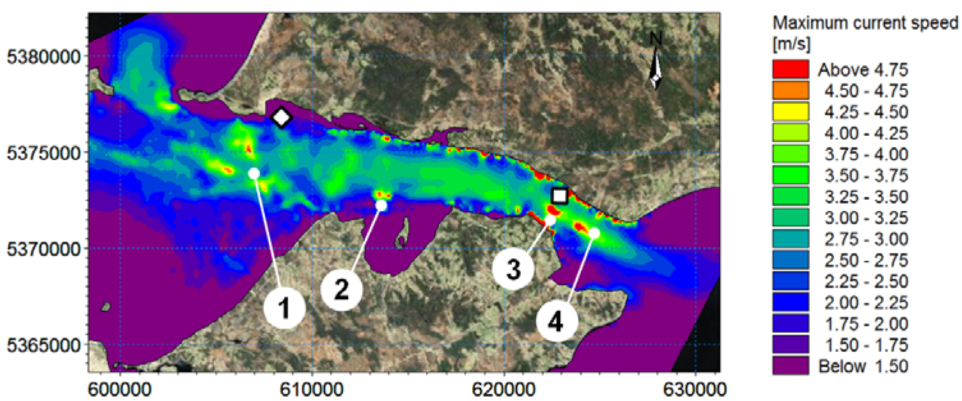

Figure 3: Maximum speeds obtained in the numerical domain. Selected locations are also depicted: Carelmapu (1), Caulín (2), Roca Remolinos (3) and Bajo Seluian (4). The symbol ◇ indicates the location of the tide gauge and □ is the location of the ADCP current meter.

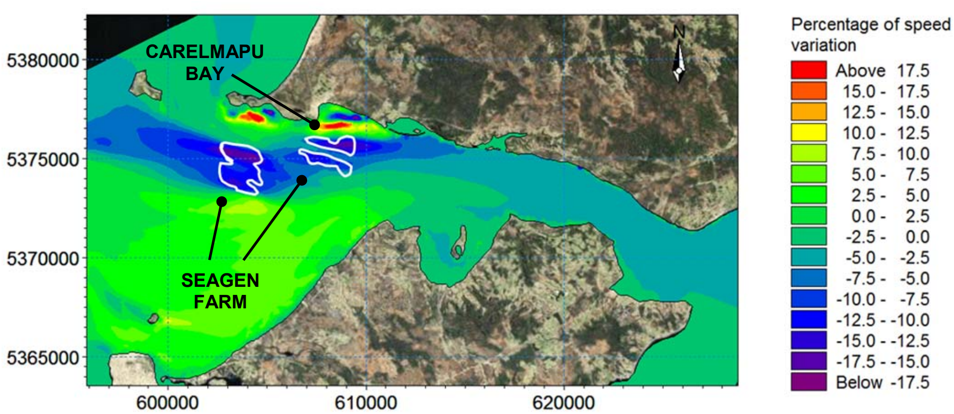

Figure 5: Difference of speed as a percentage of the undisturbed flow (α = 0.63). The turbine farm is located in the area limited by white lines.