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Salinity gradient energy potential in Colombia considering site specific constraints

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ABSTRACT

The theoretical potential of salinity gradient energy in river mouth systems is the maximum amount of energy that can be extracted from the controlled mixing of river water and seawater. It is calculated using the Gibbs free energy of mixing equations considering as inputs the mean rivers' discharge and the long term salinity of the ocean basin. However, this theoretical amount of energy can be far from the reality because both, the river discharge and the salinity of the ocean, have natural variations in different time scales. In this paper we expose the site constraints related with the variability of the salinity gradients that must be considered in order to make a more accurate estimation of the available resources and calculate the so-called site specific potential for the most important and feasible river mouths of Colombia. The results show that in Colombia a mean site specific potential of 15.6 GW can be achieved, mainly in the Magdalena River mouth (97% of total). But more important, the results show that the salinity structure of the studied systems have different responses to variations of the environmental forcing, despite being located in the same ocean basin, and therefore, the energy potential for each river mouth has different variability patterns at different time scales. Decreases of the estimated energy potential up to 69% were found when the site specific potential is calculated instead of the theoretical potential. This prove that more detailed input data than long term discharges and salinities are necessary in order to make accurate estimations of local and regional salinity gradient energy potentials.

1. Introduction

Salinity gradient energy (SGE), the energy that can be obtained from mixing two water masses with different salt concentration (e.g. in river mouth systems where rivers discharge into the ocean), is potentially one of the largest sources of renewable energy on earth [1]. It is a completely renewable energy source, as this mixture is part of the natural water cycle and its exploitation produces no CO_2 emissions or other significant effluents that may interfere with global climate [2]. Several estimations of the global theoretical SGE potential have been carried out (Table 1), all of them on the basis of mean ocean salinity in regional scales and mean rivers' discharges. Few additional down scale estimations have been reported in the literature. Post [3] and Stenzel and Wargen [4] estimated the global potential by continents. Estimations at country level have been done for United States [5], China [6] and Norway (Reported in Ref. [2]); and referring to particular rivers, the theoretical potential for Jordan river (and other tributaries of the Great Salt Lake) [7] and Mississippi river [8] in United States, and for Rhine and Meuse rivers in The Netherlands [3] have been estimated, also based in the mean conditions the rivers and ocean.

The use of mean salinity and river discharges for the estimation of the potentials at global and regional scales is justified, but for more detailed evaluations it is necessary to consider the variability of the salinity gradients in river mouths at different temporal scales, which may significantly influence the SGE potential. In this paper the so-called site specific potential is introduced. It refers to the estimation of the theoretical potential considering the variability of the salinity in the intake points of freshwater and seawater, and it is shown for the most feasible river mouth systems of Colombia. The potential is calculated from hydrodynamic simulations of the salinity structure of the river mouth systems considering the intra-annual and inter-annual variability of this structure.

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Table 1
Estimations of the global theoretical SGE potential.

Authors	Year	Estimated (TW)
Isaacs and Seymour [9]	1973	1.4
Wick and Schmitt [10]	1976	2.6
Aaberg [11]	2004	0.23
Post [3]	2009	1.72
Stenzel and Wargen [4]	2010	3.16

2. Methods

2.1. Selection of river mouths

Colombia is located in the northwest corner of South America and has coastal areas in the Caribbean Sea and the Pacific Ocean (Fig. 1). Numerous rivers flow into both Colombian Seas, but not all the river mouths offer suitable conditions for the generation of SGE. To exploit this energy, fresh and salt water are required in the minimum possible distance in order to avoid large pipeline systems for water transport from the intake areas beyond the brackish water zone to the generation plants. Larger pipes mean higher frictional losses reducing the net power output of the plant [4].

Depending on the salinity structure, the river mouths can be classified as salt wedge, strongly stratified, partially mixed or vertically mixed [12]. Salt wedge and strongly stratified mouths result from large to moderate river discharges and weak to moderate tidal prism (micro-tidal regime), their averaged salinity profiles have a well-developed halocline with weak vertical salinity variations above and below the halocline [12]. These river mouths offer suitable conditions for SGE plants because of the feasibility of shorter transport systems due to the vertical salinity gradients and stable salinity conditions [4]. In Colombia only the Caribbean Sea presents micro-tidal regime [13], therefore, for the estimation of the Colombian potential we did not consider the rivers discharging into the Pacific Ocean.

In Table 2 the rivers accounting for 99% of the total freshwater discharge to the Colombian Caribbean Sea are listed; the locations of the mouths are shown in Fig. 1B. For the analysis of the Colombian potential the Rivers Magdalena, Atrato, Canal del Dique and León (that account for 95% of total discharge) were considered. The mouths of Sinú and Don Diego Rivers are located in protected areas far from industrial or urban zones, so its exploitation lacks environmental and economic reason.

2.2. Theoretical potential estimation

The theoretical potential is the maximum usable energy if ideal efficiency could be achieved. For SGE it is given by the Gibbs free energy of mixing independently of the harnessing technology [4]. The free energy of mixing a concentrated and a diluted solution E_{mix} is [3]:

$$E_{\text{mix}} = (E_{\text{c}} + E_{\text{d}}) - E_{\text{b}} \tag{1}$$

where [E] is the free energy (J), [c] represents the concentrated solution (e.g. seawater), [d] the diluted solution (e.g. river water) and [b] the brackish solution after mixing. For ideal dilute solutions (i.e. no change in the enthalpy, $\Delta H = 0$), it can be shown that the Gibbs free energy of each electrolyte solution (diluted, concentrated or brackish) is given by:

$$E_i = -T_i \Delta S_i \tag{2}$$

with $i = c, d, b$; [T] is the absolute temperature (K). The entropy increase of each solution [ΔS_i] is calculated using the equation:

$$\Delta S_i = -V_i m R [x_i \ln(x_i) + y_i \ln(y_i)] \tag{3}$$

where [V_i] are the volumes (m^3) of the water in the mixing ($V_{\text{b}} = V_{\text{c}} + V_{\text{d}}$), [$m$] is the total number of moles per cubic meter of water solution (mol/m^3), (it can be assumed constant for all solutions), [R] is the universal gas constant (8.314 J/mol•K), and [x] and [y] are the molar fractions of ions (Na^+ and Cl^-) and water respectively [15].

2.3. The site specific potential

From the equations (2) and (3) it can be seen that the energy potential per unit volume depends mainly of the salinity of the diluted and concentrated solutions. So far, theoretical potentials of SGE (Table 1), have been estimated assuming constant salinity gradients in the river mouths systems, however, the environmental forcing influencing the salinity structure in river mouths (river discharge, winds, heat flux parameters, etc.), have a site specific variability at intra-annual (seasonal) and inter-annual scales [16–22]. Hence, those estimations cannot be used for the evaluation of the feasibility of implementation of SGE at local scales. We call site specific potential to the potential calculated using the Gibbs free energy equations considering the variability of the salinity in the intake points of freshwater and seawater at intra-annual and inter-annual time scales.

To consider this variability, the salinity patters of the four river mouths were simulated using the three-dimensional hydrodynamic model ELCOM (Estuary, Lake and Coastal Ocean Model). This model solves the unsteady, viscous Navier–Stokes equations for incompressible flow using the hydrostatic assumption for pressure. Modeled and simulated processes include baroclinic and barotropic responses, rotational effects, tidal forcing, wind stresses, surface thermal forcing, inflows, outflows, and transport of salt, heat and passive scalars [23]. This model has been applied successfully for the prediction of the hydrodynamic behavior of river mouth systems [24–26].

2.4. Selection of simulation cases

To analyze the variability of the salinity gradients, representative one-month scenarios of the intra-annual and inter-annual climatic variability were simulated for each river mouth. The physical phenomenon with highest influence in the intra-annual hydro-climatology of Colombia is the latitudinal migration of the Inter-Tropical Convergence Zone (ITZC). The migration of the ITZC determines the existence of two climatic seasons in the Colombian Caribbean Coast: a rainy season from August to October and a dry season from December to April; the rest of the year is transitional between these two seasons [27,28]. At the inter-annual scale, the hydro-climatology of Colombia is strongly dominated by El Niño/South Oscillation (ENSO). During the warm ENSO phase (El Niño), there is a reduction of the mean flows of the rivers and a rise in the mean air temperature, while during the cold phase (La Niña), the opposite situation occurs, as there is a rise in the mean flows of the rivers and a reduction of the mean air temperature. Both phases generate anomalies in the displacement of the ITZC, which implies anomalies in the wind regimes [20,29].

Six simulation scenarios were selected in order to consider the two seasons (intra-annual variability) and the three ENSO stages (inter-annual variability). Table 3 shows the simulation periods. To consider the warm and cold ENSO stages, scenarios were selected between 1997 and 1999, when strong anomalies in the Multivariate ENSO Index (MEI) occurred, with a shift from El Niño to La Niña stages [30]; February and September were selected as representative of the dry and rainy seasons respectively. Not the same year