Salinity gradient energy harnessing at river mouths

From theoretical to extractable resources

Oscar Alvarez-Silva
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“Yo he preferido hablar de cosas imposibles,
porque de lo posible se sabe demasiado”

Silvio Rodríguez
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Abstract

Salinity gradient energy (SGE) is the clean and renewable energy that can be obtained from controlled mixing of two water masses with different salt concentration. River mouths, where fresh water mixes with saline seawater, are manifest locations for harnessing SGE, since provide the sought salinity gradients and abundant water resources worldwide. Most of the research in SGE has been focused on improving the performance of the energy generation techniques; however, as these techniques reach higher stages of development, more attention must be paid to the challenges that harnessing SGE from natural systems will bring.

This thesis addresses persistent gaps on the research of suitability, available potentials and extractable resources of SGE at river mouths. These topics are approached at global and local scales from three strategies: hydrodynamic modelling of temporal and spatial variability of the salinity structure of river mouths; analysis of databases of variables and resources related with SGE at river mouths; and parameterization of the physical relations among environmental forcings, stratification and SGE potentials.

The results of this research show that only river mouths with mean tidal range lower than 1.2 m are suitable locations to generate SGE; 20% of the mean discharge of rivers may be extracted for SGE generation; harnessing SGE at river mouths is very reliable with average capacity factor of 84%; and 625 TWh/y of SGE are extractable from river mouths worldwide considering site-suitability and environmental constraints.

But beyond these numbers, most important contributions of this thesis are: development of the concept of site-specific potential for more precise assessment of the SGE resources at river mouths; description of the relation between stratification and SGE potential; classification of river mouths according to the suitability for harnessing SGE; mapping of the global distribution of available SGE resources; proposing a methodology to assess extractable SGE resources from particular systems; and overall discussion of physical and environmental constraints for SGE generation at river mouths. Together, these findings constitute a significant progress in the study of opportunities of harnessing SGE at river mouths in the upcoming future.

Keywords: Marine energy; Salinity gradient energy; Extractable energy; River mouths; Sustainable harnessing.
Resumen

La energía de gradiente salino (SGE, por su sigla en inglés) se puede generar a partir de la mezcla controlada de dos masas de agua con diferente concentración de sal. Las desembocaduras de los ríos en el mar son sistemas donde se podría aprovechar este tipo de energía ya que proveen los gradientes de salinidad requeridos y abundantes recursos hidráulicos en todo el mundo. Hasta ahora la mayor parte de la investigación en SGE se ha enfocado en la optimización de las tecnologías de generación de energía. Sin embargo, a medida que las tecnologías alcanzan mayor desarrollo, se debe prestar más atención en los desafíos que involucra el aprovechamiento de SGE en sistemas naturales.

Esta tesis trata sobre los vacíos de investigación relacionados factibilidad técnica, los potenciales disponibles y recursos extraíbles de SGE en desembocaduras. Estos temas son abordados a escala global y local desde tres estrategias: modelación de la estructura de salinidad de desembocaduras; análisis de bases de datos de los forzadores ambientales y recursos hidráulicos relacionados con la SGE en desembocaduras; y parametrización de las relaciones entre los forzadores, la estratificación y los potenciales de SGE.

Los resultados muestran que: sólo en desembocaduras con rango medio de marea menor a 1.2 m es factible generar SGE; 20% del caudal los ríos puede ser utilizado para la generación de SGE; el aprovechamiento de SGE en desembocaduras tiene una alta confiabilidad con 84% de factor de capacidad; y 625 TWh/y de SGE son extraíbles las desembocaduras alrededor del mundo considerando restricciones técnicas y ambientales.

Pero más allá de estas cifras, las contribuciones más importantes de estas tesis son: el desarrollo del concepto de “site-specific potential” para estimar los recursos de SGE en desembocaduras con mayor precisión; la descripción de la relación entre estratificación y potencial de SGE; la clasificación de las desembocaduras de acuerdo con la factibilidad para el aprovechamiento de SGE; los mapas de la distribución global de los recursos; el planteamiento de una metodología para estimar los recursos extraíbles de desembocaduras particulares; y la discusión general de las restricciones físicas y ambientales de la generación de SGE en desembocaduras. En conjunto, estas contribuciones constituyen un avance significativo en el estudio del aprovechamiento de SGE en desembocaduras.

**Palabras claves:** Energías marina; energía de gradiente salino; Energía extraíble; Desembocaduras; Aprovechamiento sostenible.
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# List of Symbols and abbreviations

## Symbols with latin letters

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<th>Definition</th>
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<td>$A$</td>
<td>Tidal range</td>
<td>m</td>
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<tr>
<td>$a$</td>
<td>Fit parameter</td>
<td>-</td>
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<td>$b$</td>
<td>Fit parameter</td>
<td>-</td>
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<td>$CF$</td>
<td>Capacity factor</td>
<td>h/y</td>
<td>Eq. 3.1, 3.3</td>
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<tr>
<td>$E$</td>
<td>Dimensionless energy potential number</td>
<td>-</td>
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<tr>
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<td>Wh/y</td>
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<td>$D$</td>
<td>Diameter</td>
<td>m</td>
<td>Eq. 2.4</td>
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<tr>
<td>$f$</td>
<td>Friction factor</td>
<td>-</td>
<td>Eq. 2.4</td>
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<tr>
<td>$G$</td>
<td>Gibbs free energy of mixing</td>
<td>J/m³</td>
<td>Eq. 2.1</td>
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<tr>
<td>$H$</td>
<td>Energy losses</td>
<td>J/m³</td>
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<tr>
<td>$h$</td>
<td>Depth</td>
<td>m</td>
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<td>$M$</td>
<td>Dimensionless stratification number</td>
<td>-</td>
<td>Eq. 2.8</td>
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<tr>
<td>$m$</td>
<td>Number of moles</td>
<td>mol/m³</td>
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<tr>
<td>$L$</td>
<td>Distance between intake points</td>
<td>m</td>
<td>Eq. 2.1</td>
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<tr>
<td>$P$</td>
<td>Water intake point</td>
<td>-</td>
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</tr>
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<td>$Q$</td>
<td>Discharge (flow or runoff) of rivers</td>
<td>m³/s</td>
<td>Eq. 2.1</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant</td>
<td>J/(mol K)</td>
<td>Eq. 2.3</td>
</tr>
<tr>
<td>$S$</td>
<td>Salinity</td>
<td>g/L</td>
<td>Eq. 2.5</td>
</tr>
<tr>
<td>$SSP$</td>
<td>Site-specific potential</td>
<td>J/m³</td>
<td>Eq. 2.1</td>
</tr>
<tr>
<td>$T$</td>
<td>Absolute temperature</td>
<td>K</td>
<td>Eq. 2.3</td>
</tr>
<tr>
<td>$TP$</td>
<td>Theoretical potential</td>
<td>W</td>
<td>Eq. 1.4, 3.1</td>
</tr>
<tr>
<td>$t$</td>
<td>Time scenario</td>
<td>-</td>
<td>Eq. 2.1</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
<td>m³</td>
<td>Eq. 4.3</td>
</tr>
<tr>
<td>$x$</td>
<td>Longitudinal axes of the river mouths</td>
<td>-</td>
<td>Eq. 2.5</td>
</tr>
<tr>
<td>$x_i$</td>
<td>Molar fraction of Na⁺ and Cl⁻</td>
<td>-</td>
<td>Eq. 2.3</td>
</tr>
<tr>
<td>$y_i$</td>
<td>Molar fraction of water</td>
<td>-</td>
<td>Eq. 2.3</td>
</tr>
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## Symbols with greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Term</th>
<th>Unit IS</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta S$</td>
<td>Entropy change</td>
<td>J/K</td>
<td>Eq. 4.2</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>Kg/m$^3$</td>
<td>Eq. 2.4</td>
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## Subindexes

<table>
<thead>
<tr>
<th>Subindex</th>
<th>Term</th>
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<tbody>
<tr>
<td>$b$</td>
<td>Brackish solution</td>
</tr>
<tr>
<td>$c$</td>
<td>Concentrated solution</td>
</tr>
<tr>
<td>$d$</td>
<td>Diluted solution</td>
</tr>
<tr>
<td>$des$</td>
<td>Refers to design flow</td>
</tr>
<tr>
<td>$eco$</td>
<td>Refers to ecological or environmental flow</td>
</tr>
<tr>
<td>$hd$</td>
<td>High discharge scenario</td>
</tr>
<tr>
<td>$ld$</td>
<td>Low discharge scenario</td>
</tr>
<tr>
<td>$max$</td>
<td>Maximum</td>
</tr>
<tr>
<td>$min$</td>
<td>Minimum</td>
</tr>
<tr>
<td>$op$</td>
<td>Refers to operation flow of the power plant</td>
</tr>
<tr>
<td>$r$</td>
<td>River water (fresh water)</td>
</tr>
<tr>
<td>$res$</td>
<td>Residual river flow after water extraction</td>
</tr>
<tr>
<td>$riv$</td>
<td>Instantaneous flow or discharge of the river</td>
</tr>
<tr>
<td>$s$</td>
<td>Seawater</td>
</tr>
<tr>
<td>$sm$</td>
<td>Suitable river mouths</td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical axes of the river mouths</td>
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Term</th>
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<tbody>
<tr>
<td>CapMix</td>
<td>Capacitive mixing</td>
</tr>
<tr>
<td>PRO</td>
<td>Pressure retarded osmosis</td>
</tr>
<tr>
<td>RED</td>
<td>Reverse electrodialysis</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable energy sources</td>
</tr>
<tr>
<td>REP</td>
<td>Reduced extraction periods</td>
</tr>
<tr>
<td>SGE</td>
<td>Salinity gradient energy</td>
</tr>
<tr>
<td>SSP</td>
<td>Site-specific potential</td>
</tr>
<tr>
<td>SSS</td>
<td>Sea surface salinity</td>
</tr>
<tr>
<td>SST</td>
<td>Sea surface temperature</td>
</tr>
<tr>
<td>ZEP</td>
<td>Zero extraction periods</td>
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</tbody>
</table>
1. Introduction

There is no doubt that the modern increase of atmospheric CO₂ has been driven by human activity, primarily by fossil fuel combustion. This increase represents the clearest and best documented signal of human alteration of the Earth system [1]. Analysis of air bubbles extracted from the Antarctic and Greenland ice caps shows that the concentration of CO₂ in the atmosphere was stable around 280 parts per million (ppm) for thousands of years until near 1800, and has increased exponentially since then [2]. Current atmospheric CO₂ concentration is around 370 ppm, unchanged it will pass 550 ppm this century [3]. Climate models and paleoclimate data indicate that this CO₂ concentration could eventually produce global warming comparable in magnitude but opposite in sign to the global cooling of the last ice age [4]. Even levels of 450 ppm could be enough for thermo-haline circulation shutdown and disintegration of the West Antarctic Ice Sheet [5].

Increased atmospheric concentration of CO₂ represents the biggest human contribution to the greenhouse effect [5], may drive substantial changes in the species composition and dynamics of all terrestrial ecosystems [6], and cause ocean acidification that may in turn produce massive coral bleaching, corrosion of shells and skeletons and changes in the morphology, metabolic state, physical activity and reproduction of many marine organisms [7]. Additionally, the combustion of fossil fuel brings major economic drawbacks such as the depletion of finite resources, increasing prices and dependence on few oil-exporting regions [8]. Each of these concerns provides enough motivation for drastically reducing the consumption of fossil fuels.

Currently the global primary energy supply is 560 EJ/year, of which 86.6% is fossil fuelled [9]; therefore, the most effective way to reduce CO₂ emissions with economic growth and equity is developing revolutionary changes in technologies for energy production, distribution, storage and conversion [10]. New renewable forms of energy are needed without thermal pollution, free of emissions of environmentally harmful substances or greenhouse gasses, and locally available [11,12].

The extractable resources of the most extensively implemented renewable energy sources such as hydropower, wind power and bio-energy are limited compared to the ever growing
demand for energy [11], therefore, efforts should be made to impulse the extended use of other existent RES [13]. A relatively young member of renewable energy sources is the Salinity Gradient Energy (SGE), the energy that can be obtained from the controlled mixing of two waters with different salt concentration.

The concept of harvesting energy from mixing fresh water and saline water was first proposed by Pattle in 1954 [14], and was further developed in the 1970’s [15]-[18]; however the stage of development and cost of the energy conversion technologies at that time, did not allow practical harnessing of SGE. In the last decade this energy source has come back into focus as the need and interest for clean and sustainable energy grows and the development of required technologies have substantially increased while the costs have fallen [8].

Several natural and artificial systems offer water resources with gradients of salinity [19], however, the most evident are the river mouths, where rivers mix with the ocean. The SGE potential from mixing fresh water and seawater at river mouths may theoretically supply the current worldwide electricity consumption; it is in foremost completely clean as this mixture is part of the natural water cycle and the exploitation produces no CO₂ emissions or other significant effluents that may interfere with global climate; additionally, SGE systems at river mouths could be non-periodic, unlike wind, waves or solar power [20].

This thesis discusses the opportunities and limitations of harvesting SGE from fresh water and seawater at natural river mouths. The abundance of these systems worldwide (most of the cases in cities or industrial zones), the huge availability of water resources and the presence of the sought salinity gradients, make of it a promising source of renewable energy for the upcoming future.

1.1 Background

1.1.1 Energy from mixing fresh water and seawater

When rivers run into the ocean, spontaneous mixing of fresh- and sea-water occurs driven by the difference in chemical potential caused by the difference in salinity. If the mixing is controlled, the Gibbs free energy released from this mixing can be converted in electricity [21,22].

The Gibbs energy (\( G \), in Joules) that might theoretically be gained from the mixing of a concentrated solution (\( c \)) (e.g. seawater) and a diluted solution (\( d \)) (e.g. river water), is
given by the Gibbs energy of the solutions before mixing and the Gibbs energy of the brackish solution \( b \) after mixing [9]:

\[
G = (G_c + G_d) - G_b
\]  

(1.1)

where the Gibbs energy of each electrolyte solution \( i = c, d, b \) can be described by:

\[
G_i = -T_i \Delta S_i
\]  

(1.2)

where \( T \) (in kelvin) is the absolute temperature and \( \Delta S \) is the entropy change of each solution:

\[
\Delta S_i = -V_i m_i R [ x_i \ln(x_i) + y_i \ln(y_i) ]
\]  

(1.3)

where \( V \) are the volumes of water (m\(^3\)) involved on the mixing \( V_b = V_c + V_d \), \( m \) is the total number of moles in a cubic meter of solution (mol/m\(^3\)), \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), and \( x \) and \( y \) are the molar fractions of ions (both cations and anions) and water, respectively [22]. Equations 1.2 and 1.3 show that released Gibbs energy depends on the salinity, temperature and volumes of the concentrated and diluted solutions in mixing. The theoretical amount of SGE from mixing 1 m\(^3\) of concentrated- and 1 m\(^3\) of diluted- NaCl -solutions for an extensive range of concentrations in both solutions, at 293 K, is shown in the Figure 1-1.

![Figure 1-1](image_url)

**Figure 1-1.** Theoretical energy potential (MJ) from mixing 1 m\(^3\) of concentrated- and 1 m\(^3\) of diluted -sodium chloride solutions at 293 K.
Concentration of NaCl in seawater is about 0.6 mol/L, and concentration in river fresh water is about 0.01 mol/L. Therefore, the theoretical energy potential from this mixing is ~ 1.8 MJ/m³ of fresh water.

1.1.2 Suitability of harnessing SGE at river mouths

Most of the assessments of available SGE resources at river mouths have been carried out on the basis that all systems can in principle be used for SGE generation [15,17,18,24]; however, in practice only part these systems offer suitable conditions. Constraints might be for exploitation at river mouths with high-value ecosystems where any disturbance of the environment is intolerable [25], or in systems where management rules of the water resources are incompatible with SGE generation [26].

However, the major prerequisite to determine the suitability of river mouths for harnessing SGE is the steady availability of fresh water and seawater in the minimum distance [26,27]. In river mouths with extensive mixing zones, large and costly pipeline systems are required to bring fresh- and sea-water from beyond brackish zones toward the power plants; in this case, the frictional losses in the transport system may considerably reduce the net power output of the plant. Furthermore, the costs of the transport system might make the project economically unfeasible [27].

Depending on the salinity structure, river mouths can be classified as: salt-wedge, strongly stratified, partially mixed or vertically mixed [28]; this classification considers the trade-off between the buoyancy forcing from river discharge and the mixing forcing from tides. Salt-wedge and strongly stratified systems result from high to medium river discharges and low to medium tidal range; the average salinity structure of those systems have a well-developed halocline with small vertical variations above and below the halocline. On the other hand, partially mixed and vertically mixed systems result from low to medium river discharges and high to medium tidal range; the mean salinity profile here either has a weak halocline or is practically uniform from the surface to the bottom [28]. Salt-wedge and strongly stratified river mouths offer more suitable conditions for SGE generation since shorter transport systems are feasible due to the presence of higher and more stable salinity gradients.

Based on this criterion Stenzel and Wargen [27] made a selection of regions from the GIWA division of coastal areas [29] where harnessing SGE might be suitable. The authors selected regions where tidal impact is low and hence salt-wedge river mouths are assumed to be predominant. Polar regions with low tidal impact are included, but stating that these regions may be unsuitable due to the possible ice-coverage during winter season. Regions with mostly fjord-type estuaries, where deep waters are not influenced by tidal
mixing, are also included. More detailed or spatially explicit studies have not been conducted.

### 1.1.3 SGE resources at river mouths

Quantification of available SGE resources at river mouths depends largely on the variables involved on its derivation. These variables may be related only with the magnitude of salinity gradients and water resources, or may also include efficiencies of energy conversion, environmental constraints, cost of installation and generation or even management regulations of the river mouths. The authors coincide in the relevance of three different potentials to quantify the SGE resources [8,27]: theoretical potential, technical potential, and environmental potential.

#### Theoretical potential

For renewable energies the theoretical potential is the physical maximum available energy of a particular source in a given region. For SGE it is equivalent to the total free energy dissipated at river mouths and can be calculated from equations 1.1 – 1.3 independently of the conversion technology [8,27]. The entire discharge of the rivers is used for estimating the theoretical potential, and regional and global assessments have assumed that all river mouths can be used for SGE generation.

Various authors have estimated the global theoretical SGE potential at river mouths; most recent calculations range from 1.7 to 3.2 TW (equivalent to 15102 and 27664 TWh per year, respectively) [24,27], which is the same order of magnitude of the worldwide electricity consumption for 2011 (20407 TWh) [7]. Comparing with other forms of ocean energy, SGE resources are two times smaller than wave’s energy and thermal gradients energy and two times greater than tidal energy and ocean currents energy resources [30].

Besides the global potentials, estimations at country level have been done for The United States of America [14], China [31] and Norway (Reported in Ref. [20]); and referring to particular rivers, the theoretical potential for Jordan river (and other tributaries of the Great Salt Lake) [32] and Mississippi river [33] in The United States of America, and for Rhine and Meuse rivers in The Netherlands [12] have been estimated. All these global to local assessments of the theoretical potential are based on average magnitudes of salinity and temperature of rivers and seas.

#### Technical potential

In practice, only part of the theoretical resources can be recovered with the existing technologies. The technical potential (or conversion efficiency) is the fraction of the
theoretical potential that can be converted in useful energy due to the technical constraints of energy conversion processes. It depends of the harnessing technology since the stage of development and limitations of each are different.

Various technologies have been proposed for harnessing SGE [20,22], but two of them are in latter stages of development: pressure retarded osmosis (PRO) [25] and reverse electrodialysis (RED) [34]. Both technologies are based on semi-permeable membranes that use the chemical potential difference between concentrated and diluted solutions to produce transport of the solvent or solutes across the membranes. In PRO the transport of water towards the concentrated solution chamber results in pressurization of the water in this chamber that can be used to generate electrical power in a turbine. In RED sodium ions permeate in the direction of the cathode and chloride ions permeate in the direction of the anode. Electro-neutrality of the solutions in the anode and cathode compartments is maintained through electrochemical reactions at the electrodes. As result an electrical current can be produced from the anode to the cathode via an external electric circuit [12].

Both technologies are in constant development and the efficiencies, and therefore, the technical potentials that may be reached in real scale plants are still not known with certainty. Yip & Elimelech [35] have shown that the maximum reachable efficiency for PRO systems is 91.1%, considering the intrinsic inefficiencies due to the entropy production during water permeation and the unutilized energy due to the discontinuation of water permeation, but assuming zero losses from the system components. On the other hand, for RED, Post et al. [36] showed from laboratory experiments that efficiencies of more than 80% could be expected, but taking into account only the energy losses for ionic transport.

The global technical potential based on PRO and RED technologies have been estimated in 0.647 TW and 0.983 TW, respectively [27,24], equivalent to 21% and 57% of the theoretical potentials estimated in the same studies. However, different technical constraints were taken into account for both estimations, hindering a comparative analysis.

Regardless of the technology, the main challenges related with the technical potential are on the improvement of the performance of the technology, e.g.: concentration polarization, perm-selectivity, durability and fouling tendency of the membranes [8,37,38]; and not directly linked with the river mouths or other systems where they might be used.
Environmental potential

Both theoretical and technical potentials are calculated based on the assumption that the entire discharge of the rivers might be used for energy generation, however, the extraction of large amounts of fresh water and seawater from river mouths may potentially produce imbalances in: mixing and circulation patterns, water quality, ecosystems, sediment balance, and alternative uses of the river mouths [27,39]; therefore, this assumption is neither practical nor sustainable. Accordingly, an extraction factor or percentage of the discharge of the rivers for SGE purposes that allow a trade-off between energy production and environmental sustainability should be defined.

The environmental potential is the fraction of the theoretical potential that may be exploited considering restrictions for water extraction at river mouths. It is commonly defined in terms of the technical potential rather than in terms of the theoretical potential; however, in practice only the environmental potential may be exploited in sustainable conditions, and therefore, it represents the upper limit for the technical potential and not the way around.

The environmental potential (EP) may be expressed in terms of the extraction factor (EF) and the theoretical potential (TP) as:

\[ EP = EF \times TP \]  

(1.4)

where \( EP \) (in Watts) may be interpreted as the theoretical installed capacity of SGE plants considering environmental constraints.

Although the relevance of the environmental potential for implementing SGE at river mouths is evident, very few studies have addressed this issue. Stenzel and Wargen [27] propose an extraction factor of 10% of the mean discharge of rivers, based on the criterion that the resulting rivers flow after water extraction does not fall below a specified environmental flow to warrant ecological stability. They analyzed the discharge of German rivers to define this extraction factor. Other studies have discussed possible environmental impacts of SGE exploitation at river mouths [25], but a large gap on quantification of those impacts and the subsequent implications for the environmental potentials is still evident in the literature.

1.2 Research gaps and challenges

Most of the research efforts in the field of SGE have been focused on the technical potential i.e., on improving the performance of the energy generation technologies in order
to bring them to an economically competitive stage [25,40,41]. However, as the technologies approach the feasibility of implementation in real scale power plants, more attention must be paid to the challenges that this implementation implies. Several gaps in the analysis of suitability, theoretical potentials and environmental potentials of SGE at river mouths can be identified from the previous background:

About the suitability of river mouths, a relation between tidal forcing and coastal regions where SGE exploitation may be possible has been previously described [27]; however, an explicit quantification of the relation between the magnitude of the forcing controlling the salinity structure of river mouths (including tides) and the suitability of harnessing SGE for particular systems has not been conducted yet.

Meanwhile, the theoretical potential is assessed from average salinities, temperatures and river discharges, although these variables fluctuate temporally and spatially in different scales [42-46]; indeed, the average ocean salinity is 34.9 g/l, but range between 0 g/l and 42 g/l; and the average temperature is 3.5°C, but varying between -2°C to 30°C [47]. Furthermore, the theoretical potential does not consider that in river mouths a brackish zone separates the fresh- and sea-water, and these waters must be transported towards the power plants, reducing the net available energy potential depending on the extension of the brackish zone. Therefore an alternative site-specific potential should be proposed to assess the net available SGE resources at river mouths considering the spatiotemporal dynamics of the salinity structures.

In relation to the environmental potential, it has been discussed that the extraction of fresh- and sea-water and back discharge of brackish water might generate non-negligible environmental impacts on several dynamics of river mouths, depending on the extraction factor [27,39]. However, the relation between extraction factor and environmental impacts is strongly site-specific depending on ecosystems value and vulnerability, and on relative importance of other uses of the systems, among others. Therefore, is not practical to propose a unique extraction factor to calculate the environmental potential for all river mouths; rather, an analysis of the effects of different extraction factors at global and local scales should be carried out to suggest operation ranges and thresholds for sustainable exploitation.

This thesis addresses the previous identified gaps from both global and local scales approaches; therefore, the suitability, theoretical potential and environmental potential are treated repeatedly with different focus throughout the thesis as the spatial scale is reduced and the temporal scale is enlarged.
1.3 Aims

1.3.1 Main aim

Investigate the suitability and potentials of harnessing salinity gradient energy from river mouths at global and local scales considering spatiotemporal variability of environmental forcing and salinity structures.

1.3.2 Specific aims

- Analyze the effect of main environmental forcings influencing the stratification in the suitability of river mouths for harnessing SGE.
- Determine the relation between the spatiotemporal dynamics of salinity structures and the site-specific SGE potentials of river mouths.
- Evaluate the effects of SGE generation in the hydraulic regime and salinity structure of river mouths and how these effects in turn limit the environmental potentials.
- Integrate the previous elements to assess the extractable SGE resources from river mouths at global and local scales.

1.4 Outline

This thesis starts with the definition of site-specific potential and the analysis of suitability of river mouths for harnessing SGE in Chapter 2. The salinity structure of several representative river mouths is studied and the relation between stratification and site-specific potential is identified. From this analysis, a descriptor for general assessment of the site-specific potential is derived and a classification of river mouths according to the suitability for SGE generation is proposed.

This classification of suitability is used to re-estimate the global theoretical SGE potential in Chapter 3. Additionally, the effect of the extraction factor on the global environmental potential is analyzed and the capacity factor of SGE at river mouths is calculated. From these results, the global extractable SGE resources are assessed and their global distribution is mapped.

In Chapter 4 the spatial scale is reduced and the temporal scale is enlarged. The 3D hydrodynamics of suitable river mouths for harnessing SGE in Colombia is modelled for
six seasonal and inter-annual representative climatic scenarios, in order to analyze in more
detail the effect of temporal variability of salinity structures on the available SGE
resources.

Main previous finding are summarized in Chapter 5 in a methodology that can be taken
as a basis to assess the SGE potential of particular river mouths. This methodology is
applied to a river mouth with suitable conditions for harnessing SGE and high site-
specific potential. The design parameters of a SGE plant in this system are assessed; the
technical potential and operation parameters assuming PRO technology are calculated;
and the effects of the plant operation on the hydrology and salinity structure of the river
mouth are analyzed.

References

1. P. Vitousek, H. Mooney, J. Lubchenco, Human domination of Earth’s ecosystems,
2. D.S. Schimel et al., in Climate Change 1994: Radiative forcing of climate change,
3. M.I. Hoffert, K. Caldeira, G. Benford, D. Criswell, Advanced technology paths to
4. M.I. Hoffert, C. Covey, Deriving global climate sensitivity from paleoclimate
5. B.C. O’Neill, M. Oppenheimer, Dangerous Climate Impacts and the Kyoto Protocol,
6. G.W. Koch, H.A Mooney, Carbon dioxide and terrestrial ecosystems, Academic
http://www.ocean-acidification.net/OAdocs/SPM-lorezv2.pdf, accessed: [06/04/12].
8. J.W. Post, J. Veerman, H.V.M. Hamelers, G.J.W. Euverink, S.J. Metz, K. Nymeijer,
et al., Salinity-gradient power: Evaluation of pressure-retarded osmosis and reverse
10. M.I. Hoffert et al., Energy implications of future stabilization of atmospheric CO₂
documentlibrary/82766661EN6.pdf, accessed: [04/04/12].
12. J.W. Post, Blue Energy: electricity production from salinity gradients by reverse
13. O. Edenhofer, K. Seyboth, F. Creutzig, S. Schlömer, On the sustainability of
26. S.E. Skilhagen, J.E. Dugstad, R.J. Aaberg, Osmotic power — power production based on the osmotic pressure difference between waters with varying salt gradients, Desalination. 220 (2008) 476-482.
33. S. Loeb, Large-scale power production by pressure-retarded osmosis, using river water and sea water passing through spiral modules, Desalination. 143 (2002) 115-122.
2. River mouths as source of salinity gradient energy

River mouths are potentially abundant locations for the exploitation of the clean and renewable salinity gradient energy (SGE) as here perpetually fresh water mixes with saline seawater. However, the practical yield of SGE depends on the spatiotemporal variability of the salinity structure. Here we show this relationship for exemplary river mouths. Depending on characteristics of the salinity structure, SGE resources can be reduced to only 0.2% of the theoretical potential. We derive a descriptor for a quick general assessment of the site specific potential and propose a classification of river mouths according to their suitability for SGE generation. It is shown that the tidal range is the most limiting factor for the harnessing of SGE at river mouths. Systems with a tidal range greater than 1.2 m seem not to be suitable locations.

This chapter has been published as:
2.1 Introduction

Salinity gradient energy (SGE) can be gained from the controlled mixing of two solutions with different salt concentrations, taking advantage of the chemical potential difference [1]. Two technologies for harvesting SGE are in latter stages of development: pressure retarded osmosis (PRO) [2] and reverse electrodialysis (RED) [3]. Additionally, capacitive mixing (CapMix) is another emerging technology that has recently developed quickly [4]. River mouths (estuaries and deltas) are manifest locations for SGE exploitation with a global availability of adjacent water resources of different salt concentrations. Most recent assessments of the maximal theoretical power potential of river mouths systems range from 1.724 to 3.158 TW (equivalent to 15102 and 27664 TWh per year, respectively) [5,6], which is on the same order of magnitude as worldwide electricity consumption in 2011 of 20407 TWh [7].

Available global, regional, and local estimates are based on average salinity differences between the fresh water of rivers and the nearby ocean [5,6,8-10]; however, for more realistic estimations of the potential, the site specific spatiotemporal variability of the salinity in river mouths must be taken into account [11–13]. River mouths with extensive salt and fresh water mixing zones must be discarded because larger distances between the intake points of diluted and concentrated solutions imply greater energy losses for the transport of water toward the power plants [6]. Extensive mixing zones occur in weakly stratified to well-mixed river mouths, associated with moderate to strong tidal forcing and weak to moderate river discharge [14]. On the other hand, narrow mixing zones occur in strongly stratified and salt — wedge river mouths, associated with weak to moderate tidal forcing and moderate to large river discharge [14]. The salinity gradients may also change temporally as the mixing zone migrates on seasonal time scales because of the variability of the river discharge [15]. Here we further develop the recently introduced concept of a site specific potential (SSP) [12,13] and show how the theoretical SGE resources in river mouths are reduced to a practical yield depending on the local salinity structure of river mouths and energy losses.

2.2 Methods

The necessity of a site specific potential analysis taking into account environmental forcing at river mouths where SGE projects are proposed was first discussed by Ortega et al. [12] and later defined as the theoretical net energy density (energy per unit volume of the diluted solution) considering the temporal variability of the salinity at the intake locations of diluted and concentrated solutions [13]. As mentioned before, the most important effect of the salinity structure’s behavior at river mouths in terms of SGE harnessing, apart from the variability of the theoretical potential, is the relation between
the extension of the brackish zone and the energy losses. Accordingly, the concept of SSP is extended here to the net energy density considering the temporal variability of the salinity and the energy losses caused by the transport of water toward the power plant. It can be expressed as

\[
SSP(L, t) = G(L, t) - H(L)
\]  

where \( G \) (joules per cubic meter) is the theoretical SGE potential or Gibbs free energy of mixing per unit volume, \( H \) (joules per cubic meter) is the longitudinal energy losses for water transport, \( L \) (meters) is the distance between intake points of diluted and concentrated solutions \( [P_d \text{ and } P_c] \), respectively (Figure 2-1), and \( t \) is the temporal variability of the salinity structure represented by temporal scenarios as explained below. \( G \) is expressed as [8]

\[
G = (G_c + G_d) - G_b
\]

where \( c \) and \( d \) indicate the concentrated and diluted solutions, respectively, and \( b \) indicates the brackish solution after mixing. For ideal dilute solutions, the Gibbs free energy \( (G_i) \) of each electrolyte solution \( (i = c, d, \text{ or } b) \) is given by

\[
G_i = T_i m_i R (x_i ln(x_i) + y_i ln(y_i))
\]

where \( T_i \) (kelvin) is the absolute temperature of each solution, \( m_i \) is the total number of moles per cubic meter, \( R \) is the universal gas constant \((8.314 \ \text{J mol}^{-1} \ \text{K}^{-1})\), and \( x \) and \( y \) are the molar fractions of ions \((\text{Na}^+ \text{ and } \text{Cl}^-)\) and water, respectively. Meanwhile, the energy losses are calculated from the energy conservation equation in pipes [22] as

\[
H = 8 f Q^2 \rho L/(\pi^2 D^5)
\]

for a unitary flow \( Q = 1 \ \text{m}^3/\text{s} \), density \( \rho = 1000 \ \text{kg/m}^3 \) for both solutions, friction factor \( f \) is estimated with the Colebrook – White equation using a roughness height of \( 3.5 \times 10^{-6} \ \text{m} \) (characteristic of the pipes used in desalination plants [23]), and pipe diameter \( D = 0.71 \ \text{m} \ (28 \ \text{in.}) \) optimized to minimize the friction factor.

In river mouths with a mixing zone of fresh water and seawater, the usable salinity difference of the solutions depends on where along the estuary the water intake points \( P_d \) and \( P_c \) can be located (Figure 2-1). According to eq. 2.1, the optimal distance between intake points \( (L) \) is a trade-off between the maximal expected salinity difference and thus the theoretical potential \( G \) and energy losses \( H \). An optimal location for \( L = 0 \) in stratified estuaries is the point at which the time-averaged vertical salinity difference \( \overline{\Delta S_z} \)
(grams per liter) is maximal (Figure 2-1), as at zero longitudinal distance, the average salinity difference between the surface and the bottom is maximal (and hence the theoretical energy potential), with minimal energy losses.

The salinity structure of river mouths can be highly variable on seasonal time scales depending on the river discharge; [15,16] the energy potential of two extreme steady states is considered to represent the temporal variability of the salinity structure: the high- and low-river discharge scenarios \(t_{hd}\) and \(t_{ld}\) respectively) (usually associated with dry and wet seasons [17–19] or winter and summer [20,21]). Then the time-averaged vertical salinity difference is defined as

\[
\overline{\Delta S_z}(x) = \left(\Delta S_z(x, t_{hd}) + \Delta S_z(x, t_{ld})\right)/2
\]

(2.5)

The SSP here is estimated for seven exemplary river mouths for which the longitudinal salinity structures for high- and low- river discharge scenarios averaged over a neap-spring tidal cycle are known: Chesapeake (United States) [17], Huangmaohai (China) [24], Magdalena (Colombia) [13], Pamlico (United States) [25], Pearl (China) [18,19], Sepik (Papua New Guinea) [26], and Weser (Germany). Temperature structures were used where there are known and average values otherwise. The relation between SSP and the theoretical SGE potential may be quantified with a dimensionless energy potential number

\[
E = \overline{SSP_{\text{max}}}/G_{\text{max}}
\]

(2.6)

in which \(\overline{SSP_{\text{max}}}\) (joules per cubic meter) is the average of the maximal SSP for high- and low-river discharge scenarios:
\[ \overline{SSP_{\text{max}}} = \frac{(SSP_{\text{max}}(t_{hd}) + SSP_{\text{max}}(t_{ld}))}{2} \] (2.7)

where \( SSP_{\text{max}}(t) = \max\{SSP(L,t)\}_t \) and \( G_{\text{max}} \) (2.55 MJ/m³) is the maximal theoretical energy density of the ocean, calculated assuming the salinity of the concentrated solution is the maximum for the ocean (0.72 mol/L = 42 g/L) [27], the salinity of the diluted solution is the average for the rivers (0.0022 mol/L = 0.13 g/L) [28], the volumetric ratio is 1:1, and the temperature of both solutions is the maximum of the ocean (40 °C) [27].

The spatiotemporal variability of SSP depends on the characteristics of the stratification of river mouths, and this in turn depends on the physical forcings acting on the river mouths. Estuarine stratification characteristics commonly are quantified by descriptors like the Richardson number [32], the Canter – Cremers number [32], the Ippe – Harleman number [33], or the stratification level number [33], among others. As these require detailed information about river mouth density structure and turbulent quantities, we here introduce a simple dimensionless stratification number for which input data for several other systems are accessible, to relate the dimensionless energy potential \( E \) with the degree of stratification:

\[ M = \frac{\bar{Q}\bar{h}}{(\Delta \bar{Q}\bar{A})} \] (2.8)

where \( \bar{Q} \) (cubic meters per second) is the mean discharge of the river, \( \bar{h} \) (meters) is the mean depth of the river mouth, \( \Delta \bar{Q} \) (cubic meters per second) is the difference between the monthly maximal discharge (\( \bar{Q}_{\text{max}} \)) and the monthly minimal discharge (\( \bar{Q}_{\text{min}} \)), and \( \bar{A} \) (meters) is the mean tidal range. Greater values in the numerator imply stronger stratification, while greater values in the denominator imply higher variability of the mixing zone (with greater \( \Delta \bar{Q} \)) or weaker stratification (with greater \( \bar{A} \)).

### 2.3 Results and discussion

The site specific potential of all the studied river mouth systems is higher during the high-river discharge scenario, and different ranges of variability are observed (Figure 2-2): the Magdalena system features the highest SSP values (up to 2.06 MJ/m³) with low temporal variability, while the Weser system presents the lower SSP (up to 0.01 MJ/m³) also with low variability. The other systems range between these extremes. A higher variability of SSP is related to the higher variability of the salinity structure. This is the case for the Chesapeake, Huangmaohai, and Pamlico systems that change from stratified or partially mixed conditions during high river discharge to partially mixed or well-mixed conditions during low river discharge [17,24,25]. In terms of the spatial behavior of SSP, all systems show maximal values for \( L < 2000 \) m. When comparing SSP with theoretical SGE
potential using the energy potential number $E$, we found reductions in the practical yield of up to 99.8% (Table 2-1).

![Graph showing site specific potential as a function of distance between intake points.](image)

Figure 2-2. Site specific potential as a function of the distance between the intake points of diluted and concentrated solutions for high-river discharge (---) and low-river discharge (•••) conditions. Negative values are not plotted. $G_{\text{max}}$ is shown.

<table>
<thead>
<tr>
<th>River mouth</th>
<th>$\bar{Q}$ (m$^3$/s)</th>
<th>$\bar{Q}_{\text{max}}$ (m$^3$/s)</th>
<th>$\bar{Q}_{\text{min}}$ (m$^3$/s)</th>
<th>$\bar{A}$ (m)</th>
<th>$\bar{h}$ (m)</th>
<th>$M$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magdalena</td>
<td>7200</td>
<td>10287</td>
<td>4068</td>
<td>0.5</td>
<td>11</td>
<td>25.5</td>
<td>0.797</td>
</tr>
<tr>
<td>Sepik</td>
<td>3700</td>
<td>4700</td>
<td>2600</td>
<td>0.8</td>
<td>6</td>
<td>13.2</td>
<td>0.376</td>
</tr>
<tr>
<td>Chesapeake</td>
<td>2262</td>
<td>4162</td>
<td>922.6</td>
<td>0.46</td>
<td>6.8</td>
<td>10.3</td>
<td>0.098</td>
</tr>
<tr>
<td>Huangmaohai</td>
<td>1500</td>
<td>2800</td>
<td>650</td>
<td>1.34</td>
<td>10</td>
<td>5.2</td>
<td>0.038</td>
</tr>
<tr>
<td>Pamlico</td>
<td>90</td>
<td>400</td>
<td>20</td>
<td>0.15</td>
<td>3</td>
<td>4.7</td>
<td>0.035</td>
</tr>
<tr>
<td>Pearl</td>
<td>5150</td>
<td>10500</td>
<td>1800</td>
<td>1</td>
<td>7</td>
<td>4.1</td>
<td>0.018</td>
</tr>
<tr>
<td>Weser</td>
<td>323</td>
<td>527</td>
<td>172</td>
<td>3.6</td>
<td>9</td>
<td>2.3</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 2-1. Mean, maximal, and minimal monthly discharges, mean tidal ranges, mean depths, stratification numbers ($M$), and energy numbers ($E$) for the studied river mouths

$^a$Main references for data: 18 – 20, 25, 26, and 29 – 31.

Observed stronger and more stable salinity stratification in the river mouths (i.e., higher $M$ values) results in a higher SSP (Table 2-1). For the seven river mouth systems, a significant dependency between $M$ and $E$ can be identified. The sigmoid function:

$$E = E_{\text{max}}/(1 + e^{-a(M - b)})$$  \hspace{1cm} (2.9)
describes the relation between both dimensionless numbers with a coefficient of correlation of 0.96, where $a = 0.22$ and $b = 17.7$ are fit parameters representing the growing rate and the inflection point of the function, respectively (Figure 2-3). The sake of this formulation lies in the easy application to various river mouth systems for an assessment of SSP, yet the confidence interval of the function is broad, because of the limited number of reference studies describing the spatiotemporal variability of the salinity structure of river mouths with the required resolution (averaged structure over a spring-neap tidal cycle under high- and low-river flow conditions). As more studies are conducted and included in the fit, the confidence interval will be narrower.

![Graph](image)

**Figure 2-3.** Sigmoid function relating stratification number and energy potential number in river mouths. Black dots represent the seven exemplary studied systems used for the fitting. Dashed lines show the confidence interval with a significance level of 95%. Gray dots are estimations for 20 river mouths. Green, orange, and red areas show the intervals of suitable, partially suitable, and unsuitable systems for SGE exploitation, respectively. The standard error [50] of the fit is 0.060.

The function was used to predict the average maximal SSP for 20 systems worldwide, where relevant parameters could be obtained from the literature (Table 2-2). These river mouth systems may be classified according to the technical suitability of SGE exploitation into “suitable systems” ($M > 12$), like Magdalena and Sepik, that feature high SSPs during high- and low-flow conditions; “partially suitable systems” ($4.5 < M < 12$), like Chesapeake, Pamlico, and Huangmaohai, where there is high to medium SSP under high-
flow conditions but low potential under low-flow conditions; and “unsuitable systems” \((M < 4.5)\), like Pearl and Weser, where there is low SSP under both flow conditions.

**Table 2-2. Stratification numbers and average maximal SSPs for 20 representative river mouths**

<table>
<thead>
<tr>
<th>river mouth</th>
<th>(Q) (m³/s)</th>
<th>(\bar{Q}_{\text{max}}) (m³/s)</th>
<th>(\bar{Q}_{\text{min}}) (m³/s)</th>
<th>(\bar{A}) (m)</th>
<th>(\bar{h}) (m)</th>
<th>(M)</th>
<th>(\overline{SSP_{\text{max}}}) (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congo</td>
<td>42000</td>
<td>75500</td>
<td>24700</td>
<td>1.1</td>
<td>400</td>
<td>301</td>
<td>2.55</td>
</tr>
<tr>
<td>La Plata</td>
<td>22000</td>
<td>22496</td>
<td>20714</td>
<td>1</td>
<td>20</td>
<td>247</td>
<td>2.55</td>
</tr>
<tr>
<td>Nile</td>
<td>1254</td>
<td>1741</td>
<td>1034</td>
<td>0.2</td>
<td>6.5</td>
<td>57.7</td>
<td>2.55</td>
</tr>
<tr>
<td>Rhone</td>
<td>1693</td>
<td>2050</td>
<td>1150</td>
<td>0.4</td>
<td>9</td>
<td>42.3</td>
<td>2.54</td>
</tr>
<tr>
<td>Ebro</td>
<td>424</td>
<td>662</td>
<td>135</td>
<td>0.2</td>
<td>5</td>
<td>25.1</td>
<td>2.12</td>
</tr>
<tr>
<td>Niger</td>
<td>1044</td>
<td>1424</td>
<td>750</td>
<td>0.8</td>
<td>7.7</td>
<td>14.9</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**Partially Suitable systems \((4.5 < M < 12)\)**

<table>
<thead>
<tr>
<th>river mouth</th>
<th>(Q) (m³/s)</th>
<th>(\bar{Q}_{\text{max}}) (m³/s)</th>
<th>(\bar{Q}_{\text{min}}) (m³/s)</th>
<th>(\bar{A}) (m)</th>
<th>(\bar{h}) (m)</th>
<th>(M)</th>
<th>(\overline{SSP_{\text{max}}}) (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mississippi</td>
<td>15360</td>
<td>57900</td>
<td>2830</td>
<td>0.3</td>
<td>12</td>
<td>11.2</td>
<td>0.49</td>
</tr>
<tr>
<td>Brazos</td>
<td>222</td>
<td>331</td>
<td>82</td>
<td>0.5</td>
<td>6</td>
<td>10.7</td>
<td>0.45</td>
</tr>
<tr>
<td>Po</td>
<td>1511</td>
<td>2102</td>
<td>936</td>
<td>0.5</td>
<td>4</td>
<td>10.4</td>
<td>0.43</td>
</tr>
<tr>
<td>Strymon</td>
<td>60</td>
<td>122</td>
<td>18</td>
<td>0.3</td>
<td>3</td>
<td>6.2</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Unsuitable systems \((M < 4.5)\)**

<table>
<thead>
<tr>
<th>river mouth</th>
<th>(Q) (m³/s)</th>
<th>(\bar{Q}_{\text{max}}) (m³/s)</th>
<th>(\bar{Q}_{\text{min}}) (m³/s)</th>
<th>(\bar{A}) (m)</th>
<th>(\bar{h}) (m)</th>
<th>(M)</th>
<th>(\overline{SSP_{\text{max}}}) (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delaware</td>
<td>341</td>
<td>629</td>
<td>178</td>
<td>1.7</td>
<td>7</td>
<td>3.1</td>
<td>0.10</td>
</tr>
<tr>
<td>Ems</td>
<td>86</td>
<td>154</td>
<td>34</td>
<td>2.3</td>
<td>9</td>
<td>2.8</td>
<td>0.10</td>
</tr>
<tr>
<td>Cape Fear</td>
<td>161</td>
<td>730</td>
<td>15</td>
<td>1.3</td>
<td>11.6</td>
<td>2.0</td>
<td>0.08</td>
</tr>
<tr>
<td>Gironde est.</td>
<td>1000</td>
<td>1800</td>
<td>400</td>
<td>3.3</td>
<td>8</td>
<td>1.7</td>
<td>0.08</td>
</tr>
<tr>
<td>Tweed</td>
<td>78</td>
<td>140</td>
<td>30</td>
<td>3.3</td>
<td>7</td>
<td>1.5</td>
<td>0.07</td>
</tr>
<tr>
<td>Godavari</td>
<td>3038</td>
<td>11568</td>
<td>87</td>
<td>1.5</td>
<td>7</td>
<td>1.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Seine</td>
<td>450</td>
<td>650</td>
<td>200</td>
<td>5</td>
<td>6</td>
<td>1.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Selangor</td>
<td>53</td>
<td>122</td>
<td>23</td>
<td>2.7</td>
<td>6</td>
<td>1.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Mekong</td>
<td>14904</td>
<td>40000</td>
<td>2000</td>
<td>2.9</td>
<td>6.3</td>
<td>0.8</td>
<td>0.06</td>
</tr>
<tr>
<td>Tamar</td>
<td>34</td>
<td>290</td>
<td>3</td>
<td>3.5</td>
<td>24</td>
<td>0.8</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Main references for data: 21 and 34 – 49.*

Interestingly, the river discharge is not the main influencing factor of SGE suitability; rivers with mean discharge from tens of cubic meters per second to tens of thousands can be found in all categories. The same applies for the average depth, where similar values can be found for all categories. However, all river mouths that are classified as suitable and partially suitable are micro-tidal systems, with mean tidal ranges \(\bar{A} \leq 1.1\) m. Other river mouths like those of the Delaware, Cape Fear, and Godavari rivers, with mean tidal range \(\bar{A} \geq 1.3\) m, are classified as unsuitable systems. We thus conclude that the tide is the most restrictive driving force in terms of suitability of SGE exploitation in river mouths and that a threshold in the mean tidal range around 1.2 m may be suggested as a
limit beyond which harnessing this renewable energy may not be suitable. It has to be mentioned that deep river mouth systems with less impact of tidal mixing, e.g., fjords, are an exception to this conclusion because here tidal mixing may not influence the stratification [33].

An additional factor possibly restricting the technical feasibility of particular river mouths is the water quality, as pretreatment of the water (to reduce fouling and clogging) must be considered. Energy consumption of RED plants has been estimated to be 50 KJ/m³, [5] approximately half of which corresponds to water pretreatment [51]. Alternative less energy expensive antifouling techniques related to flow switching or disturbance in the energy generation devices have shown significant reductions in the level of fouling on experimental scales [52]. However, this parameter still needs to be investigated further for large scale SGE power plants.

For potential future implementation of large scale SGE plants in river mouths, the environmental impact must be taken into account. The extraction of large amounts of fresh water and seawater may potentially produce imbalances in the mixing and circulation patterns, water quality, ecological systems, sediment balance, and other uses of the river mouths [6,12,49]. Therefore, detailed studies of the environmental flows and maximal water extraction factors for SGE purposes should be conducted to determine the exploitation thresholds that ensure ecosystem functions and the balance between energy production and environmental sustainability. Recently, it has been stated that up to 20% of the mean river discharge may still be considered tolerable [12]; however, more research along this line is necessary. SGE generation does not produce harmful effluents; nevertheless, attention must be paid to how the effluent brackish water is discharged into the environment (see Chapter 5). Additionally, if chemicals are used for cleaning or antifouling purposes, precautions are required to prevent leakage to the environment. River mouths with valuable ecosystems or river mouths very sensitive to salinity changes might not be suitable for the harnessing of SGE from environmental and social points of view. Additional environmental considerations are discussed in ref 10.

Approximately 30% of the coastal zones of the world have a mean tidal range of >1.2 m, [53] including coasts with relevant river mouths like the Gulf of Alaska, Hudson Bay, North Brazil, United Kingdom, Bay of Biscay, North Sea, Norwegian Sea, Mozambique Channel, east Bay of Bengal, Yellow Sea, Timor Sea, and New Zealand, among others. Thus, the estimations of global and regional potential conducted under the assumption that all river mouths can be exploited for SGE generation should be re-evaluated; it will lead to smaller but more accurate quantification of the global amount of this valuable energy source.
References


3. Extractable SGE resources at global scale

Salinity gradient energy (SGE) is a clean and renewable energy source that can be harnessed from the controlled mixing of two water masses of different salt concentration. Various natural and artificial systems offer conditions under which SGE could be harnessed, however river mouth are the only locations that play a role in a global assessment. The theoretical SGE potential at river mouths has been previously estimated to be 15102 TWh/a, equivalent to 74% of the worldwide electricity consumption; however, the practical extractable SGE from these systems depends on several physical and environmental constraints that are discussed here. The suitability, sustainability and reliability of the exploitation of this renewable energy are considered based on quantified descriptors. It is shown that realistically 625 TWh/a of SGE are globally extractable from river mouths, equivalent to the 3% of the global electricity consumption. Although this is much smaller than the theoretical potential, is still a significant amount of clean energy higher than the electricity consumption of most of the countries.

This chapter has been submitted as:
3.1 Introduction

Society needs renewable and locally available energy sources, which may be found at river mouths, where settlement is dense and renewable energy potential is always present in the form of salt concentration gradients. When two waters of different salt concentration mix, a release of free energy occurs driven by the difference in chemical potential between them [1,2]. If the mixing is controlled, the chemical potential can be used to generate electricity [3]. This power source is called salinity gradient energy (SGE); it is in principle completely clean and produces no CO₂ or any other harmful threat to the environment [4]. River mouths, where fresh water from terrestrial drainage mixes with saline seawater, are the most manifest locations for harnessing SGE since here the sought salinity gradients are available and many of them are located near to cities and industrial communities [5,6].

Early studies previously estimated the global theoretical SGE power potential at river mouths between 1.4 and 2.6 TW [6-8], more recently it has been estimated to 1.724 TW (15102 TWh/a) [9], equivalent to 74% of the electricity consumption in 2011 [10]. This theoretical potential (TP) quantifies the maximum SGE resources existing at river mouths. It is calculated from average salinities and temperatures of fresh- and sea-water (either in a spatially implicit [6-8] or explicit [9] manner), under the assumption that all river mouths and the entire fresh water discharge of rivers are usable for energy generation. However, the share of the global theoretical potential that is practically extractable depends on several constraints limiting the achieved yield. These constraints are related to the suitability, sustainability and reliability of the energy exploitation at river mouths:

First, not all river mouths offer suitable conditions for harnessing SGE, in particular locations with weak salinity gradient, poor water quality, or where resources are not permanently accessible are unsuitable locations for SGE generation [5, 11-13], and must not be considered in a balance of extractable potential.

Besides, it is not sustainable to exploit the entire discharge of rivers for energy generation; evidently, such intervention would generate a strong imbalance of the ecological, hydrodynamic and sedimentological processes at river mouths. Therefore, only a fraction of the mean discharge of rivers (extraction factor, EF) may be used for SGE purposes to ensure environmental stability of the systems [11, 14].

Additionally, the energy generation cannot be constant in time due to the natural variability of fresh water discharge and the variability of salinity and temperature gradients between seawater and fresh water. This variability affects the reliability of
harnessing SGE that is quantified by a capacity factor $(CF)$ [14], which compares the annual energy yield of a power plant with the ideal energy generation in the same period of time.

Considering the previous constraints, the practical extractable global SGE potential from river mouths $(EE)$ may be expressed taking into account the theoretical potential, the extraction factor, and the capacity factor, as:

$$EE = \sum_{k=1}^{sm} (TP_k \ast EF_k \ast CF_k)$$

(3.1)

In which only suitable river mouths $(sm)$ are considered.

The next section derives each term of Equation 3.1, assesses the global theoretical potential from river mouths where the variability of rivers’ discharge is known (required for estimating the extraction and capacity factors), and shows the criteria to determine the suitability of river mouths. Later the extractable global SGE potential and its worldwide distribution are presented and discussed.

### 3.2 Materials and methods

#### 3.2.1 Theoretical potential

The theoretical SGE potential (in W) from mixing seawater and fresh water in a river mouth $k$ is given by:

$$TP_k = (G_{sk} + G_{rk}) - G_{bk}$$

(3.2)

in which $G_s$, $G_r$ and $G_b$ are the Gibbs free energy of mixing of seawater $(s)$, fresh water $(r)$ and brackish water after mixing $(b)$, respectively. For ideal dilute solutions, the free energy of each of electrolyte $i = s, r, b$ is given by:

$$G_i = T_i Q_i m_i R [x_i \ln(x_i) + y_i \ln(y_i)]$$

(3.3)

in which $T$ (in K) is the absolute temperature, $Q$ (in m$^3$/s) is the water flow rate ($Q_b = Q_s + Q_r$), $m$ (in mol/m$^3$) is the total moles per unit volume, $R$ is the universal gas constant (8.314 J mol$^{-1}$ K$^{-1}$), and $x$ and $y$ are the molar fractions of ions (Na$^+$ and Cl$^-$) and water respectively [15].

The global theoretical potential based on the individual potential of all river mouths worldwide K in data sums up to:
\[ TP = \sum_{k=1}^{K} TP_k \]  

The theoretical potential of each river mouth depends on the fresh water discharge, the ratio between fresh- and sea-water volumes in mixing (volume ratio), and the salinity and temperature of both waters (equation 3.3).

For a global assessment here the fresh water runoff dataset by Dai and Trenberth [16] was used; it includes monthly stream flow at farthest downstream station for the world’s 921 largest ocean-reaching rivers (Figure 3-2), accounting for 73% of the global total runoff; average records length is 35.5 a, and 49.1 a for world’s top 200 rivers [17]. Long term mean discharge was used for calculating the theoretical potential (however, for the assessment of the extraction and capacity more detailed monthly rivers’ discharge data is needed). A volume ratio of 1:1 \((Q_r = Q_t)\) was assumed.

Monthly sea surface salinity (SSS) for the year 2012 in the vicinity of river mouths from Aquarius [18] and SMOS [19] satellite missions were used to define the salinity of seawater. These databases differ in the spatial domain at the edge to the continents, where river mouths are located (Figure 3-2A); we used SSS from the closest point to each river mouth where data is available independently of the database, and SMOS where data from both sources is available at same distance (Figure 3-2B). The salinity of rivers’ fresh water was assumed constant and equal to the global mean \((0.0022 \text{ mol/l} = 0.13 \text{ PSU})\) [20].

The temperature of both waters was assumed to be equal to the sea surface temperature (SST) near to the mouths \((T_r = T_s = T_b)\). Monthly climatology of SST for years 1971 – 2000 from NOAA\_OL\_SST\_V2 was used [21,22].

As monthly salinities and temperatures, but mean rivers’ discharge were used for calculations, the global theoretical potential as a function of the seasonal variability of salinity and temperature of the ocean was obtained.

### 3.2.2 Suitable river mouths

For several reasons a river mouth may be unsuitable for SGE generation, but the most important physical condition is the steepness and stability of the salinity gradient [5,11]. Only in river mouths where strong stratification induces high and steady salinity differences over a short distance the theoretical SGE potential is higher than the energy required to deliver the fresh- and sea-water towards the power plants [13].
Figure 3-1. Data and its spatial distribution in relation to the location of river mouths. A) coverage areas of Aquarius and SMOS sea surface salinity data; B) location of sea surface salinity and sea surface temperature data for each river mouth; C) coastal regions with mean tidal range ≤ 1.2 m (FES2012 model. http://www.aviso.altimetry.fr/).
The stratification of river mouths depends on the buoyancy forcing by fresh water discharge and the mixing by tides; strongly stratified river mouths conditions result from high to medium river discharges and low to medium tidal ranges [23]. It has been shown that the tidal range sufficiently characterize mixing as the most limiting factor for harnessing SGE at river mouths and that only river mouths located in regions where the mean tidal range is smaller than 1.2 m (Figure 3-2C) are considered to be suitable locations [13].

River mouths in polar regions are neither considered as suitable locations since the ice coverage, mainly during winter time [24], constrains the water extraction for SGE generation [11]. Additionally satellite SSS data in those regions is scarce.

Hence here the global theoretical potential at suitable river mouths $TP_{sm}$ was calculated as the sum of the theoretical potential of river mouths located in non-polar regions with mean tidal range lower than 1.2 m.

### 3.2.3 Design flow and extraction factor

Most rivers feature seasonal changes of the natural flow $Q_{riv}$, which are a major constraint for SGE power plants design. These seasonal changes determine the assessment of the fresh water design flow $Q_{des}$, i.e. the amount of river discharge that can be extracted from the river system for energy generation. The assessment of the design flow must consider the environmental impact of water extraction and also technical and economic issues [14]. Environmental considerations limit the amount of water that can be extracted to reduce the impact on the flora, fauna, nutrients, circulation, sediment transport and alternative uses of fresh water resources. Technical and economic considerations aim to avoid a high variability of the energy generation rate in order to optimize plant capacity. As a general concept for a global assessment, the residual river flow after extraction $Q_{res} = Q_{riv} - Q_{des}$ must not fall below a critical value known as the “environmental flow condition” $Q_{eco}$[14], which refers to the fraction of the discharge that must remain to satisfy the environmental demands of the rivers [25].

A high number of methodologies have been described for assessing the environmental flow. The most common being the Tennant method due to the considerable collection of data involved in its development and the simplicity of its application [26]. According to this method fair ecological conditions are preserved at an environmental flow of 30% of the mean rivers’ discharge and the minimum recommended is 10%. More robust habitat simulation and holistic methods may be applied in local scales when the attributes of the riverine ecosystems are known in detail [25], however, at global scales, the application of a
non-resource intensive method is more feasible. Here following the Tennant method, the environmental flow was defined as 30% of the mean rivers’ discharge.

The threshold condition $Q_{ecs} \geq Q_{eco}$ may lead to periods where extraction of fresh water must be reduced (reduced extraction period, REP), or even stopped completely (zero extraction period, ZEP) for times when the natural flow is lower than the defined environmental flow (Figure 3-2). A higher design flow leads to longer periods of reduced extraction. Extensive periods at critical environmental flow conditions shall be avoided. Also for economic reasons, periods of reduced fresh water supply to the power plants shall be minimized.

![Figure 3-2.](image)

Figure 3-2. Effects of fresh water extraction for SGE generation on the annual hydrologic regime of an exemplary river. Grey line: natural river discharge before fresh water extraction $Q_{riv}$. Black line: residual river discharge after fresh water extraction $Q_{eco}$. Mean river discharge ($\bar{Q}$) and Environmental flow ($Q_{eco}$), are shown. Green belts show the periods when the power plant operates at full load ($Q_{op} = Q_{dec}$), here the difference between natural discharge and residual discharge represents the design flow. Yellow belts show the periods when power plant operates at partial load ($Q_{op} = Q_{riv} - Q_{eco}$), here the residual flow after extraction is the environmental flow, those are reduced extraction periods (REP). Red belts show the periods when power plant is in shut down, natural discharge is lower than environmental flow, exploitation is not performed ($Q_{op} = 0$), those are zero extraction periods (ZEP).

Here we determine the design flow in a way that the reduced extraction periods have the same length than the zero extraction periods. Under this design the extraction factor (and hence the extractable energy) is optimal at an environmental stress induced by water extraction which is not greater than what the river mouths handle in natural conditions.
The design flow of a SGE power plant at a river mouth is calculated as a fraction of the mean (natural) discharge $\bar{Q}$ as: $Q_{des} = EF \cdot \bar{Q}$ in which $EF$ is the extraction factor. Taking into account this equation, the environmental flow condition: $Q_{eco} = 0.3\bar{Q}$ and the criterion: REP = ZEP, the design flow was assessed for each river mouth calculating first the ZEP as the time per year that the monthly river discharge $Q_{riv}$ is lower than the environmental flow; meanwhile the REP were calculated as those when $Q_{eco} < Q_{riv} < (Q_{eco} + Q_{des})$; here $Q_{des}$ increases progressively as the extraction factor is increased from 0 to 1. The extraction factor for which REP = ZEP defines the $Q_{des}$ to be selected.

3.2.4 Capacity

From the considerations above it follows that SGE plants may not operate at full load throughout the whole year, instead, three power plant operation flows ($Q_{op}$) may occur [14]:

i) if $Q_{riv} > (Q_{des} + Q_{eco})$: full capacity operation, $Q_{op} = Q_{des}$ (standard mode).

ii) if $Q_{eco} < Q_{riv} < (Q_{des} + Q_{eco})$: partial capacity operation, $Q_{op} = Q_{riv} - Q_{eco}$.

iii) if $Q_{riv} < Q_{eco}$: no operation $Q_{op} = 0$.

The ratio between the actual annual energy yield of a power plant, and the theoretical annual generation calculated assuming that the power plant operates permanently at full load, is the capacity factor [15].

In this study the capacity factor was calculated for each river mouth as the ratio between the sum of the annual operation flow time series $Q_{op}(t)$, and the sum of the ideal annual operation flow time series assuming permanent standard operation mode i).

To assess the extractable energy, the capacity factor is expressed as full load hours per year by multiplying this factor by the total hour per year (8760 h/a). In this way, the capacity factor refers to the hours per year that a SGE plant may operate at full load to produce the actual annual energy yield [14].

3.3 Results and discussion

3.3.1 Theoretical potential

In this study the global theoretical SGE potential has been assessed to be 1183 GW on average, equivalent to 50.7 % of the worldwide electricity consumption in 2011 [10] ranging between 1063 GW in March and 1328 GW in October due to the local seasonal
variability of SSS and SST. These numbers are based on all available data on rivers discharge in monthly resolution which include the 921 largest rivers, accounting for 73% of the total global fresh water runoff into the ocean. A linear extrapolation to 100% runoff would lead to 1621 GW of theoretical potential which is in the same order of magnitude as most recent estimation by Kuleszo et al. of 1724 GW [9] (carried out from measured and simulated mean discharge of 5472 rivers).

Only 448 river mouths of 921 were found to be suitable locations for SGE generation; the theoretical potential for these suitable river mouths $TP_{sm}$ is 412 GW, with seasonal variability between 404 GW and 427 GW.

3.3.2 Design flow and extraction factor

The average ZEP for analyzed systems corresponds to 11% of the year, and the extraction factor producing REP the same length of time is ~0.20; which defines the design fresh water flow for power plants to 20% of mean rivers’ discharge (Figure 3-3).

![Graph showing percentage of time of the year with ZEP and REP, statistics for all suitable river mouths assuming environmental flow of 30% of the mean flow.]

For an extraction factor ~0.40, the percentile 95th of the REP curve reach 50% of the year (6 months); it means that for an extraction factor around 0.40, the 5% of the river
mounths would present REPs six months per year, which implies strong environmental stress conditions and also a major economic limitation for energy generation, since the power plants located in those river mouths would operate at partial load half part of the time. The percentage of river mouths subject to this environmental and economic unfeasible conditions increase fast with further increases of the extraction factor; e.g. for extraction factor of 0.75, 50% of the systems would present environmental flow conditions six months per year or more.

The relation between the extraction factor and the theoretical potential is known as the environmental potential \( EP \), for a river mouth \( k \):

\[
EP_k = EF_k \times TP_k
\]  

(3.5)

It may be interpreted as the maximum extractable SGE potential from river mouths considering only environmental constraints, and assuming ideal reliability and energy conversion efficiency, therefore, it is equivalent to the potential capacity of the SGE plants.

For an extraction factor of 0.2, the global environmental potential of SGE at suitable river mouths is 82.5 GW, with seasonal variability between 80.9 GW and 85.4 GW.

### 3.3.3 Capacity

The capacity of a SGE plant depends on the extraction factor (as it defines the design flow) and on the environmental flow (as it defines the lower limit for fresh water exploitation). The effect of these two variables on the global capacity is shown in Figure 3-4.

For an extraction factor of 0.2 and an environmental flow of 30%, the capacity factor of SGE generation at river mouths is 0.84 on average, equivalent in full load hours to: 7358 h/a. It shall be noted that this capacity factor is very high compared to other renewables; it is more than double of the 40% estimated as maximum for waves and tidal energy power plants [27], and also higher than the 45% and 23% calculated for wind energy and solar photovoltaic energy respectively [28,29].

### 3.3.4 Extractable energy

According to the previous analysis and equation 3.1, the global extractable SGE potential was calculated to 625 TWh/a; equivalent to 17% of the theoretical potential for suitable river mouths \( TP_{\text{theo}} \).
Figure 3-4. Capacity factor of SGE at river mouths. Statistics calculated for worldwide suitable river mouths as a function of the extraction factor and the environmental flow ($Q_{eco}$).

The worldwide distribution of the global extractable potential is shown in Figure 3-5. Here can be seen that SGE is a decentralized energy source; suitable river mouths can be found all over the world, making SGE appropriate for cities and industries located close to river mouths, but also for remote communities settled near these systems and lacking centralized energy access.

The top 30 river mouths with greatest extractable energy are listed in Table 3-1. These account for 77% of the total resources, however, 286 systems in 64 countries have a potential capacity of 10 MW or greater, being Brazil, United States, Mexico, Japan and Malaysia the countries with highest number of systems.

34% of river mouths with an energy density greater than 2.0 MW/m$^3$ (i.e. energy potential per cubic meter of fresh water) are located in the Mediterranean Sea and 29% in the Caribbean Sea and Gulf of Mexico, being the regions with better oceanographic conditions for harnessing SGE (Table 3-2). The Mediterranean Sea particularly is a semi-enclosed basin where the excess of evaporation over precipitation and runoff make the basin progressively more saline from the open boundary to the interior [30], which is reflected in the increase of energy density eastward of the basin. River mouths with
highest energy density are not necessarily the systems with highest extractable energy (Table 3-2), due to the low fresh water discharge of the rivers; however, the implementation of several small and medium size power plants in high energy density regions could compensate the low individual potentials.

![Global map of extractable salinity gradient energy resources](image)

**Figure 3-5.** Global map of extractable salinity gradient energy resources. A) Extractable energy (TWh/a). B) Energy density (MJ/(m³/s)).

Two variables defining the extractable SGE resources are subject to design: the extraction factor and the environmental flow. Previous results are based on extraction factor of 0.2 and environmental flow of 30%. The behavior of the global extractable energy as a
function of these two variables is shown in Figure 3-6. Higher values of the extractable energy would be derived considering higher extraction factors or lower environmental flows, e.g. assuming extraction factor of 0.4 and environmental flow of 10%, the extractable energy would rise to 1321 TWh/a. However, cautious considerations in environmental terms are desirable for global scale estimation, letting less conservative scenarios for detailed local scales analysis.

Table 3-1. World’s top 30 river mouths with highest extractable energy.

<table>
<thead>
<tr>
<th>River</th>
<th>Country</th>
<th>Basin</th>
<th>Energy density (MW m⁻³ s⁻¹)</th>
<th>Mean discharge (m³/s)</th>
<th>Theoretical potential (GW)</th>
<th>Potential capacity (MW)</th>
<th>Extractable potential (TWh/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congo</td>
<td>CD</td>
<td>SEA</td>
<td>1.64</td>
<td>39858</td>
<td>65.2</td>
<td>13046</td>
<td>114.3</td>
</tr>
<tr>
<td>Orinoco</td>
<td>VE</td>
<td>NWA</td>
<td>1.85</td>
<td>31163</td>
<td>57.8</td>
<td>11554</td>
<td>73.2</td>
</tr>
<tr>
<td>Mississippi</td>
<td>US</td>
<td>NWA</td>
<td>1.68</td>
<td>17039</td>
<td>28.6</td>
<td>5722</td>
<td>49.9</td>
</tr>
<tr>
<td>Parana</td>
<td>AR</td>
<td>SWA</td>
<td>1.57</td>
<td>15544</td>
<td>24.4</td>
<td>4876</td>
<td>42.7</td>
</tr>
<tr>
<td>Amur</td>
<td>RU</td>
<td>OKH</td>
<td>1.82</td>
<td>9720</td>
<td>17.7</td>
<td>3530</td>
<td>19.7</td>
</tr>
<tr>
<td>Magdalena</td>
<td>CO</td>
<td>CBN</td>
<td>1.89</td>
<td>7130</td>
<td>13.5</td>
<td>2690</td>
<td>23.6</td>
</tr>
<tr>
<td>Xijiang</td>
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<td>SCS</td>
<td>1.87</td>
<td>6961</td>
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<td>2601</td>
<td>15.6</td>
</tr>
<tr>
<td>Yukon</td>
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<td>BRN</td>
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<td>6372</td>
<td>11.1</td>
<td>2221</td>
<td>11.7</td>
</tr>
<tr>
<td>Niger</td>
<td>Ni</td>
<td>NEA</td>
<td>1.76</td>
<td>5700</td>
<td>10.0</td>
<td>2003</td>
<td>13.2</td>
</tr>
<tr>
<td>Uruguay</td>
<td>AR</td>
<td>SWA</td>
<td>1.57</td>
<td>5646</td>
<td>8.9</td>
<td>1771</td>
<td>15.5</td>
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<tr>
<td>Ogooué</td>
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<td>1657</td>
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<td>Sepik</td>
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<td>SWP</td>
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</tr>
<tr>
<td>Godavari</td>
<td>IN</td>
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<td>3038</td>
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<td>1041</td>
<td>3.3</td>
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<td>NWA</td>
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<td>1899</td>
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<td>729</td>
<td>5.3</td>
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<tr>
<td>Sanaga</td>
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<td>NEA</td>
<td>1.68</td>
<td>1985</td>
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<td>Mahanadi</td>
<td>IN</td>
<td>IND</td>
<td>1.72</td>
<td>1883</td>
<td>3.2</td>
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<td>MED</td>
<td>1.88</td>
<td>1707</td>
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<td>641</td>
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<tr>
<td>Jacui</td>
<td>BR</td>
<td>SWA</td>
<td>1.76</td>
<td>1735</td>
<td>3.1</td>
<td>611</td>
<td>5.4</td>
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<tr>
<td>Krishna</td>
<td>IN</td>
<td>IND</td>
<td>1.74</td>
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<td>2.1</td>
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<tr>
<td>Atrato</td>
<td>CO</td>
<td>CBN</td>
<td>1.58</td>
<td>1768</td>
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<td>559</td>
<td>4.9</td>
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<tr>
<td>Po</td>
<td>IT</td>
<td>MED</td>
<td>1.81</td>
<td>1513</td>
<td>2.7</td>
<td>549</td>
<td>4.8</td>
</tr>
<tr>
<td>Nile</td>
<td>EG</td>
<td>MED</td>
<td>2.08</td>
<td>1254</td>
<td>2.6</td>
<td>523</td>
<td>4.6</td>
</tr>
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<td>SCS</td>
<td>1.87</td>
<td>1335</td>
<td>2.5</td>
<td>499</td>
<td>3.4</td>
</tr>
<tr>
<td>Doce</td>
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<td>SWA</td>
<td>1.98</td>
<td>1244</td>
<td>2.5</td>
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<tr>
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<td>GH</td>
<td>NEA</td>
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<td>1075</td>
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<td>416</td>
<td>2.1</td>
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<tr>
<td>Huanghe</td>
<td>CN</td>
<td>YLW</td>
<td>1.65</td>
<td>1183</td>
<td>2.0</td>
<td>391</td>
<td>3.2</td>
</tr>
<tr>
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<td>US</td>
<td>NWA</td>
<td>1.86</td>
<td>919</td>
<td>1.7</td>
<td>342</td>
<td>2.8</td>
</tr>
<tr>
<td>Biô Bío</td>
<td>CL</td>
<td>SEP</td>
<td>1.66</td>
<td>1010</td>
<td>1.7</td>
<td>335</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Table 3-2. World’s top 20 river mouths with highest energy density.

<table>
<thead>
<tr>
<th>River</th>
<th>Country</th>
<th>Basin</th>
<th>Energy density (MWm$^3$ s$^{-1}$)</th>
<th>Mean discharge (m$^3$/s)</th>
<th>Theoretical potential (GW)</th>
<th>Potential capacity (MW)</th>
<th>Extractable potential (GWh/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bueyuek Mendere</td>
<td>TR</td>
<td>MED</td>
<td>2.10</td>
<td>99</td>
<td>207</td>
<td>41</td>
<td>290</td>
</tr>
<tr>
<td>Nile</td>
<td>EG</td>
<td>MED</td>
<td>2.08</td>
<td>1254</td>
<td>2613</td>
<td>523</td>
<td>4579</td>
</tr>
<tr>
<td>Ceyhan</td>
<td>TR</td>
<td>MED</td>
<td>2.08</td>
<td>223</td>
<td>464</td>
<td>93</td>
<td>565</td>
</tr>
<tr>
<td>Assi</td>
<td>SY</td>
<td>MED</td>
<td>2.08</td>
<td>30</td>
<td>63</td>
<td>13</td>
<td>68</td>
</tr>
<tr>
<td>Yarmuk</td>
<td>JO</td>
<td>MED</td>
<td>2.08</td>
<td>9</td>
<td>18</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>Papeno</td>
<td>PF</td>
<td>PAC</td>
<td>2.07</td>
<td>13</td>
<td>27</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>Papeia</td>
<td>PF</td>
<td>PAC</td>
<td>2.07</td>
<td>6</td>
<td>13</td>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>Vjosa</td>
<td>AL</td>
<td>MED</td>
<td>2.05</td>
<td>146</td>
<td>299</td>
<td>60</td>
<td>394</td>
</tr>
<tr>
<td>Maritza</td>
<td>BG</td>
<td>MED</td>
<td>2.05</td>
<td>110</td>
<td>225</td>
<td>45</td>
<td>352</td>
</tr>
<tr>
<td>Achehos</td>
<td>GR</td>
<td>MED</td>
<td>2.05</td>
<td>52</td>
<td>106</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>Aliakmon</td>
<td>GR</td>
<td>MED</td>
<td>2.05</td>
<td>50</td>
<td>103</td>
<td>21</td>
<td>119</td>
</tr>
<tr>
<td>Nestos</td>
<td>GR</td>
<td>MED</td>
<td>2.05</td>
<td>40</td>
<td>81</td>
<td>16</td>
<td>114</td>
</tr>
<tr>
<td>Osumi</td>
<td>AL</td>
<td>MED</td>
<td>2.05</td>
<td>32</td>
<td>65</td>
<td>13</td>
<td>81</td>
</tr>
<tr>
<td>Devoli</td>
<td>AL</td>
<td>MED</td>
<td>2.05</td>
<td>30</td>
<td>61</td>
<td>12</td>
<td>80</td>
</tr>
<tr>
<td>Arachos</td>
<td>GR</td>
<td>MED</td>
<td>2.05</td>
<td>20</td>
<td>42</td>
<td>21</td>
<td>127</td>
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<tr>
<td>Macacu</td>
<td>BR</td>
<td>SWA</td>
<td>2.04</td>
<td>11</td>
<td>22</td>
<td>4</td>
<td>39</td>
</tr>
<tr>
<td>Grande de Anasco</td>
<td>PR</td>
<td>CBN</td>
<td>2.04</td>
<td>9</td>
<td>18</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>Culebrinas</td>
<td>PR</td>
<td>CBN</td>
<td>2.04</td>
<td>8</td>
<td>17</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Damuji</td>
<td>CU</td>
<td>CBN</td>
<td>2.03</td>
<td>9</td>
<td>17</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Itabapoana</td>
<td>BR</td>
<td>SWA</td>
<td>2.03</td>
<td>57</td>
<td>116</td>
<td>41</td>
<td>290</td>
</tr>
</tbody>
</table>

Certainly there are still considerable steps between the extractable SGE resources discussed here and the finally generated energy, which are related to the technical potential or efficiencies of the energy conversion techniques. Estimations of the technical potential at global scale have been carried out for reverse electrodialysis and pressure retarded osmosis [9,11]; however recent findings on the implementation of these techniques at river mouths should be taken into account in later assessments.

3.4 Conclusions

The extractable SGE potential from river mouths has been assessed considering main constraints affecting the theoretical potential related to the suitability, sustainability and reliability of SGE harnessing at these natural systems.
Figure 3-6. Global extractable SGE from river mouths as function of the extraction factor and the environmental flow ($Q_{env}$) for worldwide suitable river mouths, comparing with the ideal extractable energy (ideal EE) calculated for CF = 8760 h/a.

Constraints are quantified in the extraction factor, the capacity factor (both depending in turn on the environmental flow), and the selection of suitable systems, and define the extractable potential according to equation 3.1, which behind its simple form involves several physical and environmental considerations.

With an overall of 49% of river mouths considered to be suitable location, an environmental flow of 30% of the mean rivers discharge, an extraction factor of 0.2, and an average capacity factor of 0.84, the global extractable potential has been found to be 625 TWh/a, equivalent to 3% of the global electricity consumption [10]. Even though it is much smaller than previous theoretical estimations of the resources, is still more clean energy than the electricity consumption of most of the countries [10] keeping the SGE as an interesting alternative for future green economic growth.

The high capacity factor indicates that SGE is reliable and continuous, basic requirement for competitiveness of renewable energies that are major drawbacks for other sources [31,32].

Not only the global extractable SGE potential, but also its worldwide distribution has been presented here. The global maps show that SGE is a decentralized and broadly
available energy source. Suitable river mouth with potential installed capacity of more than 10 MW can be found all over the world.

References

19. SMOS Ocean surface salinity data were provided by the Integrated Climate Data Center, University of Hamburg, Germany, from the Web site: http://icdc.zmaw.de
22. NOAA_OI_SST_V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/
4. Dynamics of salinity structures and site-specific potential

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 from 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 reality because both river discharge and ocean salinity have natural variations in different time scales. In this chapter we expose the site constraints related with the variability of salinity gradients that must be considered in order to make more accurate estimations of the available resources and calculate the so-called site-specific potential for suitable river mouths of Colombia. Results show that the salinity structures of studied systems have different responses to variations of environmental forcing, despite being located in the same ocean basin, and therefore, the energy potential for each river mouth has different variability patterns. Decreases of the energy potential up to 69% were found when the site-specific potential is calculated instead of the theoretical potential. This prove that more detailed than long term data are required to carry out accurate estimations of local and regional salinity gradient energy potentials.

This chapter has been published as:
4.1 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 CO₂ 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 4-1) on the basis of mean ocean salinity in regional scales and mean rivers’ discharge. 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.

Table 4-1. Estimations of the global theoretical SGE potential.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Estimated (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isaacs and Seymour [9]</td>
<td>1973</td>
<td>1.4</td>
</tr>
<tr>
<td>Wick and Schmitt [10]</td>
<td>1976</td>
<td>2.6</td>
</tr>
<tr>
<td>Post [3]</td>
<td>2009</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Assuming mean salinities and river discharges for estimating SGE potentials at global and regional scales is justified, but estimations for particular river mouths require considering the variability of the salinity gradients at different temporal scales, which may significantly influence the SGE potential. In this chapter the effects of salinity variability on the site-specific potential of suitable river mouths of Colombia is analyzed by considering the variability of the salinity in the intake zones of fresh water and seawater. It is approached from hydrodynamic modelling of the salinity structure of the river mouths considering representative scenarios of the intra-annual and inter-annual variability of these systems.
4.2 Methods

4.2.1 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 (Figure 4-1). Numerous rivers flow into both Colombian Seas, but not all river mouths offer suitable conditions for the generation of SGE (Chapter 2). To exploit this energy, fresh and saline 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, 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 estimating the Colombian potential, rivers discharging into the Pacific Ocean were not considered.

In Table 4-2 the rivers accounting for 99% of the total fresh water discharge to the Colombian Caribbean Sea are listed; the locations of the mouths are shown in Figure 4-1B.

Table 4-2. Mean annual discharge of the six rivers accounting for 99% of the fresh water discharged into the Colombian Caribbean basin. Taken from Ref. [14].

<table>
<thead>
<tr>
<th>River</th>
<th>Mean water discharge [km$^3$ yr$^{-1}$]</th>
<th>Years with data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magdalena$^a$</td>
<td>228.1</td>
<td>1975 - 1995</td>
</tr>
<tr>
<td>Atrato$^a$</td>
<td>81.08</td>
<td>1982 - 1993</td>
</tr>
<tr>
<td>Sinú</td>
<td>11.76</td>
<td>1963 - 1993</td>
</tr>
<tr>
<td>Canal del Dique$^a$</td>
<td>9.43</td>
<td>1981 - 1993</td>
</tr>
<tr>
<td>León$^a$</td>
<td>2.47</td>
<td>1978 - 1993</td>
</tr>
<tr>
<td>Don Diego</td>
<td>1.14</td>
<td>1973 - 1993</td>
</tr>
<tr>
<td>Total Colombian Caribbean</td>
<td>337.68</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Selected mouth for detailed study
Figure 4-1. A) Colombia in northern South America; B) Main rivers flowing to the Colombian Caribbean Sea; C-F) River mouths studied in detail showing the location of the vertical transects used to analyze the salinity structures. Altitude in meters above the sea level.
To analyze the Colombian potential rivers Magdalena, Atrato, Canal del Dique and León (accounting 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, thus its exploitation lacks environmental and economic reason.

4.2.2 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 $G$ of mixing a concentrated and a diluted solution is [3]:

$$G = (G_c + G_d) - G_b$$  \hspace{1cm} (4.1)

where $G$ 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), it can be shown that the Gibbs free energy of each electrolyte solution (diluted, concentrated or brackish) is given by:

$$G_i = -T_i \Delta S_i$$  \hspace{1cm} (4.2)

with $i = c, d, b$; $T$ is the absolute temperature (K). The entropy change of each solution $\Delta S_i$ is calculated using the equation:

$$\Delta S_i = -V_i mR [x_i \ln(x_i) + y_i \ln(y_i)]$$  \hspace{1cm} (4.3)

where $V_i$ are the volumes (m$^3$) of the water in the mixing ($V_b = V_c = V_d$), $m$ 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].

4.2.3 Site-specific potential

From equations 4.2 and 4.3 it can be seen that the theoretical SGE potential per unit volume of fresh water (energy density), depends mainly on the salinity difference between the diluted- and concentrated solutions. This potential is commonly estimated assuming constant salinity difference between fresh water and seawater in river mouths; however, the environmental forcings influencing the salinity structure of these systems are subject to local (site-specific) variability at seasonal and inter-annual scales [16-22]. Hence, the theoretical potential per se only gives rough estimation of the available SGE resources.
Meanwhile, the site-specific potential (SSP), as described in Chapter 2, considers the temporal variability of the theoretical potential due to the variability of salinity in the intake points of fresh water and seawater. The SSP considers also the energy losses caused by the transport of the waters towards the power plant; however this chapter is focused only on the effect of the variability of salinity in SSP, which represents indeed the energetic input for SGE generation.

To consider this variability, the salinity patterns of the four river mouths were modelled 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. 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].

4.2.4 Selection of simulation scenarios

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 hydroclimatology 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 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 rivers and a rise in mean air temperature, while during the cold phase (La Niña), the opposite situation occurs, as there is a rise in the mean flows of rivers and a reduction of mean air temperature. Both phases generate anomalies in the displacement of the ITZC, which implies anomalies also in wind regimes [20,29].

Six scenarios were simulated in order to consider the two seasons (intra-annual variability) and the three ENSO stages (inter-annual variability) (Table 4-3). To consider the warm and cold ENSO phases, 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 dry and rainy seasons respectively. Not the same year was selected to simulate the no-
ENSO phase for all river mouths because for Atrato and León systems, especially good field data was available for 2006-2007 and 2009 respectively.

Table 4-3. Simulation scenarios for each river mouths.

<table>
<thead>
<tr>
<th>River</th>
<th>no-ENSO year</th>
<th>El Niño year</th>
<th>La Niña year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry season</td>
<td>Rainy season</td>
<td>Dry season</td>
</tr>
<tr>
<td>Magdalena</td>
<td>feb-97</td>
<td>sep-96</td>
<td>feb-98</td>
</tr>
<tr>
<td>Atrato</td>
<td>feb-07</td>
<td>sep-06</td>
<td>feb-98</td>
</tr>
<tr>
<td>Canal del Dique</td>
<td>feb-97</td>
<td>sep-96</td>
<td>feb-98</td>
</tr>
<tr>
<td>León</td>
<td>feb-09</td>
<td>sep-09</td>
<td>feb-98</td>
</tr>
</tbody>
</table>

4.2.5 Data for simulations

Several data are required for startup, calibration and validation of the hydrodynamic model, including the environmental forcing influencing circulation, stratification and mixing such as winds, river flows and tides, to define the boundary conditions; and variables quantifying the circulation, stratification and mixing such as velocity, salinity and temperature of the water, to define the initial conditions and compare with model results. For all scenarios, with the exception of no-ENSO scenarios for Atrato and León rivers, winds and heat flux parameters were obtained from the North American Regional Reanalysis (NARR) databases [31]. For Atrato and León rivers these data were obtained from field measurements. Rivers discharges were obtained from the databases of the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEM), and tides from the sea level station of Cristobal City - Panama. Salinity and temperature profiles for Atrato, Canal del Dique and León rivers were obtained from field campaigns, and profiles for Magdalena River from measurements by the Oceanography and Hydrography Research Center (CIOH) of the Colombian Navy. These data was used to calibrate and validate the model, details can be found in Refs. [32,33].

4.2.6 Location of water intake points

Fresh water and seawater intake points were selected from simulation results as the closest points where mean salinity for all scenarios is lower than 1 g/L for fresh water, and higher than 35 g/L for seawater, and considering that the salinity does not exceed a threshold of ±1 g/L from the mean, for more than 1% of the simulated time. For Atrato and Canal del Dique, fresh water intake points fulfilling these conditions were not found due to particular feasibility constraints (explained later). Hence, points with minimum average salinity in the simulation domain were selected as diluted solution intake points.
4.3 Results

Several vertical transects were analyzed to identify the temporal variation of the salinity patterns of the river mouths; two of them showing the main features of each system were selected for visualization (Figure 4-1C-F). These patterns allow identifying mixing zones, distance between fresh water and seawater, variation of this distance, and location of water extractions to ensure permanent fresh- and salt-water conditions.

4.3.1 Magdalena River mouth

There is a very stable salt-wedge structure in the mouth of Magdalena River independently of the season and ENSO phase (Figure 4-2). For all scenarios seawater intrusion into the river channel occurs at the bottom in last 1000 m and does not salinize the superficial waters of the river. The highest reduction of seawater salinity occurs during the rainy season in La Niña scenario, when a mean salinity of 35 g/L is found at 10 m - 15 m depth, for other scenarios this salinity can be found in shallower depths.

![Figure 4-2. Mean salinity patterns in Transect M1 (boxes A-F) and Transect M2 (boxes G-L) in Magdalena River mouth, for all simulated scenarios. Black and white dots in boxes A-F correspond to fresh water and seawater intake points, respectively.](image-url)
Fresh- and seawater intake points are also shown in Figure 4-2; the distance between them is 880 m in horizontal- and 22 m in vertical –direction, respectively. As explained in paragraph 4.2.6, these locations were selected from the mean salinity patterns but considering also the temporal variability, it is shown in Figure 4-6A,B. Salinity series are shown from the sixth day of simulation skipping the model spin up during the first five days. In the fresh water intake point, salinity is almost zero for all scenarios, showing a small increase during dry season for the no-ENSO scenario, but never exceeds 1 g/L. In the seawater intake point, all scenarios show stable salinity between 35.5 g/L and 36.7 g/L most of the time, with the lowest values during rainy season scenarios due to the rise of fresh water discharge.

4.3.2 Canal del Dique River mouth

This river discharges by three main mouths; two of them are located in Barbacoas Bay and one in Cartagena Bay. The analysis in Barbacoas Bay is focused, where two of three mouths discharge. Figure 4-3 shows the mean salinity patterns and the location of fresh water and seawater intake points.

Figure 4-3. Mean salinity patterns in Transect B2 (boxes A-F) and Transect B1 (boxes G-L) in Canal del Dique mouth in Barbacoas Bay, for all simulated scenarios. Black and white dots in boxes A-F correspond to fresh water and seawater intake points, respectively.
The salinity variability in both points is shown in Figure 4-6C,D. In this river mouth fresh water cannot be found until the main channel before bifurcation of the branches (see Figure 4-1D); in the final stretch of the river, in the diluted water intake zone, salinity shows a tidal signal reaching values above 20 g/L in both seasons during El Niño year scenarios; for other scenarios, the salinity is lower but up to 15 g/L in part of the tidal cycle. In the seawater intake zone, salinity is very stable around 35.3 g/L, with highest during dry season and lowest during rainy season.

4.3.3 Atrato River mouth

Fresh water intake point for this river mouth was selected at the East side of the gulf where the mouth is located, close to the City of Turbo (Figure 4-1E), because West side is a well conserved natural zone where there is no significant demand of energy, no infrastructure and high environmental value.

![Figure 4-4. Mean salinity patterns in Transect A1 (boxes A-F) and Transect A2 (boxes G-L) between Atrato River mouth and the Municipally of Turbo, for all simulated scenarios. Black and white dots in boxes A e F correspond fresh water and seawater intake points respectively.](image-url)
Salinity transects show a strong variability of the salinity patterns in the first 5m depth between dry and rainy season (Figure 4-4). Mean surface salinity during rainy season, for all ENSO phases, varies between 4 g/L and 6 g/L, while during dry season mean surface salinity increase about 10 g/L, varying between 14 g/L and 16 g/L. Salinity increases very fast with depth reaching 35 g/L around 10 m for all scenarios. Seawater intake was also selected eastward of the gulf at 13 m depth and 2400 m in horizontal distance from fresh water intake. Fig. 6E shows the strong seasonal variability of salinity in the fresh water intake point, with higher values during dry season at intra-annual scale and during El Niño years at inter-annual scale. In the seawater intake, the salinity is very stable around 35.5 g/L for all scenarios.

4.3.4 Leon River mouth

In León River (Figure 4-5) higher variation of salinity patterns occurs at seasonal scale.

Figure 4-5. Mean salinity patterns in Transect L1 (boxes A-F) and Transect L2 (boxes G-L) in León River mouth for all simulated scenarios. Black and white dots in boxes A-F correspond fresh water and seawater intake points respectively.
Figure 4-6. Salinity in the fresh water intake zone (boxes A, C, E and G) and in the seawater intake zone (boxes B, D, F, H), for Magdalena (A-B), Canal del Dique (C-D), Atrato (E-F) and León (G-H) Rivers mouths. Salinity in g/L.
During dry season persists a superficial layer of fresh water until 5 m - 7 m depth, followed by a narrow mixing area where the salinity increases fast; seawater with mean salinity of 35 g/L is found at 12 m - 14 m depth. In contrast, during rainy season higher salinities are present in surface (around 12 g/L) and a salt-wedge appears in the central channel of the river mouth; salinity increases progressively with depth reaching again 35 g/L at 12 m - 14 m. In the fresh water intake zone, salinity is lower than 1 g/L more than 99% of the time, with sporadic rises during dry season scenarios (Figure 4-6G). In the seawater intake salinity is very stable between 35 g/L and 36 g/L for all cases (Figure 4-6H). Distance between both intake points is 3750 m and 19 m in horizontal and vertical directions respectively.

4.4 Discussion

4.4.1 Site-specific potential

The site-specific potential was calculated for all river mouth from salinity in fresh- and seawater intake points (Figure 4-6) using eq. 4.1 – 4.3; results are shown in Figure 4-7. Mean, maximum and minimum SSP values for all scenarios are summarized in Table 4-4.

![Figure 4-7. Site-specific potential for all the scenarios, in A) Magdalena, B) Canal del Dique, C) Atrato, and D) León river mouths.](image-url)
Table 4-4. Site-specific potential per cubic meter [MJ/m³].

<table>
<thead>
<tr>
<th>River</th>
<th>no-ENSO year</th>
<th></th>
<th>El Niño year</th>
<th></th>
<th>La Niña year</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry season</td>
<td>Rainy season</td>
<td>Dry season</td>
<td>Rainy season</td>
<td>Dry season</td>
<td>Rainy season</td>
</tr>
<tr>
<td>Magdalena</td>
<td>Max</td>
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<td>2.18</td>
<td>2.17</td>
<td>2.18</td>
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<td>2.16</td>
<td>2.14</td>
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</tr>
<tr>
<td></td>
<td>Min</td>
<td>1.82</td>
<td>2.09</td>
<td>2.12</td>
<td>2.07</td>
<td>2.09</td>
</tr>
<tr>
<td>Canal del Dique</td>
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<td>1.95</td>
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<tr>
<td></td>
<td>Mean</td>
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<td>2.02</td>
<td>0.39</td>
<td>0.82</td>
<td>2.05</td>
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<tr>
<td></td>
<td>Min</td>
<td>0.38</td>
<td>1.82</td>
<td>0.02</td>
<td>0.16</td>
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<tr>
<td>Atrato</td>
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<tr>
<td>León</td>
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<td>2.17</td>
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</tr>
<tr>
<td></td>
<td>Mean</td>
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<td>2.05</td>
<td>1.33</td>
<td>2.08</td>
</tr>
</tbody>
</table>

For Magdalena and León river mouths, the site-specific potential is very high and stable around 2 MJ/m³, showing both systems very suitable conditions for SGE exploitation. In Canal del Dique SSP is also around 2 MJ/m³ during higher discharge scenarios (La Niña/Dry Season, La Niña/Rainy Season and No-ENSO/Rainy Season), but reduces to 0.93 MJ/m³ on average during the other scenarios due to the increase of salinity in the last stretch of the river in correspondence with the tidal cycle.

For Atrato River mouth, there is a marked difference in SSP between dry and rainy seasons; during dry season the average SSP is 0.26 MJ/m³, while during rainy season it reaches 1.02 MJ/m³. This is the system with lowest site-specific potential because the intake point of diluted water is close to the City of Turbo instead of in the river itself (Figure 4-4); if the theoretical potential is calculated without considering local constraints this potential will be greater but less realistic in terms of feasibility of exploitation.

Multiplying the site-specific potential by the discharge of the rivers, a preliminary approximation of the available SGE resources is derived (Table 4-5), where the comparatively high SGE potential of Magdalena River is evident. The considered discharges were respectively: mean discharge of Magdalena river (7232 m³/s); mean discharge of Matumilla mouth, the southern and biggest mouth of Canal del Dique in Barbacoas Bay (105 m³/s); mean discharge of Coco Grande mouth, the closest Atrato River mouth to the Municipally of Turbo (129 m³/s); and mean discharge of León River (89 m³/s).
Table 4-5. SGE potential for the mean discharge of the rivers [MW].

<table>
<thead>
<tr>
<th>River</th>
<th>Max</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Min</th>
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<th>Mean</th>
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<td>El Niño year</td>
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<td></td>
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<td>8</td>
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<tr>
<td>Rainy season</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td>La Niña year</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Dry season</td>
<td>15776</td>
<td>15496</td>
<td>14562</td>
<td></td>
<td></td>
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<td>Rainy season</td>
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</tbody>
</table>

Magdalena River accounts for 97% of the potential, with 15157 MW on average; it is actually one of the systems with highest SGE potential worldwide (Chapter 3). León River has a non-negligible potential of 187 MW, but more important, is the system with more stable potential for all scenarios. The others two systems, Canal del Dique and Atrato, have mean potentials of 154 MW and 93 MW, respectively, but with higher fluctuations at different temporal scales.

The theoretical potential was also calculated for studied river mouths assuming seawater salinity and temperature of 35.6 g/L and 27.8 °C, respectively, according to WOA09 data [34,35], and the same temperature for fresh water. Theoretical potentials of 14954 MW for Magdalena, 217 MW for Canal del Dique, 267 MW for Atrato and 184 MW for Leon, were found with the same discharges than before. This represents a ratio between site-specific potential and theoretical potential of 1.01 for Magdalena, 0.71 for Canal del Dique, 0.31 for Atrato, and 0.97 Leon. These results reveal that when local variability of salinity structures is considered, available SGE resources at Magdalena and Leon rivers are similar to theoretical potentials; but for Canal del Dique and Atrato rivers, it reduces 29% and 69%, respectively.

### 4.4.2 Technical and environmental constraints

The site-specific potential considers ideal efficiencies in the energy conversion process and that mean rivers flow can be used for energy generation. However, technical and
environmental constraints have to be considered in order to go from the site-specific potential to the exploitable potential.

The technical SGE potential is defined as the fraction of the site-specific potential that can be recovered taking into account the efficiencies of the energy conversion process. This potential depends on the harnessing technology, since the constraints of each technology and the state of development are different. Two exploitation technologies for SGE are in greatest stage of development: Pressure Retarded Osmosis (PRO) [36-39] and Reverse Electrodialysis (RED) [40-42]. For PRO, Yip & Elimelech [43] showed from thermodynamic analysis that the maximum possible efficiency that can be reached in constant-pressure PRO systems is 91.1%, considering the intrinsic inefficiencies due to the entropy production during water permeation and the unutilized energy due to the discontinuation of water permeation, but assuming zero losses from the system components. On the other hand, for RED, Post et al. [44] showed from laboratory experiments that efficiencies of >80% could be expected, but taking into account only the energy losses for ionic transport; additionally Post [3] and Kuleszo et al. [41] estimated the energy requirements of a RED power plant (for water transport and pretreatment) in 50 kJ/m³. Both technologies are still in constant development and the efficiencies that will be reached in real scale plants are not known with certainty; the technical potential will increase as the membranes and other components of the systems are improved.

The environmental SGE potential is defined as the fraction of the site-specific potential that takes into account environmental restrictions for water extraction. The available SGE resources are calculated assuming that the mean rivers discharge is usable for energy generation, but just a fraction of this discharge, the extraction factor, can be actually used ensuring stability of physical dynamics and sustainability of ecosystems of the river mouths. It is shown in Chapter 5 that for León River, using an extraction factor of 20% and considering an environmental flow of 12% of mean discharge, the impacts on the salinity structure of the river mouth are limited to a slight movement of the mixing zone landward, mainly during the rainy season. However, more detailed studies are needed to assess the environmental impacts in terms of ecosystems response, sediment dynamics and water quality.

4.5 Conclusions

The Caribbean Sea reveals suitable conditions for generation of salinity gradient energy (Chapter 3). A detailed study of the site-specific potential was carried out for river mouths discharging the 95% of fresh water into de Colombian Caribbean Sea. Results show that Magdalena River mouth accounts for 97% of the total resources in Colombia with average site-specific potential of 15157 MW. Leon River mouth, even with a
comparatively low but non-negligible potential of 187 MW, presents the most stable intra- and inter-annual potential among the studied systems, making from this a very interesting system from the point of view of the confidence in energy production (Chapter 5). For the other studied systems the energy potential is not as high and stable as for the former two.

Most remarkable conclusion in terms of further estimations of local SGE potentials is that detailed analysis of the dynamics of salinity structures are requires in order to derivate accurate estimations of the available SGE resources. Reductions of the estimated resources up to 69% were found when the site-specific potential considering intra- and inter-annual variability of the salinity patterns was calculated instead of the hitherto used theoretical potential based on mean long term river runoff and water salinity.

References


5. Extractable SGE resources analysis at local scale

In order to implement SGE as a renewable energy source it is necessary to take into account the site-specific characteristics of any river mouth location where a project is proposed. This includes the salinity structure, inter- and intra-annual flow variations, environmental and social restrictions of the flow extraction, among others. Using the case of a location with suitable conditions for harnessing SGE, the León River mouth at the Colombian Caribbean Coast is analyzed in detail. An analysis is undertaken to determine the appropriate size of an SGE plant by studying the relationships of the flow extraction with the installed capacity, load factor and yearly generation of the power plant assuming Pressure Retarded Osmosis conversion technology. Furthermore, environmental characteristics of the river are taken into account. Once the design flow is determined, the impact of the flow extraction on the salinity structure is analyzed for different climatic scenarios defined by the ENSO phases. The developed methodology can be taken as a basis to assess the SGE potential of other rivers on a worldwide level.

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5.1 Introduction

Salinity gradient energy is released during the mixing of river and ocean water due to the difference in salt concentrations between these two masses of water. There are several technologies for the conversion of salinity gradients into electric energy, but the more developed nowadays are Pressure Retarded Osmosis (PRO) and Reverse Electrodialysis (RED) [1-4]. There are still many technical challenges to be solved in order to implement both technologies and to make them commercially feasible in the short term. These include: concentration polarization, reverse salt flux, water permeability and solute selectivity of the membrane, mechanical strength of membranes and membrane fouling tendency in the case of PRO [5,6], and concentration polarization, ion permeability and water selectivity of the membranes and the “spacer shadow effect” in the case of RED [1,7,8]. However, recent developments in some of the mentioned topics, like those of Chou et al. [9], suggest that PRO may become an interesting alternative for power generation in the medium term.

The Caribbean was identified as one of the most appropriate regions for the harnessing SGE (Chapter 3)[10]. This is because of the low tidal range of the Caribbean, which permits the presence of estuaries and deltas with relatively stable vertical salinity gradients. In comparison to well-mixed estuaries with horizontal salinity gradients, the vertical salinity gradients allow the use of short water transport systems, to and from the power plant. This is a central requisite for the limitation of the overall power plant cost.

Marine power assessments show that SGE may be the most promising marine renewable power source for Colombia, because of the mixing conditions and the very large flows of the Colombian Rivers into the Caribbean Sea [11]. To determine the potential of SGE on a regional level a detailed site-specific potential analysis is required, which must consider the varying conditions in estuaries (e.g. salinity and temperature structures, river flows), as well as technical, environmental and social conditions and restrictions. Here we show the development of a general methodology for potential evaluation and the results of its application to the León River in Colombia.

5.2 General methodology

In general, SGE plants exploit the potential of salinity gradients between river and ocean water. In PRO plants both water streams are contacted in membrane modules to each other. Before entering the membrane modules, the ocean water is pressurized to approx. 10-13 bar which equates to half the osmotic pressure. In the membrane modules the river water permeates through the membrane against the pressure difference according to the
osmotic effect. The pressurized stream which leaves the modules can be used for electricity generation in a water turbine. The technical process is described in Ref. [12].

The most influential parameters for determining the potential of SGE plants are the salinity difference between river and ocean water, the availability of river and ocean water, the water quality (including the need for pre-treatment) and the losses of the energy conversion. The major energy losses from the mechanical equipment of the PRO plants occur in the pumps, pressure exchanger, filtration systems and in the turbine-generator unit. The overall mechanical efficiency of osmotic power plants is calculated to approx. 70%, and the Gibbs-efficiency\textsuperscript{1} can reach values up to 45% depending on the operation conditions [10,12].

The availability of ocean water is usually uncritical, so this methodology focuses in the availability of river water, as it is one of the main influence parameters. To determine the river water availability a site-specific analysis of the discharge behavior is a prerequisite. Figure 5-1 shows the applied methodology to determine the river water operation. The methodology involves hydrological parameters of the river to define the characteristics of the power plant, this is made through the analysis of the time series of the river discharge. A flow duration curve analysis is used to determine the amount of river water which can be extracted for a use in a SGE plant. As it becomes evident that not the whole river flow can be extracted due to practical and environmental constraints, a fresh water extraction factor needs to be determined (Chapter 3).

The design flow ($Q_{de}$) represents the installed capacity of the power plant. The environmental flow ($Q_{env}$) is defined as the minimum flow which has to remain in the riverbed after water extraction to sustain the ecological stability of the river. The environmental flow limits the water extraction during low discharge periods. To determine the environmental flow an environmental restriction parameter is required (see Section 5.3.3). Considering both design- and environmental flow, a power plant operation flow ($Q_{op}$) is determined for each time step according to the flow conditions of the river discharge (see Section 5.3.4).

Once the characteristics of the power plant are defined, the environmental impacts of the operation flow may be analyzed. In this research the main environmental focus is the change of the salinity structure and its behavior in different seasons. Salinity is a key parameter for the ecosystem as it defines the environmental conditions in the river mouth

\textsuperscript{1} Gibbs-efficiency is defined as net energy power plant output (including losses) to the Gibbs energy of mixing river and ocean water (described in Chapter 1).
where specialized species live. The study of the salinity structure is also important from an operational point of view, as large changes in the structure could change the salinity in the water intake locations, altering the power generation of the power plant. Environmental impacts regarding hydrodynamics and sediments, flora and fauna, water quality, etc. are not considered so far, but can later be implemented within the presented approach.

Figure 5-1. Methodology for evaluating the extractable SGE resources at local scales. In blue: input parameters.
To decide whether the environmental impacts are tolerable or not decision criteria, legal regulations, social implications have to be considered. In the case that the impacts are not tolerable, the environmental restriction parameter and the water availability should be adjusted, and the power plant operation flow and the environmental impact are analyzed again. This process is repeated until the impacts are classified as tolerable. Once the iteration ends, the final power plant parameters (e.g. full load hours/capacity factor, electricity generation) can be calculated, and the extractable SGE potential of the considered river mouth is defined.

In the following, the presented methodology for potential evaluation is applied to the León River in Colombia.

5.3 The León River

León River discharges in the Urabá Gulf in the northwestern region of Colombia, South America (Figure 5-2), near the town of Apartadó (about 120000 habitants). It has a mean flow of 88.75 m³/s and it is used for navigation and fishing.

![Figure 5-2. Location of the León River Mouth. Location of the (a) Urabá Gulf in Colombia; and (b) León River Mouth in the Urabá Gulf. (c) The León River Mouth and the longitudinal and transversal transects defined for the simulation.](image)

Leon River presents a uni-modal annual cycle of flow variations, influenced mainly by the geographical position of the Inter-Tropical Convergence Zone (ITCZ), which defines a rainy season (August-October) and dry season (December-April) in the Colombian Caribbean Coast. The rest of the year is transitional between these two seasons [13,14]. The maximum flows of the León River occur in October while the minimum flows occur in March [15].
In an inter-annual scale, Colombian hydro-climatology is strongly forced by the occurrence of El Niño/South Oscillation Phenomenon (ENSO). During the warm phase of the ENSO (El Niño) there is a significant reduction of the precipitation in the country, and consequently in the river flows. During the cold phase (la Niña) the opposite situation occurs, as the precipitation and the river flows significantly rise [16,17]. The Urabá Gulf has a micro-tidal range with mean tidal range of 0.15 m and spring tidal range of 0.24 m [18]. This permits the creation of saline wedges near the river mouth [15].

5.3.1 Salinity structure

It has been shown in Chapter 4 that the salinity structure of the León River is appropriate for harnessing SGE because of the low tidal range and the abundant fresh water. The tridimensional hydrodynamic model ELCOM (Estuary, Lake and Coastal Ocean Model), developed by the Centre for Water Research of the University of Western Australia, was used to study the dynamics and behavior of the river mouth. This model solves the unsteady, viscous Navier-Stokes equations for incompressible flow using the hydrostatic assumption for pressure [19].

Simulations show that there are important variations in the overall salinity structure between dry and rainy seasons. However, despite this variability, a salinity difference of 35 g/L between the last stretch of the river and a depth of 17 m is maintained constant all year round. Figure 5-3 shows the behavior of the salinity structure during dry and rainy seasons. Locations of the longitudinal and transversal transects are shown in Figure 5-2.

The behavior of the salinity structure in the León River is counterintuitive [15]. At first glance, it would be expected that during the rainy season the seawater would be found at a greater depth because of the excess fresh water in the river mouth. However, the opposite situation arises. This phenomenon can be explained because of the geographical location of the León River mouth, south of the Atrato River. The Atrato River has a mean flow of 2740 m³/s [18] and during the dry season, the winds blow southward, sending the discharge majority to the south of the Urabá Gulf, where the León river mouth is located [15,20]. As a result, the fresh water is abundant during dry season and the saline water is found at a greater depth.
Figure 5-3. Behavior of the salinity structure of the Leon River mouth in the longitudinal (a, c) and transversal (b, d) transects during dry (a, b) and rainy (c, d) seasons, in a no-ENSO year. Concentrations are shown in g/L [15].

5.3.2 Discharge analysis

A hydrological analysis of the long-term river discharge time series is used to determine the design flow of the power plant. A higher design flow leads to greater installed power plant capacities. As the installed capacity increases, so do the power generation and the installations costs, but at the same time the capacity factor\(^2\) decreases. As the installed

\(^2\) The capacity factor is defined as the ratio between the annual production and the maximum technically possible production of a power plant. With the capacity factor it is possible to calculate the full load hours (= capacity factor x 8760 h in a year) of a power plant. The full load hours is
capacity decreases, environmental impacts are smaller and the power plant can be operated at full capacity during a higher percentage of the time. However, potential available surplus water resources remain unused. A flow that balances the generation, efficiency and environmental impacts has to be determined.

Hydropower run-of-river plants in Colombia are located in the Andean mountains on very steep rivers with no navigation and very few macro fauna. Although each hydropower project is different, the regular design flow ranges from 1 to 1.05 times the mean flow.

For SGE plants a design flow comparable to run-of-river plants would be excessive because it would significantly alter the salinity structure and the hydrodynamics of the river mouth, let alone impacts on the flora, fauna and navigation. The operation flow for SGE plants is directly taken out of the river by water extraction with submerged or sub-riverbed intakes without the presence of a dam. After the energy production in the power plant the extracted water is discharged further downstream in the natural mixing zone of the river mouth.

To take into account these aspects, the chosen flow must be lower compared to run-of-river plants. An extraction factor equal to 20% of the mean flow is proposed as a reference value for the design flow (Chapter 3), equivalent to 17.75 m³/s for the León River case. This serves as a first estimation; the impacts of different flows are further analyzed in Section 5.4.

This value is evaluated in the following chapter to assess the reliability of the operation and the water availability, as well as the tolerance to the social and environmental impacts.

5.3.3 Reliability and flow availability

The Colombian electric system is highly reliant on hydropower, as it accounts for 68% of the total installed capacity. This provides cheap and clean energy for the country, but makes the system very sensitive to the dry seasons, and especially to the warm phase of the ENSO that significantly reduces the river flows and the reservoir levels.

To account for the reliability of a new power plant, a flow duration curve must be constructed, and the flow with 95% of exceedance probability (meaning that it is available defined as the theoretical number of hours that the power plant is operated at full (nominal) load in order to produce the annual energy yield.
95% of the time) is chosen. The electric energy generated with this flow is called “firm energy”, and is accounted to be reliable to the electric system [21].

It is desirable that the design flow is available most of the time, as it guarantees higher capacity factors and more firm generation. The flow duration curve aids in the selection of an appropriate design flow, incorporating the unique discharge characteristics of the river. The discharge analysis is based on the discharge time series for 1991-2003. The resulting flow duration curve is shown in Figure 5-4.

![Flow duration curve](image)

**Figure 5-4.** Flow duration curve of the León River using daily river flow time series for 1991-2003. The black crosshair shows the design flow in the curve. The dotted crosshair represents the location of the reliable flow, defined as the exceedance probability of 95%.

The curve shows that the chosen design flow is equivalent to the 91.5% exceedance flow of the river. This value is very close to the reference value of 95% exceedance accounted as reliability in the Colombian electric market. This means that a power plant with such flow will have abundant fresh water availability.
5.3.4 Environmental and social restrictions

According to the Colombian Law, for a hydropower project it is mandatory that a minimum flow in the riverbed remains after the intake of a power plant in order to sustain the fauna and the flora of the ecosystem. This environmental flow is to be calculated using a methodology that takes into account hydrological, ecosystem, biological and water quality aspects [22]. Because of the lack of necessary biological and water quality information for the León River, this methodology is not applied in this case. Instead, two alternative methods to estimate the environmental flow were considered. One of them defines the environmental flow as 25% of the lowest value of the multiannual monthly flow series (scenario 1). The other one defines the environmental flow as the mean value of the minimum annual daily flow (scenario 2). For these two scenarios the environmental flow is calculated to be 7.1 m³/s (scenario 1) and 10.5 m³/s (scenario 2). Out of these two values, the more conservative option has been chosen, so at any time during the power plant operation the remaining flow in the river after the water extraction cannot be lower than 10.5 m³/s. The design flow and the environmental flow are compared to the discharge time series of the river in Figure 5-5.

![Graph showing daily flow of the León River and comparison with the mean, design and environmental flows.](image)

**Figure 5-5.** Daily flow of the León River and comparison with the mean, design and environmental flows.

The design flow is significantly smaller than the mean flow of the river and larger than the minimum environmental flow. Figure 5-4 shows that most of the time the river has a
flow that surpasses design flow and occasionally carries less flow. This has a positive impact on the capacity factor of the plant, which will be discussed further.

5.3.5 Site criteria

To choose the site of the power plant, several criteria must be considered to have an optimal location. The fresh water and saltine water intakes and the discharge must be at a minimum distance from the powerhouse. The powerhouse should be located near the shoreline, but protected from coastal dynamics and with enough space. Considering that in the León River delta the salinity remains around 35 g/L all year round at a 17 m depth (Figure 5-2), the place chosen for intake on seawater must reach this depth. To reduce the hydrodynamic disturbance in the river mouth, the fresh water intake is located 1 km upstream. The mixed waters are to be discharged in the bay at a depth of 5 m, where the natural salinity is similar to the salinity of the brackish water discharged from the plant. Considering such conditions, a location east of the river mouth is chosen for the powerhouse and it is shown in Figure 5-6.

Figure 5-6. Possible plant and intake locations. Coordinates are in the Colombia West Reference System.
5.4 Technical and environmental potential scenarios and power plant design

The power factor is used to calculate the technical and environmental potential for a PRO power plant. This factor is defined as the specific power plant capacity in dependency of the fresh (river) water flow. It takes the technical constraints of the energy conversion in the power plant into account. To calculate the power factor, a detailed power plant model is required which incorporates state of the art data of the power plant components.

According to previous studies [10], a power factor of approx. 0.6-0.85 MW/(m³/s) is achievable for osmotic power plants. For large and optimized power plants this power factor can increase to 1 MW/(m³/s) [5]. Such difference comes from different assumptions regarding the losses during the power plant operation and the operation parameters, such as volume flow ration and operation pressure. In general, the power factor should be considered as a variable input parameter and it is recommended to review the assumptions for the calculation of the power factor when performance data of realized large-scale osmotic power plants are available. A power factor of 0.8 MW/(m³/s) is used for the calculations here.

It is further assumed that the volume flow ratio between river and ocean water is 1:1. Such ratio represents an optimum regarding the power output [12]. Despite this, higher volume flow ratios might be chosen to ensure membrane fouling control.

The technical potential can be calculated by multiplying the power factor with the mean discharge. This value represents the technical maximum amount of energy which might be converted in an osmotic power plant without considering water extraction limitations. As discussed before, it is not applicable to use the whole river water flow in a SG-Epower plant and therefore the environmental potential is considered in the following as a subset of the technical potential which takes environmental constraints of water extraction into account.

According to Figure 5-5, the environmental potential is defined by the design flow \( Q_{des} \) and the environmental flow \( Q_{cco} \). With these two values and the discharge time series \( Q_{riv} \) the boundary conditions for the power plant operation can be analyzed. Overall there are three possible power plant operation points:

- \( Q_{riv} - Q_{cco} > Q_{des} \): Operation with design flow \( Q_{op} = Q_{des} \) (standard mode);
- \( Q_{des} > (Q_{riv} - Q_{cco}) > Q_{cco} \): Part load operation with \( Q_{op} = Q_{riv} - Q_{cco} \); and
- \( Q_{cco} > Q_{riv} \): Shutdown \( Q_{op} = 0 \) (operation not possible).
With these operation conventions, the operation flow time series \( Q_{op}(t) \), is determined. The full load hours and the corresponding amount of days with part load operation and the shutdown days as well as the electricity generation can be calculated. The results are shown in Table 5-1 for the years 1992 (year with lowest mean discharge) and 1995 (year with highest mean discharge) and the overall mean for the period (1991-2003).

**Table 5-1. PRO power plant parameters at León River.**

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>MQ [m³/s]</td>
<td>63.48</td>
<td>140.22</td>
<td>88.77</td>
</tr>
<tr>
<td>Design flow (( Q_{des} )) [m³/s]</td>
<td>17.75</td>
<td>17.75</td>
<td>17.75</td>
</tr>
<tr>
<td>Environm. flow (( Q_{eco} )) [m³/s]</td>
<td>10.5</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Power factor [MW/(m³/s)]</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Capacity factor [-]</td>
<td>0.799</td>
<td>0.972</td>
<td>0.891</td>
</tr>
<tr>
<td>Full load hours [h/y]</td>
<td>7,002</td>
<td>8,516</td>
<td>7,807</td>
</tr>
<tr>
<td>Part load operation days [d/y]</td>
<td>118</td>
<td>30</td>
<td>74</td>
</tr>
<tr>
<td>Part load operation days [%]</td>
<td>32.33</td>
<td>8.22</td>
<td>20</td>
</tr>
<tr>
<td>Shutdown days [d/y]</td>
<td>5</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Installed capacity [MW]</td>
<td>14.2</td>
<td>14.2</td>
<td>14.2</td>
</tr>
<tr>
<td>Electricity generation [GWh/y]</td>
<td>99.46</td>
<td>120.96</td>
<td>110.87</td>
</tr>
</tbody>
</table>

To further show the influence of the different discharge years on the power plant performance, the full load hours, and the numbers of shutdown and minimum operation days are shown in Figure 5-7 for the entire time series. It is evident that the varying discharge has a significant impact on the power plant operation. Also, the years with the lowest (1992) and highest (1995) discharge in the period are not necessarily the years with lowest and highest full load hours.

It is important to notice that years with lowest full load hours coincide with very well reported El Niño events of 1991-1993, 1996-1998 and moderate El Niño event of 2002-2005 [23,24]. Poveda [16] reported that the effects of the ENSO phenomena are manifested in Colombia by the decrease (during El Niño) and increase (during La Niña) of the river discharges.

With the selected parameters for \( Q_{des} \) and \( Q_{eco} \) the amount of shutdown days, where a power plant operation is not possible due to environmental constraints, is very limited. These days typically occur during the first 3 months of a year and it would also be possible to use this period for the scheduled shutdown for yearly maintenance. The mean full load hours are larger than 7800 h/y, which allow base load operation of the plant. An operation with high full load hours is also a prerequisite for technologies with relatively
high capacity related costs, to reach low costs of generating electricity. Larger power plants in terms of installed capacity also relatively reduce the investment of the power plant infrastructure.

![Graph showing full load hours, operation days with environmental flow (minimum operation), and shutdown days for a SGE plant at León River (1991-2003) for $Q_{des} = 17.75 \text{ m}^3/\text{s}$ and $Q_{eco} = 10.5 \text{ m}^3/\text{s}$.

Figure 5-7. Full load hours, operation days with environmental flow (minimum operation) and shutdown days for a SGE plant at León River (1991-2003) for $Q_{des} = 17.75 \text{ m}^3/\text{s}$ and $Q_{eco} = 10.5 \text{ m}^3/\text{s}$.

A critical aspect might be the amount of days with part load operation. During these days, the discharge after water extraction is constant so there might be longer time periods with no natural discharge fluctuations after the water extraction location (during part load operation the resulting flow after water extraction is the environmental flow). According to the shutdown days, the days with part load operation typically also occur during the first months of a year. This period can be limited by reducing the design flow, but this also reduces the power plant capacity. The impacts of water extraction on the river discharge are shown in Figure 5-8.

A different design flow would have an important impact on the power plant design parameters. To evidence this situation a parameter variation analysis was undertaken for the year 1998, which represents a mean discharge year ($MQ_{1998} = 88.32 \text{ m}^3/\text{s}$). This is shown in Figure 5-9. With increasing design flow the installed power plant capacity linearly increases. The electricity generation also increases but not linearly because of the decreasing capacity factor. The decreasing capacity factor is a result of the water extraction limitation by $Q_{riv}$ and $Q_{eco}$. 

Figure 5-8. Daily discharge and resulting flow after water extraction for a SGE plant at León River for the year 1998 for Qdes = 17.75 m³/s and Qeco = 10.5 m³/s.

Figure 5-9. Installed capacity [MW], electricity generation [GWh/y] and capacity factor in dependency of the design flow for a PRO power plant at León River for the year 1998 (Qeco = 10.5 m³/s).
In general, the determination of the design flow is the result of a trade-off analysis. From an economic perspective it is favorable to operate the plant with a high capacity factor and a related low design flow, which would lead to the lowest costs of generating electricity but also to small power plants in terms of capacity. On the contrary, there is an interest in high design flows to maximize the electricity generation, and to minimize the investments per installed kW, taking advantage of economies of scale.

The ecology of the river also limits the design flow. In León River, an increased design flow scenario of 45 m³/s (50% of extraction factor), would significantly increase the installed capacity and the electricity generation of the plant incorporating a still quite high capacity factor of 0.73. But under such a scenario the natural discharge behavior of the river is not sustained anymore. The consequences are 165 days a year with only constant minimum environmental discharge after water extraction, which represents a time span of 45% of the year. This suggests that due to environmental considerations the design flow has to be limited to a much lower value.

Therefore, the chosen design flow of 17.75 m³/s represent a balance between the desired goals: low costs, high electricity generation and low environmental impacts.

5.5 Environmental impacts

Simulations with ELCOM model were made to evaluate the impact of the operation of the plant on the salinity structure of the river, by comparing the change in mean salinity values in the defined transects. It shows that extracting 20% of the mean flow of the river, as much seawater, and passively discharging the brackish water at 5 m depth does not have a very distinct impact on the salinity structure, especially in the fresh- and saline water intake zones, and thus is not likely to affect the operation of the plant.

During dry season mean salinity of the mid-section (8-10 m depth) of the water column is decreased around 1 g/L due to the fact of brackish water discharge; while there is a slight increase in salinity in the riverbed near the mouth due to the reduction in river water flow(Figure 5-10). During the rainy season variation of salinity in the water column is not very significant, but there is an increase of around 10 g/L in the riverbed, caused by intrusion of saline water into the river (Figure 5-11). The fact that the mid-section of the salinity structure is not strongly affected for any season shows that the location of brackish water discharge is well selected according to natural salinities.

The salinity patterns are less influenced by the operation of the plant during the dry season than during rainy season. This is because the discharge of the rivers are low per se during dry season, therefore, the salinity patterns are more influenced by the fresh water
of Atrato River transported southward in the Urabá gulf by the dominant north winds during dry season, than by the Leon River discharge itself. Additionally, the river discharge during the power operation is never smaller than the environmental flow, so the fresh water extraction is smaller than the design flow or even null in some period during dry season.

Figure 5-10. Mean variation of the salinity (g/L) under operation conditions during the dry season, comparing with natural salinity structure.

Figure 5-11. Mean variation of the salinity (g/L) under operation conditions during the rainy season, comparing with natural salinity structure.

On the other hand, during rainy season the salinity patterns are mainly determined by the river discharge and the extracted flow is always the design flow. The reduction of the natural river discharge leads to a marked salt-wedge intrusion represented by an increase
of the salinity in the riverbed and superficially seawards comparing with non-operation conditions. Saline water intrusion may increase in the river mouth under fresh water over-pumping conditions. This highlights the importance of properly determining an environmental flow.

More detailed studies are needed to assess the environmental impacts, especially in terms of ecosystem response, sediment hydrodynamics and water quality. However, the presented results suggest that the impacts could be tolerable as there are no abrupt salinity changes in the water column.

5.6 Conclusions

The methodology presented aims to provide decision parameters to guarantee an efficient and sustainable operation of SGE plants. It focuses on main operational parameters such as fresh water availability and reliability as well as impacts on the salinity structure. This methodology can be generally applied to other locations taking into account the local conditions and environmental constraints. It serves as indication for the rough dimensioning of SGE plants, in terms of water extraction factors and the definition of design and environmental flows.

Choosing an extraction factor of 20% of the mean river discharge and setting an environmental flow equivalent the 12%, a power plant installation in León River mouth with a capacity of 14.2 MW and a mean electricity generation of 111 GWh/y could be possible. However, it is important to notice that these percentages should be properly defined for each location.

This methodology is the first step toward the definition of the operation thresholds and the optimal size of a SGE plant. It could be further expanded into an optimization technique, provided that there is abundant information and more knowledge on the site-specific environmental impacts. Nevertheless, as presented, it serves as an indicative reference of the extractable SGE resources from river mouths at local scale.

References


6. General conclusions and outlook

The next paragraphs summarize the key results and conclusions of this study in relation to the specific aims described in the introduction chapter. Afterwards the further research and outlook in the covered topics is discussed.

6.1 Suitability of harnessing SGE at river mouths

Only river mouths where stratification induces steady availability of high salinity differences over a short distance are suitable for harnessing SGE.

From comparative analysis of the SGE potential and the salinity structure under high and low river flow conditions for several representative river mouths worldwide, a classification of river mouths systems according to the physical suitability for harnessing SGE was derived. Here these systems are classified as suitable, partially suitable, and unsuitable systems (Chapter 2).

The classification is based on an introduced dimensionless stratification number depending on main hydrodynamic forcings that are readily determined for river mouths. This parameter considers both the strength and stability of the stratification: suitable systems require a persistently stratified salinity structure; partially suitable systems are less stratified, also, the strength of stratification changes in time or the mixing zone migrates along the estuary; unsuitable systems are characterized by weakly stratified or mixed salinity structures.

The tide is the most restricting forcing for harnessing SGE. Only river mouths with a mean tidal range lower than 1.2 m were found to be suitable or partially suitable systems. 30% of the coastal zones worldwide exhibit a mean tidal range exceeding 1.2 m; this includes for example the Amazon in North East of Brazil which accounts for 18% of the theoretical SGE potential from all river mouths worldwide. Thus, estimations of global and regional potentials conducted under the assumption that all river mouths can be used for SGE generation should be re-evaluated.
6.2 Site-specific potential

River mouths are brackish water systems with temporally and spatially varying salinity rather than strictly separated fresh- and saline water systems. Therefore, the available SGE resources from river mouths are not equivalent to the theoretical potential estimated from the salinity difference between fresh- and seawater as has been commonly assumed. Rather, it depends on the salinity difference between intake zones of diluted- and concentrated waters as well as on the distance between these zones, which defines the required energy to bring the waters to the power plant.

Accordingly the site-specific potential (SSP) was defined as the net available SGE potential at river mouths considering the trade-off between temporal variability of the theoretical potential and the energy losses by water transport toward the power plant.

The SSP of several river mouths was compared with the theoretical potential estimated from the maximum salinity difference between fresh- and seawater (chapter 2). Values of SSP between 0.2% and 80% of the theoretical potential were found for the studied systems, showing that the theoretical potential may substantially over-estimate the available SGE resources.

Once the intake locations of diluted- and concentrated waters are fixed the energy losses are constant, but the SSP is still variable due to the variability of the salinity in the intake locations. The effect of this salinity variability on the SSP was analyzed for various river mouths in the Colombian Caribbean Sea, by estimating the SSP without considering energy losses and comparing it with the theoretical potential (Chapter 4). Values of SSP near 100% of theoretical potential were found for Magdalena and León Rivers due to the steady salinity structures of these systems; on the other hand, SSP between 19% and 77% was found for Atrato River, depending on the season and ENSO phase. This result shows that available SGE resources from river mouths may significantly vary in correspondence with temporal variability of the salinity structure.

A sigmoidal relation was identified between stratification and site-specific potential, and a predictor for the SSP was derived (Chapter 2). The benefit of this predictor lies in the straight-forward application to a wide range of river mouths. The assessment of the SSP requires profound knowledge on the salinity structure of each river mouth, and a preliminary descriptor of the available energy resources is potentially a useful tool for rivers and energy management and policy making.
6.3 Sustainability of harnessing

SGE is, in principle, a clean and renewable energy source. The mixing of fresh water and seawater is part of the natural water cycle, the water is not consumed, heat is not added to the output stream, and greenhouse gases or other harmful effluents are not produced. However, harnessing SGE at river mouths is not totally harmless in environmental terms. The exploitation of any natural resource impacts the environment; but it remains to be determined how far the impacts are tolerable to ensure environmental sustainability.

For SGE these impacts mainly depend on the fresh water extraction factor. Analysis of the effect of extraction factor on the hydrologic regime of near 450 SGE-suitable river mouths worldwide showed that extracting 20% of the mean flow of the rivers induced low water periods are, on average, shorter than natural low water periods (Chapter 3), where low water periods are defined as the time with river flow below 30% of mean flow. This analysis also showed that an extraction factor of 40% already induces low waters during 6 months per year in various rivers, generating high environmental stress in these systems.

Local scale hydrodynamic simulations were carried out to evaluate the impact of extraction factor in the salinity structure of León River mouth (Colombia) by comparing the change in mean salinity values (Chapter 5). It was found that extracting 20% of the mean flow of the river, with as much seawater, does not have a very distinct impact on the salinity structure when the brackish output stream is discharged in a zone with similar salinity.

In conclusion, results show that a fresh water extraction factor of 20% is sustainably extractable for SGE generation, and 40% is beyond the limit for sustainable exploitation, considering the impacts on hydrology and salinity structure of studied river mouths.

6.4 Extractable resources

625 TWh/y of SGE are extractable from river mouths at a global scale considering site-suitability and environmental constraints (Chapter 3). This is equivalent to 6% of global theoretical potential from all river mouths, and 17% of theoretical potential from suitable river mouths. Extractable resources are low compared to the vast theoretical potentials; however, it is still enough clear energy to supply the individual electricity consumption of almost all countries of the world; and nearly 300 river mouths from more than 60 countries have a potential installed capacity of 10 MW or greater.
A methodology was proposed to assess the extractable SGE resources at local scales, and was applied to calculate the design parameters of a PRO power plant in León River mouth (Chapter 5). This methodology includes the main decision parameters to guarantee an efficient and sustainable SGE exploitation, such as: extraction factor, environmental flow, and capacity factor, as well as the evaluation of environmental impacts. The León river example can be used as a basis to assess the extractable SGE resources of other systems taking into account site-specific and environmental constraints.

6.5 Future research and outlook

A strong and stable stratification is the major prerequisite of river mouths for SGE generation, but it is probably not the only one. Water quality may also be decisive, as the energy required for pre-treatment reduces the net SGE potentials. The required energy depends not only on the water quality, but also on the efficiency of cleaning and anti-fouling techniques of the generation devices. Promising strategies have been recently proposed and tested in laboratory scales; however, the effect of water quality on the suitability of harnessing SGE at river mouths remains to be determined.

Limited reference studies describing the spatiotemporal variability of the salinity structure of river mouths with required resolution to assess the site-specific potential (averaged structure over a spring-neap tidal cycle under high- and low-river flow conditions) are available. Therefore, the confidence interval of the identified relation between stratification and site-specific potential is still broad. As more studies are conducted the confidence interval will be narrower, and a second generation of SSP predictor and suitability classification can be derived.

Only river mouths with tidal range lower than 1.2 m were found to be suitable locations for harnessing SGE, however, deep fjords may be an exception to this conclusion because here tidal mixing occurs relatively close to the surface and salinity remains high in deep waters even under strong tidal forcing. Further investigation is needed to determine the availability of additional extractable SGE resources from fjord-type systems.

It is important to notice that the extraction factor of 20% found to be sustainably exploitable must be considered as a reference number rather than a general rule, as only part of the possible impacts of this extraction were analyzed. Further investigations should aim for more holistic and interdisciplinary analyses of environmental effects in terms of ecosystem response, sediment dynamics and water quality. This topic is essential to determine the applicability of SGE at river mouths and is expected to be the focus of further investigation in the near future.
SGE is in an early stage of development compared to other renewables; however, several advantages make it a viable alternative energy source for the future, e.g.:

i) The capacity factor of SGE at river mouths is very high (84% on average); it is reliable and continuous, basic requirements for competitiveness that are major drawbacks for other forms of renewable energy.

ii) SGE is a decentralized energy source, the potential is very spread; the global maps of extractable resources (Chapter 3) show that suitable river mouths can be found all over the world, making SGE appropriate for cities and industrial zones, but also for remote communities settled near river mouths systems and lacking centralized energy access.

iii) For extraction factors ensuring ecological stability, SGE is a secure and sustainable energy source capable of contributing to green economic growth.

iv) SGE exploitation is not limited to river mouths; other systems provide similar or greater energy densities, e.g. desalination plants and industries whose effluents are brines; here, energy can be generated while the potentially harmful brines are diluted.

Bringing SGE to a commercially competitive stage will still be technologically and politically challenging, however, numerous investigations in recent years have shown that its development is feasible and is gaining momentum. Sustaining this trend depends on the joint effort of scientist, engineers, and decision makers.

THE END