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ABSTRACT

In this paper an attempt to analyze the feasibility of an electric energy generation system using tides as its source is made. Tides are a well known source of renewable energy, their energy is available as kinetic or potential energy and, unlike solar or wind power, tidal energy is easily predictable.

The use of this sort of energy is not new; several plants have been in existence since the 60's, such is the case of the biggest tidal barrage power plant in the world: La Rance, which is located in the estuary of the Rance River in France. It has a capacity of 240 MW(Marañón-Antolín, 2008).

Nowadays there are several types of technologies for tidal energy extraction; such is the case of those using tidal streams. While these systems are still in early development, they are expected to provide a considerable amount of electric energy in a not so distant future (IEA, 2009).

Currently, the technological capability to use tides as a source of energy exists; however, lack of detailed and thorough studies in certain specific regions is still a hindering factor.

In Mexico, the region of the Gulf of California is a well-known zone for its high tides; therefore, their effects have been studied in detail (Carbajal N. , 1993). Several papers have analyzed the possibility to use this region for electric energy generation (Hiriart-Lebert G. , 2009; Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010), but most of them lack of deep numerical analysis, geographical considerations and, in most cases, they only consider one type of technology.

An exhaustive quantitative analysis of this area will provide information and possible scenarios that may ease the decision of making a real tidal energy project for Mexico.

KEY WORDS: Tidal energy, Gulf of California, numerical analysis.

RESUMEN

En este trabajo se intentará analizar la factibilidad de un sistema de generación de energía eléctrica a partir de la energía de mareas. Las mareas son una fuente muy conocida de energía renovable en forma cinética y potencial y, a diferencia de la energía solar y eólica, es muy fácil de predecir.

La explotación de este recurso para generación de electricidad no es algo nuevo, varias plantas existen desde los años 60`s, como es el caso de La Rance en Francia, la cual es la central de energía de mareas más grande del mundo (Marañón-Antolín, 2008) del tipo embalse, con una capacidad de 240 MW.

Actualmente existen otros tipos de tecnologías que aprovechan la energía de mareas, como son los que aprovechan las corrientes generados por estas. Estos sistemas todavía están en etapas tempranas de desarrollo (IEA, 2009), pero se espera que provean una importante fracción de la energía eléctrica en un futuro.

La tecnología para el aprovechamiento de las mareas existe, sin embargo, estudios profundos del potencial de ésta en regiones específicas sigue siendo una limitante.

En México, la región del golfo de Baja California es una zona muy conocida por sus altas mareas, cuyos efectos han sido profundamente estudiados (Carbajal N. , 1993). Varios trabajos han analizado la posibilidad de aprovechar esta región para la generación de electricidad (Hiriart-Lebert G. , 2009; Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010), pero carecen de un análisis numérico profundo, de consideraciones geográficas o normalmente solo consideran sistemas de tipo embalse.

El análisis cuantitativo profundo de esta área proveerá información y posibles escenarios que facilitarían la toma de decisión sobre un proyecto real de energía de mareas en México.

PALABRAS CLAVE: Energía de mareas, golfo de baja california análisis cuantitativo.

ABSTRAKT

In dieser Arbeit wird der Versuch unternommen, die Umsetzbarkeit von einem Stromerzeugungssystem aus Gezeitenenergie zu analysieren. Die Gezeiten sind eine sehr bekannte Quelle für erneuerbare Energie, die Bewegungs- und Lageenergie enthalten und die im Gegensatz zu Wind- oder Solarenergie einfach vorhergesagt werden können.

Die Nutzung dieser Energieart zur Stromerzeugung ist nicht neu; mehrere Gezeitenkraftwerke sind seit den 60er Jahren in Betrieb, z.B. eines, das in der französischen Region La Rance in der Mündung des Flusses Rance gelegen ist. Dieses ist das grösste Gezeitenkraftwerken in Form einer Stauanlage der Welt und besitzt eine Kapazität von 240 MW (Marañón-Antolín, 2008).

Derzeit gibt es verschiedene Arten von Technologien, die die Gezeitenergie nutzen, etwa solche, die Gezeitenströmung verwenden. Diese Systeme befinden sich zur Zeit zwar noch in einem frühen Entwicklungsstadium (IEA, 2009), dennoch wird erwartet, dass Gezeitenenergie in der näheren Zukunft einen wichtigen Teil der Stromerzeugung ausmachen wird.

Gegenwärtig existiert die technologische Möglichkeit, Gezeitenenergie zu verwenden, dennoch wirkt die unzureichende Forschung in möglichen Regionen und Orten hemmend.

In Mexiko ist die Region um den Golf von Kalifornien sehr bekannt für ihre Hochflut. Daher sind ihre Auswirkungen eingehend erforscht worden (Carbajal N. , 1993). Verschiedene Arbeiten haben die Möglichkeit, diese Region zur Stromerzeugung zu nutzen, analysiert (Hiriart-Lebert G. , 2009; Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010), aber den meisten von ihnen fehlen vertiefte Berechnungen und/oder die Berücksichtigung der geographischen Bedingungen, zudem berücksichtigen sie in den meisten Fällen nur eine möglich Technologie.

Eine vertiefte mathematische Analyse dieses Bereiches würde wichtige information und mögliche Szenarien liefern, die die Entscheidungsfindung über ein tatsächliches Gezeitenenergie-Projekt in Mexiko erleichtern würden.

STICHWORTE: Gezeitenenergie, Golf von Kalifornien, mathematische Analyse.

I. INTRODUCTION

The ocean contains huge amounts of stored energy that can be used for the generation of electric energy. The forms on which this energy is present are: waves, salinity gradients, temperature gradients, hydro-thermal energy, (geological cracks at the bottom of the sea), tides and oceanic streams (IEA, 2009).

While the use of some of these sources is relatively new, some others, like the tides, have been well-known for several years.

When speaking of tidal energy, this is best known for the generation of electric energy through the use of barrages. These power plants require large extensions of land and a very big height gradient. While this power plants may offer a great production capacity, the areas where they can be located is very limited. Most of the actual electric energy coming from tides is generated with this kind of power plants and is important to mention that most of them were built between1960 and 1980 (Hammons, 1993; UK DTI, 2008).

Nowadays, due to their economical as well as ecological cost, these facilities have been slowly discarded as options, although there are still some projects for their construction around the world

At the present time, there are relatively few tidal plants constructed. The biggest one of these is the tidal energy power plant of La Rance, France. This power plant was built during the 60’s and has an installed capacity of 240 (Marañón-Antolín, 2008).

On the other hand, the energy provided by the tidal currents, has been taking importance in the last few years. Given its modular characteristics, small systems can be installed and doesn’t require high height tide levels as those required for the barrage stations. This technology, still in development, allows using tidal energy in more zones, but still it requires reaching a more mature state to be considered a solution for the energy problems (IEA-OES, 2008).

It can be noticed that, while there is enough technical knowledge on the subject to take advantage of this resource, there is still a great need for profound feasibility studies for this kind of projects in different areas around the world before this source of energy can take a place among the most important renewable energies.

In Mexico is well known that the area of the Gulf of California has the potential to be used for the generation of electric energy through the use of tides. Several studies have been realized on this subject (Hiriart-Lebert G. , 2009; Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010), but only a few offer a detailed analysis of the phenomenon in the area or do not considered other analysis but the barrage system.

A quantitative and deep study of the tidal phenomenon in the area combined with an analysis of the geographical conditions and the generation systems is required for an actual project to be developed in Mexico.

II. BACKGROUND

2.1. TIDES

Tides are a phenomenon known by humans for thousands of years, and therefore one of nature's best studied and predicted. Nowadays, there are diverse mathematical models capable of predicting and recreating the behavior of tides in any part of the world.

Tides owe their existence to the gravitational forces of the Moon, the Earth and the Sun; although there are some other conditions that affect their behavior, like the resonance, bathymetry, wind and friction at the bottom of the sea (World Energy Council, 2004).

2.1.1. Theory of Tides.

It is known from Newton's gravitational law that the gravitational force working in two objects that attract each other is directly proportional to their mass and inversely proportional to the square distance separating them, therefore.

$$f = G\frac{M_1 M_2}{d^2}$$

Where:

M_1= Mass object 1

M_2= Mass object 2

G= Universal Gravitational Constant

d= distance between the two objects

This would allow calculating the force exerted by the Sun and the Moon on a unit of mass of water in the surface of the earth.

Since the Earth and the Moon have their own rotational cycles (translation and rotation), the distance "d" will vary with the time; the combination of these movements generate two maximum forces each day (Hammons, 1993), thus creating the diurnal and semidiurnal tides.

Tides have periodical nature, which changes with the interactions of the gravitational forces of the Moon and the Sun. Based on this interactions, different kinds of tides can be found at the different points of the world (Hammons, 1993).

The centrifugal force created by the earth-moon system's rotation also plays an important role on tides. At the center of the earth, the centrifugal force and the gravitational force of the moon are balanced. On the earth´s surface this equilibrium is broken with a larger gravitational force on the side of the moon and a larger centrifugal force on the opposite side. This process is similar for the sun instead of the moon. These resulting forces are practically responsible of the presence of high tides in the whole world. The resonance of seas, semi-enclosed seas, gulfs, bays, etc with frequencies of the gravitational forcing is responsible for high tides observed in different water bodies of the world.

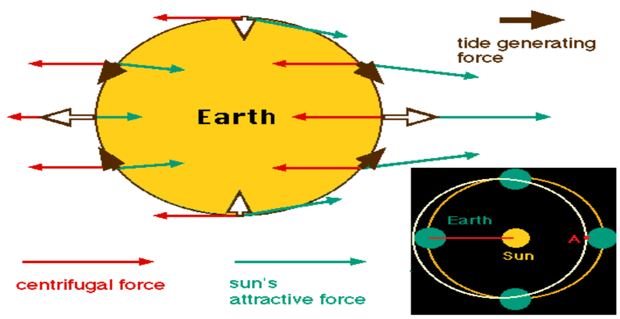

Figure 1 Centrifugal force over the surface of the Earth

Also translation creates certain degree of centrifugal force. While Earth is rotating around the Sun, this movement makes the bulge of water created by the rotational movement around the equator be bigger in one side of the earth than on the other.

2.1.2. Spring and Neap Tide

Moon's and Sun's gravitational forces are the main responsible for tides and also their forces can be constructive or destructive to each other. This is, when the Sun and the Moon are aligned in front of each other (whether it is facing each other or with Earth in the middle) their forces are constructive and generate a particularly high tide which is called "Spring Tide". On the other side, when the Sun and the Moon are not aligned but rather in a 90º position with the

Earth as an axe, their forces are destructive and tend to cancel each other; this is called neap tide. The cycle between spring and neap tide is approximately 14.7 days or twice a month.

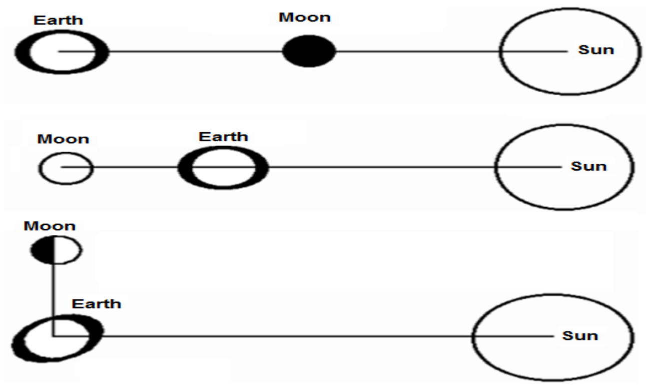

Figure 2 Spring Tide (top 2) and Neap Tide (bottom)

While tides may have a periodical nature, the amount and duration of the forces exerted over them makes it almost impossible to see a pattern and the ups and downs may seem quite erratic. Therefore, in order to make their analysis easier, tides are divided in their components by means of a Fourier analysis (see fig. 1).

The distance of the Moon to the Earth also changes due to its elliptical orbit, generating a variation also in the gravitational forces exerted on the ocean waters. When the moon is at its closest to the Earth (perigee) the tidal range increases and when is at its farthest (apogee) it decreases. If the perigee is to coincide with the spring tide, an especially high tide would arise.

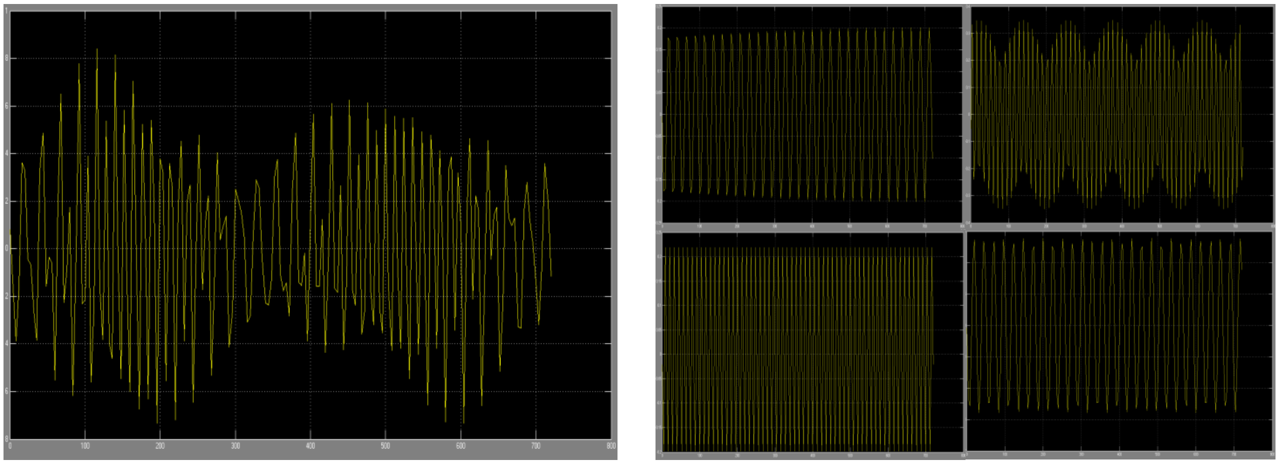

Figure 3 Harmonic analysis of a tidal wave. Left: The simulated behavior of a tidal wave. Right: Four of the main components constituting the tidal wave. Top left: K1; Top right: M2; bottom left: O1; bottom right: S2

In the Fourier analysis, a function can be represented as the sum of many harmonic components of different amplitude, frequencies and phases. Fourier transform allows representing the original function in the frequency space. The decomposition of the tides in their components is called tidal harmonic analysis (COOPS-NOAA, 2005). These components can be represented with a wave equation:

$$\zeta_n = \zeta_{n,0} cos(\omega t + \phi_n)$$

Where

$\zeta_n = Tide\ component$ "n" $height$

$\zeta_{n,0} = Height\ at\ time =\ 0$

$\omega = \frac{2\pi}{\tau}$

$t = time$

$\phi_n = wave\ phase$at Greenwich meridian

$\tau = period\ of the\ event\ (total\ time\ of\ a\ full\ cycle)$

By means of this analysis, it is possible to obtain all the components of a tidal wave. However, the main constituents, due to their effect on the tides, are those of related to the dominant astronomical configuration of the Moon and the Sun. Each one of these can be classified in diurnal and semi-diurnal components. Semidiurnal refers to those tides are present every half day or almost (hence the prefix "semi") thus generating two high tides and two low each day, and the diurnal refers to those taking close to a full-day's length and only having one high and one low tide each day.

There are several principal tidal harmonic components generated by the gravitational force of sun and moon. In theory, every planet in the solar system affects the tides, but as shown by Newton's gravitational law, their effect diminishes with the distance, therefore, the effect of most of them is infinitesimal compared to the effect of the Moon and the Sun. Considering only this two bodies and their position in relation with the Earth we can consider seven components accounting for almost 92% of the tides. The seven main components can be seen in Table 1.

Table 1 Tide components (Carbajal N. , 1993)

COMPONENT	SYMBOL	DURATION (Hours)
	Semidiurnal	
Main lunar	M_2	12.42
Main solar	S_2	12
Lunar elliptic	N_2	12.65
Lunisolar	K_2	11.96
	Diurnal	
Main lunar	O1	25.81
Main solar	P1	24.06
lunisolar	K1	23.93

It is important to mention that there are many more components for the tides phenomenon, but the seven components mentioned here are the most important in the Gulf of California due to the strength they exert on the tides.

2.2. MATHEMATICAL MODELS FOR TIDES

Mathematical models are often used to analyze and predict many natural phenomena, some as simple as heat transmission from one body to another to really complex ones like the behavior of the Earth's atmosphere. These models are quite different in form and complexity.

To successfully create a model it is necessary to know the physical basis of the phenomenon and through observation and mathematical methods, a set of equations that can describe the given phenomenon are created.

A slight introduction as to what tides are and what affects them was given; here, this factors will be explained and how are mathematically represented.

Mathematical models like the one used for this project, have several applications and derivations beyond simple tides predictions, like the growth of sand sediments (Montaño & Carbajal, 1999), pollutant dispersion, streams modeling (Carbajal N. , 1993) and like in this case, estimation of useable energy (Draper, Houlsby, & Oldfield, 2009).

The model used here, is a two-dimensional model of the implicit form and vertically integrated; this means that for this model, due to the size of the tide's phenomenon and the depth of the area of study, the change in the plane z ($\partial/\partial z$) is considered 0 and the component of velocity in z is neglected and total speed is made an average throughout the depth. This model was taken from Carbajal (1993).

There are two main equations in this model:

Linear momentum conservation: This equation describes the change of speed and direction of the fluid in the different axis (for this bi-dimensional case: x,y).

Continuity equation: Here the law of mass conservation is represented; this is that from a differential equation, the transport of a certain quantity (mass, energy, etc.) from one point to the other is described.

It is also important to notice, that within this equations are different factors that affect the movement of a fluid like viscosity (A_H), gravity (g), pressure (p), friction from the surface (wind) as well as from the bottom and, if the phenomenon lasts long enough, Coriolis force.

From these deductions, change through time of these variables in one of the axis (u) can be described:

$$\frac{\partial u}{\partial t} = -\left(\frac{u\partial u}{\partial x} + \frac{v\partial u}{\partial y}\right) + fv - g\frac{\partial \xi}{\partial x} + A_H \nabla_{\mathrm{H}}^2 u + \lambda\left|\vec{W}\right| W_x - r\left|\vec{V}\right| u$$

Where we have:

$-\left(\frac{u\partial u}{\partial x} + \frac{v\partial u}{\partial y}\right) = advective\ change$ $\quad u = transport$ in x and $v = transport$ in y

$$Coriolis\ force = 2\Omega \times \vec{V} \approx (-\mathrm{f}v, fu)$$

$g\frac{\partial \xi}{\partial x} = pressure\ gradient$ $\qquad A_H \nabla_{\mathrm{H}}^2 u = viscosity\ effect$

$\lambda\left|\vec{W}\right| W_x = surface\ friction$ (wind) $\qquad r\left|\vec{V}\right| v = bottom\ friction$

Where the absolute value of $|V|$ is given by the Euclidian norm:

$$\sqrt{u^2 + v^2}$$

And in the same way we obtained the second axis(v)

$$\frac{\partial v}{\partial t} = -\left(\frac{u\partial v}{\partial x} + \frac{v\partial v}{\partial y}\right) - fu - g\frac{\partial \xi}{\partial y} + A_H \nabla_{\mathrm{H}}^2 v + \lambda\left|\vec{W}\right| W_y - r\left|\vec{V}\right| v$$

And for the continuity equation:

$$\frac{\partial \xi}{\partial t} = \frac{\partial[u(H+\xi)]}{\partial x} + \frac{\partial[v(H+\xi)]}{\partial y}$$

$$H + \xi = total\ water\ depth, where\ \xi\ is\ the\ sea\ level\ change$$

A brief description of each term:

-Advective Change- is the movement from one point to another carried out by a fluid, causing transport, whether of mass or energy. The advection term is mathematically described as a vector (hence the representation of the term in the 2 or 2 dimensions) while the transported feature is scalar. Common examples of this are the transport of pollutants in the air or the silt in a river. Energy and enthalpy are also considered to be transported within the fluid.

-Coriolis Force (also known as Coriolis Effect)- This force is the apparent movement of an object in a non-inertial system. In the specific case of the earth, this effect is created by the angular velocity of the earth, a fixed coordinate system in the center of the earth being the inertial system and a rotating coordinate system on the surface of the earth being the non-inertial system.

Due to the fact that the earth finishes one rotation per day, the Coriolis force is quite small and can only be noticeable in phenomenon taking place over long distances and large periods of times (e.g. tides)

The Coriolis force is directly perpendicular to the earth's rotational axis and to the vector velocity of the fluid. The Coriolis acceleration would be given by the vector formula $2\Omega \times \vec{V}$ and the Coriolis force would be multiplied by the mass of the given fluid: $2m\Omega \times \vec{V}$. The dimensions for both $\Omega\ and \overrightarrow{V}$ are given by the dimensions of the model, which in this case are x and y.

For the case of earth's rotation $\Omega = 7.29x10^{-5}\, {rad}/{s}$

-Pressure Gradient- This term is determined by the height of the water column(ξ) in a given time and point$\left(\xi(x,y,t)\right)$. The pressure gradient describes in which direction and at which rate the pressure changes according to a given location.

This term finds its most significant use in atmospheric sciences. Usually, this vector is pointing upwards due to the fact that pressure decreases most dramatically with altitude. This upwards gradient is balanced with the attracting gravitational force of the earth. However, the horizontal component of the vector still plays an important role in wind and water stream circulation.

-Friction (bottom and wind)- is the force resisting the relative motion of two surfaces in direct contact with each other. The friction is dependent on the type of materials in contact and their speed. When made the calculation for a Euclidian space friction is proportional to the velocity vector $\vec{V}$ and, depending on the analyzed component, $u\ and\ v$. In geophysical fluid dynamics, a non-linear approach is often applied.

-Viscosity friction- Here is reflected the effect of the viscosity causing a certain kind of flow (e.g. turbulent, laminar) in each of the components $u\ and\ v$.

Viscosity can be described as a fluid's resistance to flow, therefore being referred to as fluid friction. The term $A_H\nabla_{\mathrm{H}}^2(u,v)$ shows the variation of the viscosity friction in the Euclidian space. Through the Laplace operator ∇_{H}^2 the change of viscosity in x and y can be represented.

The value A_H for seawater is estimated in $A_H \approx 1.88x10^{-3}Pas \cdot s$ (MIT, 2010)

2.2.1. Model Conditions

The purpose of the model above is to show the propagation of mass and energy, but for this, it is required a "initial condition" or "movement", which in this case, are the waves generated by the harmonic components of the tides.

These harmonic components provide the initial movement of mass and energy, thus they are used as the conditions at the open boundary of the system. These waves will propagate through the plane at the speeds of long waves $C = \sqrt{gH}$.

The condition at the open boundary is given by the summation of the wave equations (presented here in the harmonic analysis) of each component:

$$\sum_{1}^{n} \zeta = \sum_{1}^{n} \zeta_0 cos(\varpi t + \phi_n)$$

2.2.2. Kelvin Waves

The Kelvin waves are the natural wave motion in a rotating system like the earth. They exist in the ocean and in the atmosphere, they are modulated by earth's rotation (Coriolis Effect) and propagate along a vertical topographic boundary, located on the right side in relation to the direction of the wave propagation in the northern hemisphere or the equator (Wang, 2002). Their main feature is their unidirectional propagation, that is, that the wave will move towards the equator in a western boundary, towards the pole in an eastern one and cyclonically in a closed boundary. The movement will be counterclockwise in the north hemisphere and clockwise in the south.

Another important characteristic is that these waves reach their maximum in the boundary and decreases exponentially with distance from it.

Kelvin waves can be classified in two main groups:

- Boundary trapped
- Equatorially trapped

The lateral wall stops the flow motion across the boundary, and this absence of transversal motion is a main characteristic of a Kelvin Wave. The fluid is forced to move parallel to the boundary, thus vanishing the horizontal component of the Coriolis force and making the wave behave as if in a non-rotating system travelling with a speed $C = \sqrt{gH}$

Tides in the Gulf of California are subjected to this effect because they are transmitted as waves affected by the Coriolis force in an east-west boundary area.

2.3. TIDAL ENERGY

Nowadays, a strong dependence on energy for human society can be observed. Just have an idea, it is estimated that Mexico had 257, 455 GWh energetic consumption during 2007. From these 275 TWh is estimated that more than 80% comes from fossil fuels (IEA, 2007).

The price of these fossil fuels continues rising as they are being depleted, thus allowing renewable energies to take a more significant role in the world's energy matrix. One of these renewable energies that is still to be untapped for a large amount of power is tidal energy

Tidal energy can be found in two forms: potential and kinetic energy. Potential energy (E_p) is the work done by the rising of the mass of water from a certain level, whereas kinetic energy (E_c) is found in the speed of the water currents (Gorlov, 2001). All this can be expressed mathematically as:

$$E_p = g\rho A \int zdz = \frac{1}{2} g\rho A h^2$$

$$E_c = \frac{1}{2} m V^2$$

Where g is the force of gravity, ρ is the seawater density, zdz would be the vertical increase, A the area to consider, and h is the amplitude of the tide. In the case of kinetic energy, m is the seawater mass and V is the speed with which such body moves.

This, from a simple point of view, paints a very promising picture for the energy present in tides because of the perpetual movement of millions of tons of seawater all around the world, however it is really important to notice that, if there may be lots of energy in tides, as is the case with wind and solar energy, this energy is dispersed in large and difficult to reach areas. Some studies estimate that in tides alone can be found between 500 to 1000 TWh/year (Hammons, 1993; EA-OES, 2006), although some other sources mention some 3000 to 5000 Twh/year (Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010; Wu, 1999).

Other articles already exist on certain locations which are deemed adequate for tidal energy use. Studies on the Minas passage on the Bay of Fundy, Canada show that up to 7 GW can be extracted (Karsten, McMillan, Lickley, & Haynes, 2008); Ría de Muros, Spain was also a subject to such studies (Carballo, Iglesias, & Castro, 2009), showing that tidal currents may reach up to 2 m/s and yield $1.32x10^{-3}$MWh; and Portland Bill, UK has undergone a similar investigation (Blunden & Bahaj, 2006) such as this here elaborated.

2.3.1. Types of tidal energy generators

As mentioned before, just as with solar or wind, tidal energy is dispersed in large areas, and it has been estimated that only a third of this energy is located in shallow waters (Wu, 1999); for this reason, the first goal in tidal energy harvesting is that of recollecting it where it is more obvious and readily available: The rise of sea level.

The energy in this sort of phenomenon has been evident for centuries now, and its use as motor force is clear when looking at tidal mills all over Europe since the V century A.D. (Murphy, 2005).

It is not surprising that the first design to harvest tidal energy for the production of electricity have very similar concept: Storing of the energy generated by the increase of the sea level in the form of potential energy in a damn.

2.3.1.1. Barrage energy facility

The earliest tidal energy facilities ever build were of the barrage type, and it is worth noting here the biggest and most important of these facilities to date: France’s La Rance tidal power plant with 240 MW capacity. The rest of the existing plants don’t really have relevance in their countries’ energy matrix due to their production capacity and their country’s energy demand.

Next, a table with some of the countries with barrage power plants is display:

Table 2 Existing tidal energy power stations (Hammons, 1993; *WEC, 2007; **Lee, 2006)

Country	Location	Installed Capacity (Mw)	Damn Area (Km^2)	Mean Tide (meters)
France	La Rance	240	22	8.55
Russia	Kislaya Guba	0.4	1.1	2.3
Canada	Annapolis	18	15	6.4
China	Jiangxia	3.9	1.4	5.08
***UK**	Severn	Under development	520	7
****Korea**	Lake Sihwa	26 (under construction)	43	5.6

It is obvious from the table above that, despite the fact that tidal energy is well known, it has yet to take an important role among the renewable energies; however, several sites have been identified as potential locations for electric generation through the use of tidal energy, but most of them lack of deep thorough studies that can back up these statements. Most of these studies only cover the barrage type approach.

Another important reason for these systems not being so popular is the environmental impact they may have, high construction prices and the intermittence of electric generation (whereas tides are quite predictable and constant, they can only be used a couple of hours a day).

Table 3 Potential sites for tidal energy (Hammons, 1993;* Lopez Gonzales *et al*., 2010)

Country	Location	Potential Capacity (MW)	Área (Km^2)	Mean tide (meters)
USA	Passamaquoddy	400	300	5.5
	Cook Inlet	Up to 18000	3100	4.35
Russia	Mezen	15000	2640	5.66
	Tugur	6790	1080	5.38
UK	Severn	6000	490	8.3
	Mersey	700	60	8.4
Argentina	San Jose	7000	780	6
Korea	Bahía Carolim	480	90	4.7
MEXICO*	**San Felipe, B.C**	**200**	**50**	**5**
Australia	Secure	570	130	8.4
	Walcott	1570	260	8.4

There are some ways to solve the intermittence problem, if not completely, reduce the hours with zero production, such as the double barrage approach, where the damn is divided in two with hatches working as check valves (only allowing flow in one direction), with one side working with a high level and the other always with minimum level. Turbines are located in the divisor wall for the production of energy. Some other solutions have been proposed such as artificial lagoons and the well known pumped storage.

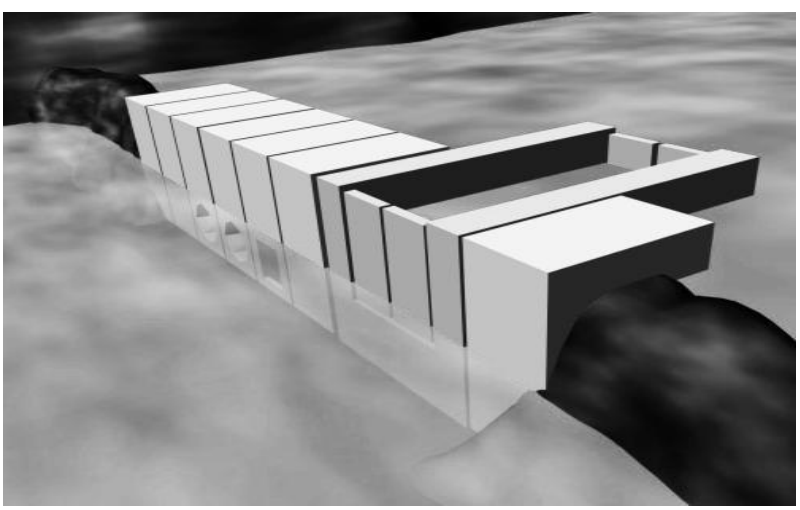

Figure 4 A double barrage system (Wikimedia Commons)

Hiriart-Lebert (2009) mentions some of the complications and limitations of working with a plant of this type. It is mentioned that the turbines will put a limit to the potential of these systems due to their diameter and the hydraulic work under which they have to operate; the diameter cannot exceed the sea minimum level. Also the effect of salt water has to be considered: corrosion and minerals crusts. Some studies already exist for the determination of sediment movement in the High Gulf of California (Carbajal & Montaño, 1999).

A simple way of analyzing the energy generated by this kind of facility begins considering a single turbine (Lopez Gonzales *et al*., 2010; Won-Oh, 2006). For this, certain factors have to be considered such as velocity, turbine area and fluid density among others. All this can be expressed in the next equations:

As mentioned before, potential energy is given by:

$$E_p = g\rho A \int z dz = \frac{1}{2} g\rho A h^2$$

And the power (P) of a turbine would then be:

$$P = \frac{1}{2}\rho g Q h$$

where:

$\rho = fluid\ density({}^{kg}/_{m^3})$ y $g = force\ of\ gravity$ (9.8 ${}^{m}/_{s^2}$)

$h = height\ difference(m)$ $Q = fluid\ flow$ (${}^{m^3}/_{s}$)

This can also be described as $Q = Av$

Where $A = Turbine\ sectional\ area\ (m^2)$ y $v = speed\ ({}^{m}/_{s})$

Speed can also be expressed as:

$$v = \sqrt{2gh}$$

From here we re-write the Power equation as:

$$P = \rho g A \sqrt{2g} h^{3/2}$$

As usual, it has to be considered that in every change of energy form, there are losses. Therefore an efficiency factor η has to be considered:

$$P = \eta \rho g A \sqrt{2g} h^{3/2}$$

Now, taking into account the periodical quality of the tides, the energy for an entire year can be calculated (in Wh).

$$E_{total} = \rho g V \frac{R}{3600}$$

Where $V = Damn\ volume\ (m^3)$ y $R = Tide\ range\ (m)$

Now, considering only the main component of the tides, M_2, a total of 705.5 periods is obtained throughout the year, so it is possible to say that the energy for a whole year is:

$$E_{year} = 705.5 \rho g V \frac{R}{3600}$$

2.3.1.2. Tidal Stream generators

This type of generators have gained interest in the last couple of years and there are several studies and projects about them (Garret & Cummins, 2005; IEA, 2009; IEA-OES, 2006). Tidal stream energy is harnessed similarly to wind energy: with rotor turbines.

A quite clear limiting factor in using this kind of technology is the sea depth; this affects in two ways: First, the deeper the sea bed is, the harder it will be to install and operate them.

Thus, their use is limited to shallow waters. Second, being installed in shallow waters limits the size of the rotor, therefore reducing the useful area.

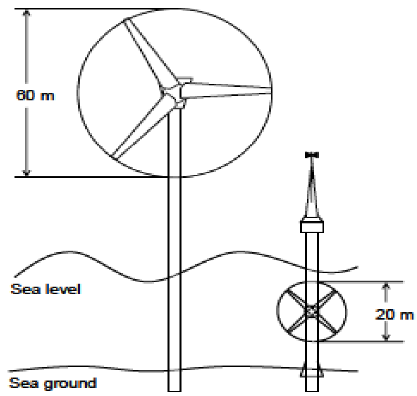

Figure 5 Comparison of a wind generator and a tidal stream generator (IEA, 2009)

If this may seem as a rather large impediment, it is necessary to analyze deeper this energy generation system. Gorlov (2001) mentions that the power derived from tidal stream is proportional to the cube of the velocity, thus, a slight increase in speed can mean a significant increase in energy. This is the exact same principle used for wind generators (Katlschmitt, Streicher, & Wiese, 2007) and the respective equation is:

$$P = \eta \frac{1}{2} \rho A v^3$$

Where:

$A = effective\ frontal\ area$ $\qquad$ $\eta = device\ effciency$

$\rho = fluid\ density\ (water)$ $\qquad$ $v = tidal\ stream\ velocity$

This way, it can be seen that for a flow of $0.1\, {}^{m}/_{s}$ the energy density is $0.5\, {}^{W}/_{m^2}$, for a flow speed of $2\, {}^{m}/_{s}$ the energy density would be $4000\, {}^{W}/_{m^2}$, this an 8000x increase in energy and only a 20x increase in speed.

Draper, Houlsby & Oldfield (2009) have developed a model that analyzes the tidal energy extraction through this system.

There are two different types of generatorswithin these devices: vertical axis and horizontal axis.

HORIZONTAL AXIS

As the name says, the difference lies on where the rotor axis is found, being these similar to the wind generators, which have their rotor axis in the horizontal plane, parallely aligned to the stream direction.

Also, within this type of generators there are two sub-classes, which are those of free flow and ducted flow. Basically, the difference is that the former are just like a wind generator using the flow that goes directly to them, whereas the ducted, use a duct to re-direct as much flow as possible towards their rotors (IEA, 2009).

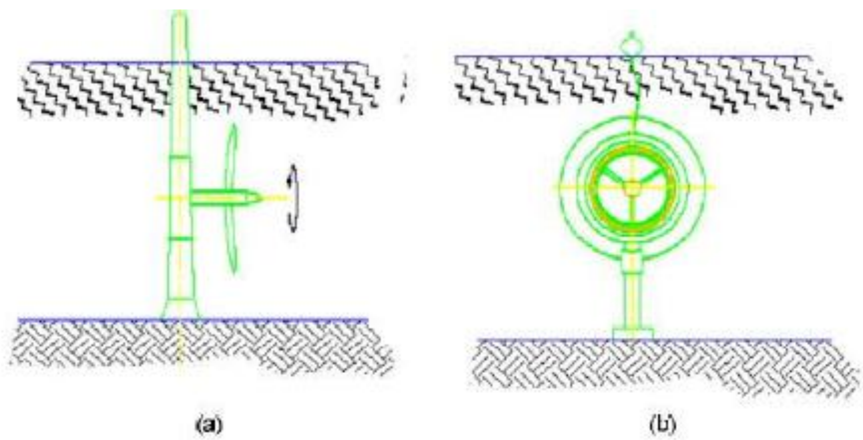

Figure 6 Scheme of horizontal axis generators. (a) Free flow (b) Ducted (IEA, 2009)

VERTICAL AXIS

This type of turbines were once also considered for wind energy generation, however, due to efficiency issues, they have been completely removed from this sector. But nowadays some ocean power companies have taken this design for its use with tidal streams. The main reason for reconsidering this design for tidal streams is that they can have larger cross-sectional area in relative shallow waters (opposite to the main disadvantage of horizontal axis turbines) (IEA, 2009).

As with the horizontal axis type, it has been proposed to have vertical axis turbines with free flow and ducted flow. A scheme can be seen in figure 4.

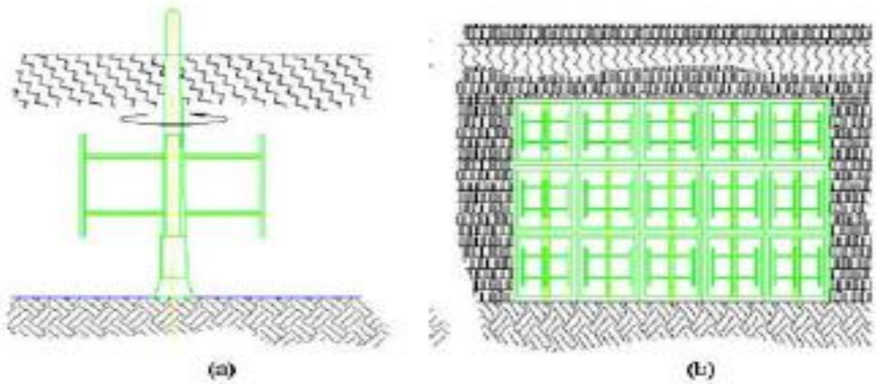

Figure 7 Scheme of vertical axis turbines with (a) free flow and (b) ducted (IEA, 2009)

2.3.2. Energy Density

An important representation of the amount of energy found in any form is its size-to-energy ratio; this is how much energy can be obtained from a unit of the source of energy. Whereas with fuels that are either solid or liquid, this will be measured either in liters, cubic meters or kilograms and usually expressed in J/kg or J/l, for some sorts of renewable energy this is best measured by area and represented in W/m^2. Wind, solar, wave and also tidal energy are best measured in this way. Reason for this is that these energies usually are time-dependent and their value is not fixed to a given amount of mass.

Depending on the type of energy the calculation will vary. For kinetic energy captured by a turbine (e.g. wind turbine, tidal stream) this would be:

$$P = \frac{1}{2}\rho v^3$$

And for potential energy (e.g. hydropower, tidal barrage):

$$P = \rho g \sqrt{2g} h^{3/2}$$

The energy density for wind is usually found to be within the range of 100-2000 W/m2 (NREL, 2002) and for solar energy this value is between 800-1300 (NASA, 1999).

2.4. RENEWABLE ENERGIES IN MEXICO

Regarding renewable energies and especially ocean derived energies, Mexico has not taken important pronouncements. Interesting is that, most of the important steps taken so far, have been with the cooperation of the German government. In 2004, the Mexican government, during the International Conference of Renewable Energies held in Bonn, Germany, made a commitment to increase at least in 40% the energy production from renewable energies regarding 2003 values. During this same event, a fair took place where German businessman and from other countries had a chance to learn about Mexican energy policies, legal framework and regulations, as well to be able to provide information of their companies to Mexican government.

In 2006, in cooperation with the GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit), the SENER (Secretaría de Energía) created a document where an overview of the status of the renewable energies in Mexico at that time (2006) was given (SENER, 2006).

As seen in the image below (Fig. 8) the amount of energy and types of renewable energies in Mexico is very small and Fossil fuels still account for 71% of the country's energy resource.

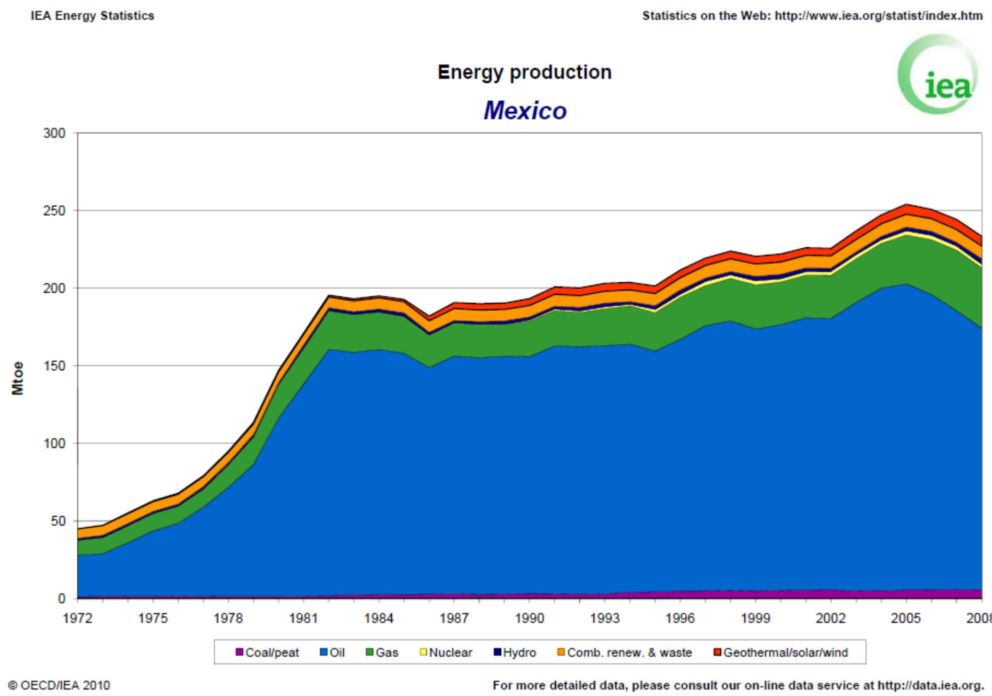

Figure 8 Energy use in Mexico by energy type (IEA, 2011)

2.4.1. Solar Energy

In 2004 there were 15 MW of photovoltaic energy installed in Mexico generating 8700 MWh/year, mostly used for electricity, waterpumps and refrigeration in rural areas. For thermal collectors, there were 570,000 m^2 of flat solar collectors installed, generating 270 GJ for water heating (SENER, 2006). Since then this sector has increased slowly. The installed capacity of photovoltaic panels for 2009 was 25.12 MW generating around 0.0429 PJ and for thermal collectors during the same year, the installed area reached 1,392,921 m^2, generating 6.71 PJ (ANES, 2011).

2.4.2. Wind energy

Currently there are several wind parks in the country, almost all of them in Oaxaca (there is only one out of this area, in Baja California), project Eurus being the biggest with 212.5 MW installed and second to this is La Venta I and Parques Ecologicos de Mexico with 83 MW and 79.9 MW respectively. This amounts for a total of 639 GWh/year (AMDEE, 2011). Several studies have been conducted regarding wind power potential in Mexico. These studies show that there are around 40,000 MW of potential in the country, locating most of this energy in three regions: Istmo de Tehuantepec, Yucatan and Baja California Peninsula.

2.4.3. Biomass

In 2004 biomass energy accounted for 8% of the primary energy consumption. This came from the bagasse burning in the sugar industry for electricity or heat production (92 PJ) and cooking and heating in rural areas (250 PJ). As of 2005, there were 19 MW generated by biogas, 70 MW from sugar cane bagasse and 224 MW through hybrid systems (oil-bagasse).

It has been estimated that it is posible to obtain between 2635 and 3771 PJ per year from bioenergies, however the actual use is 10 times less.

2.4.4. Geothermal

Mexico is one of the leading countries in energy production by geothermal energy. There is a total installed power 958 MW which amounts for 2% of the total generation capacity of the country. This facilities generate around 7000 GWh/year, which is 4% of the total electric generation (IIE, 2010).

Mexico used to hold the third place in geothermal energy generation til 2010 when was displaced by Indonesia.

There are four geothermal units in Mexico (Gutiérrez-Negrín, Maya-González, & Quijano-León, 2010):

- Cerro Prieto, B.C., 720 MW
- Los Azufres, Mich., 188 MW
- Los Humeros, Pue., 40 MW
- Las Tres Vírgenes, B.C.S. 10 MW

2.4.5. Tidal & Wave Energy

Regarding tidal and wave energy, little or nothing at all has been done in Mexico. Individual projects and reports have been published, but until now, there are only a few steps forward from part of the government. This steps, however are not unimportant and they were listed in the IEA-OES report of 2008 (IEA-OES, 2008).

- **Ocean Energy Policies**
    - A draft to promote the use of renewable energies(Law for the Advancement of Renewable Energy Sources in Mexico, LAFRE) was presented to the Congress.
- **Research & Development**
    - An amendment to the tax law was presented to create a tax exemption to those using renewable energies.
    - A law to charge 0.5% tax to energy importers was presented to support research and development in renewable energies.
- **Technology Demonstration**
    - The Federal Electricity Comission (CFE) is studying with Oceanlinx of Australia a possible joint test of a wave electricity generator.
    - CFE is studying the possible support for a Mexican inventor (Antonio Bautista) for a wave electricity generator fixed to the bottom of the sea.
    - The National University of Mexico (UNAM) has a project called IMPULSA studying the use of vere hot hydrothermal vents in the Gulf of California to generat electricity.
    - UNAM has built several models of a floating hydrogenerator (QK), and has tested them in simple channels. Plans are to test the QK in a towing tank in the USA.
    - Dr. Steven Czitrom of the Institute of Ocean Research of UNAM has developed a pump activated by the resonance of the waves. Several tests have been made.

But, despise all these advances in regulations and in technology development, there is still a lack of reports dealing with resource analysis of the ocean energy in the coasts of Mexico.

It is neccesary to create resource assessment reports in order to estimate whether the country is capable of utilizing the ocean as a source of energy.

Even in the event that the resource proved to be quite advantegeous, there is still much work to be done in the legal and political field before actually launching an actual tidal power plant in Mexico

2.5. GULF OF CALIFORNIA

2.5.1. Geographic Information

The region of sea found between the peninsula of Baja California and the main land of Mexico is called the Gulf of California or Sea of Cortez. It is bordered by the Mexican states of Baja California, Baja California Sur to the west and Sonora and Sinaloa to the east. It is 1,203 km long and 92-222 km wide and has coastline of 4,000 km and an area of 177,000 km^2.

The topography of the Gulf of California ranges from depths of 3000 meters to large areas with no more than 50 meters depth. As logical, these areas are found near the coastline, but it is also noticeable that most of the area of the upper Gulf is not below 500 meters depth (Fig. 5)

The distinction between shallow ground and deep seabed is an important factor to consider when selecting a site for energy generation. Also the distance to the coast and to local settlements will play a major role in the decision of a suitable place.

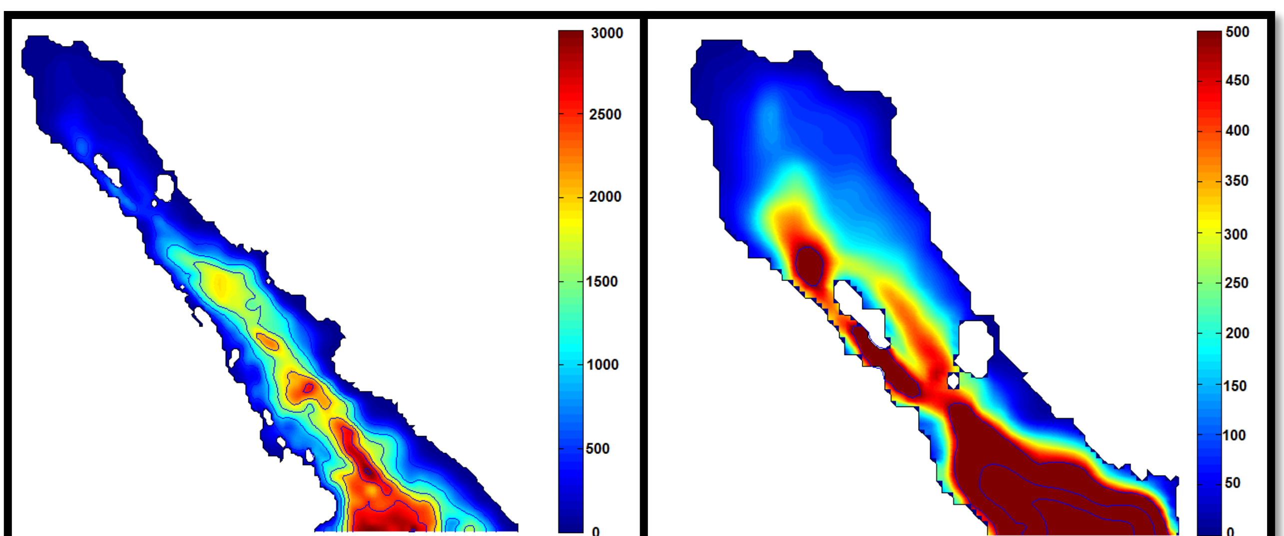

Figure 9 Left- Bathymetry of the Gulf of California. Right- Detail for the North part of the gulf. All values are meters below sea level.

2.5.2. Biodiversity

The Gulf of California is one of the most diverse marine environments in the planet and therefore it has been included in the UNESCO World Heritage list and is cited as "Islands and Protected Areas of the Gulf of California".

The Gulf is home to 695 vascular plant species, 891 fish species of which 90 are endemic, a third if the world's marine cetacean species and 39% of all marine mammals (UNESCO, 2007).

A complete list of the protected sites, the area they cover and their location can be seen in Figure 10 and Table 4.

Figure 10 UNESCO protected sites (UNESCO, 2007)

Since the Gulf of California is of such ecological importance, it is necessary to include this factor into the conditions required for a tidal power station. For the tidal power stations of the barrage approach, the impact of the ecological damage has been long a concern and for the tidal stream energy generator, this impact is still to be determined.

Table 4 UNESCO protected sites with name, location and protected area (UNESCO, 2007).

	SITE	AREA	COORDINATES
1	Upper Gulf of California and Colorado River Delta	**Property**: 86,638 Ha **Buffer zone**: 454,591 Ha	**N** 31 38 00 **W** 114 37 00
2	Archipelago of San Lorenzo	**Property**: 88,06 Ha **Buffer zone**: 49,637 Ha	-
3	Isla San Pedro Mártir	**Property**: 1,111 Ha **Buffer zone**: 29,054 Ha	**N** 28 22 30 **W** 112 20 15
4	El Vizcaino Biosphere reserve	**Property**: 49451 Ha	**N** 28 22 30 **W** 112 20 15
5	Bahia de Loreto National Park	**Property**: 206,581 Ha	**N** 25 50 35 **W** 111 13 00
6	Cabo Pulmo National Park	**Property**: 7,111 Ha	**N** 23 27 00 **W** 109 25 00
7	Cabo San Lucas	**Property**: 3,996 Ha	**N** 22 53 00 **W** 109 52 00

2.5.3. Energy in the Gulf of California

The Gulf of California is well known for its high tidal ranges (the principal lunar M2 component in the north of the Gulf may reach 120 cm) and some areas to the north work as natural channels increasing currents speed (Carbajal N. , 1993). Also to be considered is the large of extension of continental shelf in the outlet of the Colorado River. These factors provide an appealing scenario for the exploitation of the tidal resource in the Gulf of California.

Some studies have been carried out for the estimation of energy production in this area. Hiriart-Lebert (2009) makes an analysis of the production of energy through tidal barrage systems in the Upper Gulf of California where he describes two possible sites: the outlet of the Colorado River and the coast of Puerto Peñasco. The results of this study determined that the potential energy in these areas could be around 15 MW/Km^2 or 8.4 GWh/Km^2 and possibly up to 5 kW/m^2 as tidal stream energy from the channel el Infiernillo, adjacent to Isla Tiburon. Another article (Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010) considered the same approach for the port of San Felipe, also in the Gulf of California they estimated a generation of 400 GWh/year for a 50 Km^2.

In both articles the authors are explicitly stating that factors such a protected areas have not been considered and that the simulations were carried out in ideal conditions. Nevertheless, these analyses give a good starting point for some other studies regarding this case.

III. JUSTIFICATION

There is still a great amount of unexploded energetic potential in the ocean in the form of kinetic energy. Tidal energy is an example of this energy. Several studies have been developed estimating the potential of tidal energy in the entire world around 500 to 1000 TWh/year. However, real specific studies only exist in certain interesting areas, which right now account for 180 TWh/year approximately (Hammons, 1993; IEA-OES, 2006).

Most of this energy is found in unfeasible locations due to its distance or possibilities of production with the most common methods, but as the technology develops and the cost of fossil fuels increase, the appeal of this renewable resource grows.

From this point of view we can note the importance of generate thorough studies in different attractive regions for the production of electric energy from tides. One of these areas is the Gulf of California.

The Gulf of California has been considered before as an ideal place due to its known high tides in the Delta of the Colorado River, and some estimated values have been made considering this level increase (Hiriart-Lebert G. , 2009). Several studies have been made around this area using the typical approach of the barrage system (Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010), but most of them lack of a deep numerical analysis or do not consider the tidal stream approach for obtaining energy; some other papers take a quantitative focus, but are not specific in a given area (Draper, Houlsby, & Oldfield, 2009).

Based on estimated data of the Gulf of California, the generation potential of the area should be around 8.4 GWh/year or 15 MW/Km^2 (Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010).

It is important to generate a study where exact data of the energetic potential in its different forms is included, also considering the different kinds of electric generation devices without leaving behind the social, economical and environmental factors.

IV. HYPOTHESIS.

There is enough energetic potential in the tidal phenomenon in the Gulf of California to be used for the generation of electrical energy in a clean, cheap and renewable way.

V. OBJECTIVES

5.1. MAIN OBJECTIVE

- Determine the feasibility of electric energy generation from tides in the Gulf of California with different technologies based on energetic, geographic, economic and environmental factors.

5.2. SPECIFIC OBJECTIVES

- Improvement and use of a mathematical model that allows calculating kinetic energy, sea level height increase and streams velocities in the Gulf of California
- Selected and model areas considered of interest due to their qualities of stream velocity, energy and height elevation in order to obtain more precise information.
- Analyze the zones considering their topography and their geographic and environmental conditions.
- Estimate the electrical energy potential with different tidal energy generation systems.

VI. METHODOLOGY

6.1. METHODOLOGY REVIEW

Tidal energy has regained some of its popularity among the renewable energies due to the development of new devices such as the tidal stream generators. Since, several articles and reports have been written regarding the way of how to evaluate potential sites and the steps to follow previous the realization of an actual project. The purpose of these articles is to standardize the methodology and make information comparable.

Most of the reports agree in most of their steps: Site screening, resource assessment (energy, speed, and height), specific area selection, useable resource and energy extraction simulation (EPRI, 2006; Tarbotton & Larson, 2006; EMEC, 2009).

6.1.2. Site screening

According to the reports from European Marine Energy Center (EMEC, 2009) and the Electric Power Research Center (EPRI, 2006), the first step is locating an area suitable for tidal energy extraction. Usually these locations will be selected by general geographic features (bays, channels) as well as for known data of their extraordinary behavior, such as high current speed or considerable tidal range. Some other factors to considerer are the seabed geology and distance to an electric grid for interconnection.

6.1.3. Resource Assessment

Once a region has been selected, the estimation of the resource can be performed. For this task, experimental data as well as numerical models can be used. For maximum accuracy both should be compared. The numerical simulation would provide with estimated kinetic and potential energy values, which would then allow narrow down the region into specific areas of interest. It is important not to forget the previous conditions cited in the site screening section.

6.1.4. Useable resource and energy extraction simulation

If a real project is to take place in the selected area, the real resource should be estimated. That is, consider the actual extractable energy from the tidal stream without affecting its normal flow, efficiency of the system and size of the array.

Most studies have not yet reached this part or have made generalized calculation with no individualized data for a tidal stream device.

The EMEC suggest a series of steps in the evaluation of site for tidal energy. In the case of tidal energy in its potential form, the EMEC suggest to generate a monthly profile of the tidal range showing in it the points of spring and neap tide.

Overall, the main points for tidal potential energy evaluation would be:

- Annual profile of the tidal range
- Monthly profile of the tidal range showing the spring and neap tide
- A daily profile showing high and low levels during spring and neap tide

For the assessment of tidal stream energy, the main factor to evaluate is the current's speed. For this, in an initial approach, simulations may be used but field information from surveys will be necessary to corroborate this information. Also important are the major exclusion constraints for a possible project: protected areas, pipelines and cables, fishing areas (this factor is also related with the depth of the site) and some other renewable projects.

Ultimately, the EMEC gives a guideline as to how to develop the evaluation in order to provide accurate information. The total assessment project is divided in three stages, with the second one being split in two to make the difference between a pre-feasibility and a full-feasibility study.

Stage 1: Regional Analysis - Site screening

At this stage the project consist only in site screening with the purpose to locate potential locations within a large area, being a country or a region. The resource assessment would try to locate potential sites found within these areas so that they can be analyzed individually.

Stage 2a: Site assessment – Prefeasibility studies

In this stage the resource will be estimated similarly to stage one, with the difference of being performed in one of the already identified potential sites with higher detail.

Stage 2b: Site assessment –Full feasibility studies

This stage should already include all possible constraints for the project and an economical analysis should be included. If the study is favorable a permit request could be submitted (this will depend on country and local regulations).

Stage 3: Site assessment – Design development

At this point the exact area should already be identified and the required permits should be obtained. The chosen technology should be known and studied and through the results obtained from the assessment, carefully located.

Table 5 Project Stages

Stage	Category	Aim	Area	Constraints	Permit
Stage 1	**Regional Assessment**	Site screening	Region or Country	Limited constraints identified	No
Stage 2a	**Site Assessment**	Pre-feasibility	Whole estuary, channel etc.	Major constraints identified	No
Stage 2b	**Site Assessment**	Full-feasibility	Localized area in a channel, estuary etc.	All constraints identified and assessed	Applied for
Stage 3	**Design Development**	Design Development	Localized area in a channel, estuary etc.	All constraints assessed	Obtained

Additional Information for the analysis on each stage is also provided in table 5.

Table 6 Stages of the assessment of the tidal resource

	Stages of the Assessment			
	Stage 1	Stage 2a	Stage 2b	Stage 3
Harmonic analysis (minimum no. of constituents)	2	4	20	20
Modeling (grid resolution)	5 km	<500 m	<50 m	<50 m
Field Survey (period of collection)	No	2 days (transects)	1 month	3 months

According to this information, the project here presented would be considered within Stage 1, although it already considers some factors taken into account on more advanced stages.

The results obtained in Stage 1 are only meant to provide a rough estimation of the resource and to pinpoint areas of interest. Underestimation of the resource is likely to happen due to the size of the grid used for the numerical model or the distance from the measuring probe to the actual area of study if survey data is used.

6.2. GENERAL OVERVIEW

In order to accomplish this paper's objective, several simulations were carried out with a mathematical model that represents the tidal phenomenon in the Gulf of California. The model used for this task is, due to the type of phenomenon and area, is a 2-dimensional, vertically integrated implicit model.

Through this model, information about the amount of kinetic energy, sea level height increase and streams velocities in the Gulf of California were obtained. The initial modeling was carried out considering a 5.5 km grid. Once this simulation was made and the results were analyzed, the possible areas were narrowed down.

The areas were chosen based on their properties, such as energy, speed and height. These were evaluated then considering also their topography.

Other factors were considered as well, such as distance to the closest urban settlement and grid connection, as well as restricted areas (fishing, trade routes, and natural reserves) and conditions of the sea floor.

With the obtained data from the model, calculations to determine the total electrical generation from different generating devices were performed, and based on these results, suitable areas were pin-pointed.

All these activities were performed in a theoretical way. Due to the fact that there are several models for this area and the required information to complete the analyses is available to the public in general, all that is required is a thorough data recollection and a computer with one or several mathematical software such as Maple, Fortran or Matlab.

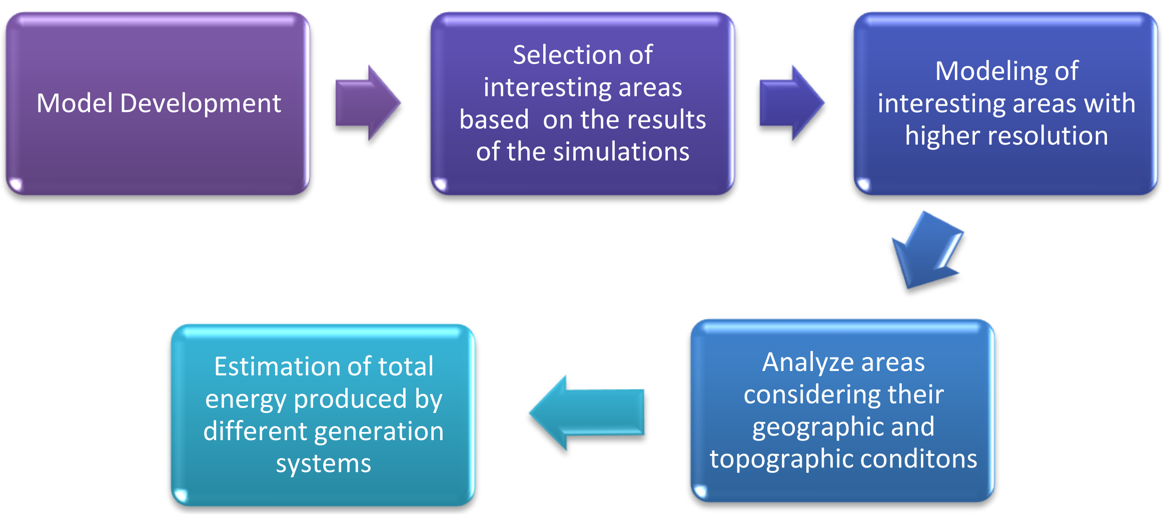

Figure 11 Scheme of the methodology

6.2.1. The Mathematical Model

The simulation's area was forced from the south points of the Gulf of California along a line joining Cabo San Lucas and Mazatlan to the northernmost points of the Colorado River mouth. Information for the bathymetry of the Gulf of California from Carbajal (1993) was used. Seven main tidal components were used at the open boundary with information from Cabo San Lucas and Mazatlan; interpolation for each point at the open boundary is calculated. These components were chosen due to the fact that they describe almost 91% of the phenomenon, although for more advanced stages of the evaluation more components will be required.

The data for the open boundary conditions is shown here:

Table 7 Amplitude & phase for the open boundary

	Period (hr)	Amplitude (m)		Phase	
		Mazatlan	Cabo San Lucas	Mazatlán	Cabo San Lucas
M2	12.4206	0.349	0.35	98.81	94.28
S2	12	0.242	0.237	102.19	100.6
K1	23.9344	0.201	0.225	177.52	182.8874
O1	25.8193	0.139	0.148	164.961	172.501
N2	12.658	0.081	0.093	93.658	89.278
K2	11.9672	0.064	0.065	101.655	101.075
P1	24.066	0.067	0.074	174.32	182.1125

6.2.2. Selection of areas of interest

As mentioned before, this project attempted to determine sites of interest for tidal energy in a wide extension. The size of the grid (5.5 Km) allows for a general overview of the whole Gulf of California, but the lack of resolution threw off actual values for about 50%-100% (depending on the grid size) (EMEC, 2009). The size of the grid does allow modeling correctly phenomenon such as Kelvin waves, which decrease exponentially as they move away from the coast or the actual speeds in narrow canals near the coast.

However, the results can be trusted to provide a general picture of the spacial distribution of the potential energy found within the Gulf of California. Locating areas with values already showing promising results with a grid this size may indicate that the actual results may be quite favorable.

Also important is the fact that some areas can already be ruled-out due to certain characteristics such as distance to grid, protected areas and such.

VII. RESULTS

As mentioned before, the model used was a vertically integrated 2-D model, simulating 7 tidal components, 3 diurnal and 4 semidiurnal. Values for the amplitude and phase of these seven components are already shown in table 7.

The model was run on a Fortran Compiler and the graphics and some additional calculations were obtained using MATLAB.

7.1. TIDAL RANGE SYSTEMS

According to the assessment protocol issued by the EMEC (2009), for the evaluation of energy generating systems using the potential energy of the tides, an assessment of the tidal range is necessary. For this purpose, the model calculated the average tidal range during a period of a year.

It is important to remember that this first estimation shows the averages of the tidal range for a year, thus does not show the maximum level possibly achievable in a region. From these results, sites of interest were selected.

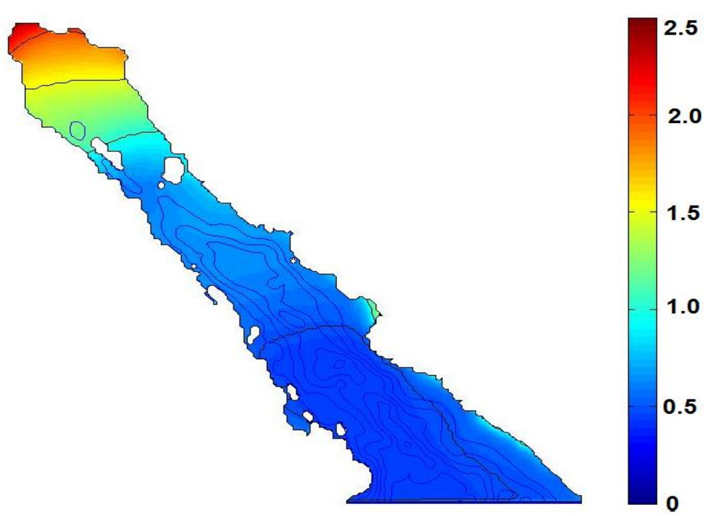

Figure 12 Annual Average Tidal Range

From figure 12, it can be seen that most of the north part of the gulf presents high tidal ranges reaching 2.5 meters in average. Some areas colored light blue and yellow on the east coast of the Gulf may also prove interesting for energy generation, especially in the bay of Yavaros, where the geography might help for a construction of this type.

Sites showing a tidal range of at least 1 m were selected. Within this range, the whole north part of the gulf can be included. The sites selected to represent these areas were the following:

- Puerto Peñasco
- San Felipe
- Puerto Refugio
- Bahia de Los Angeles
- Yavaros
- Topolobampo

These sites were elected due to the availability of simulated as well as experimental data. The amplitude and phase information on these sites was obtained from Marione (1997). The simulation of the tides behavior on this site was modeled using only three constituents: M_2, S_2 and K_1. Values for each of these places and their tidal components can be seen in table 8 and their locations can be seen in Figure 13.

Table 8 Phase & Amplitude for selected sites in the Gulf of California (amplitude is given in cm)

Location	Component					
	M2		S2		K1	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Puerto Peñasco	163	65.3	89.3	64.1	38.8	80.9
San Felipe	174	76.5	95.5	76.4	39.4	86.3
Puerto Refugio	108	66.8	57.3	64.8	35.5	81.4
Bahia de los Angeles	73.2	67.8	37.3	64.9	32.9	81.7
Yavaros	19.6	283	15.5	275.5	25.5	76.3
Topolobampo	24.5	259	18.1	259	24.2	79.8

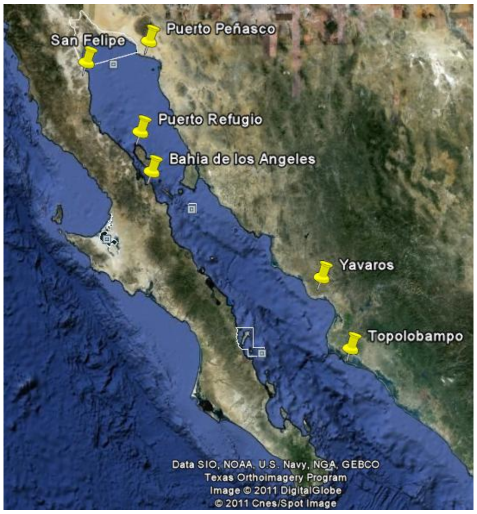

Figure 13 Selected Sites Location

The tidal range simulations were performed with a Simulink model following the wave equation for each tidal component:

$$\zeta_n = \zeta_{n,0} cos(\omega t + \phi_n)$$

As stated in the EMEC protocol, graphics showing the behavior of the tidal range during a year and a month were created for each site.

7.1.1. Puerto Peñasco

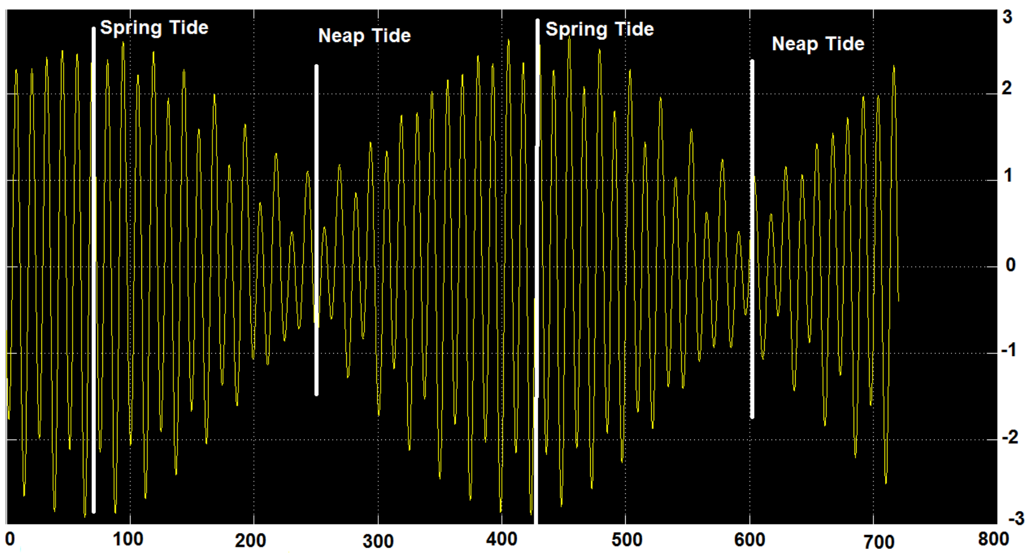

Figure 14 Tidal Range in Puerto Peñasco - 30 day Cycle

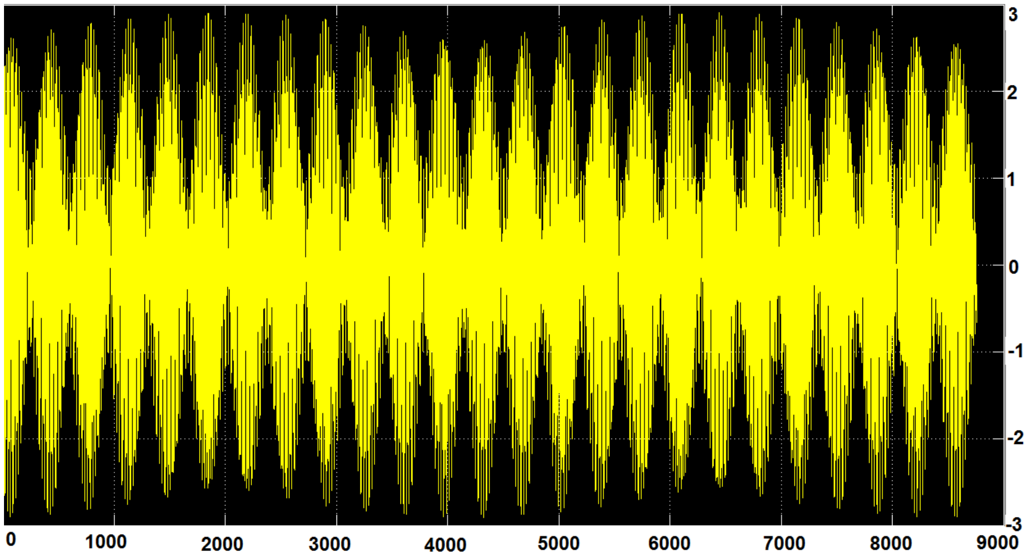

Figure 15 Tidal Range Puerto Peñasco - Full year cycle

Puerto Peñasco exhibits a tidal range of 5.8 meters at its highest and year average of 2.27 meters. Since the calculations were not made to fit exactly within a given year, the denomination of each of month will only be numerical (from 1 to 12) and shown in tables 9 to 11.

7.1.2. San Felipe

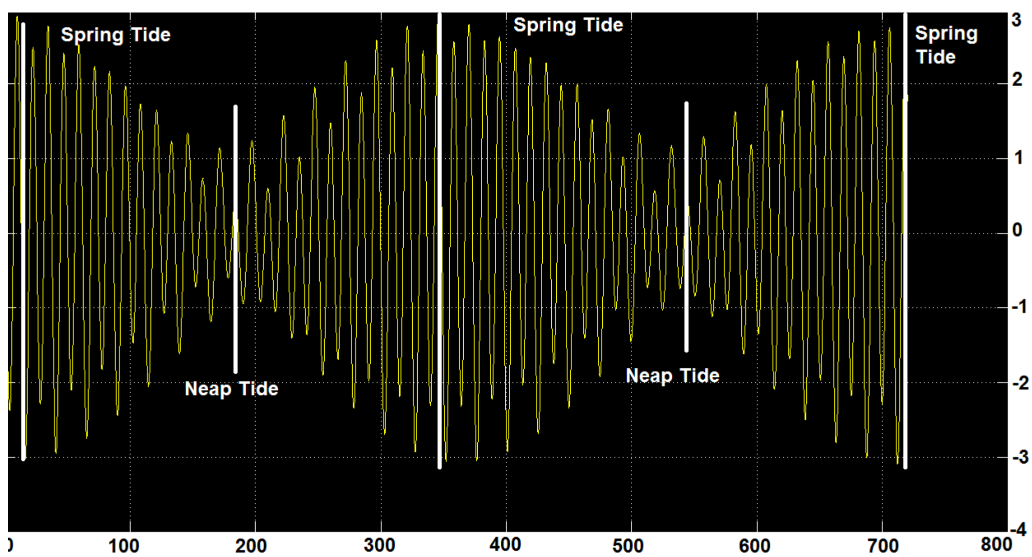

Figure 16 Tidal Range in San Felipe - 30 day Cycle

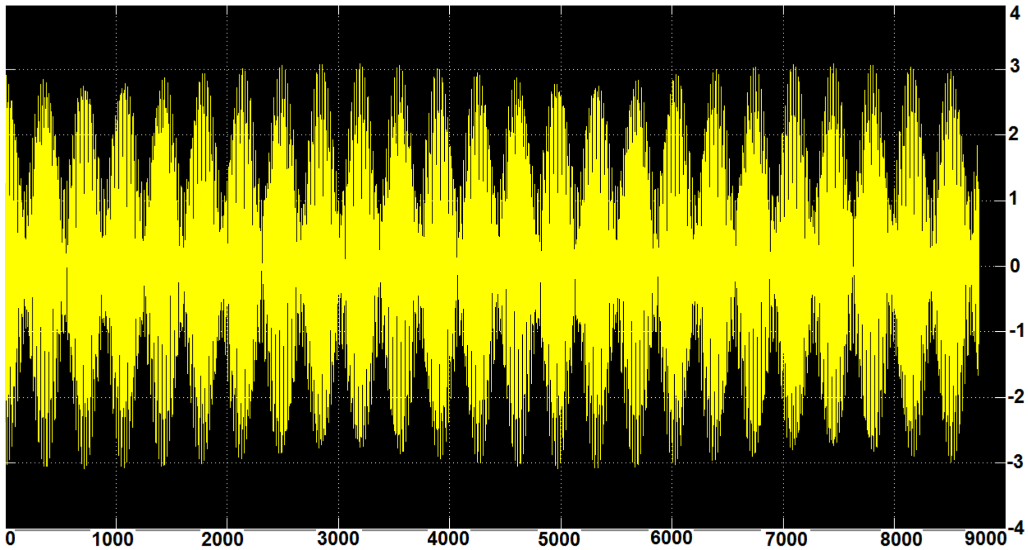

Figura 17 Tidal Range San Felipe - Full year cycle

For San Felipe, the value for an average tidal range is of 2.41 m and an average maximum of 6.12 m. The maximum tidal range is 6.17 m.

7.1.3. Puerto Refugio

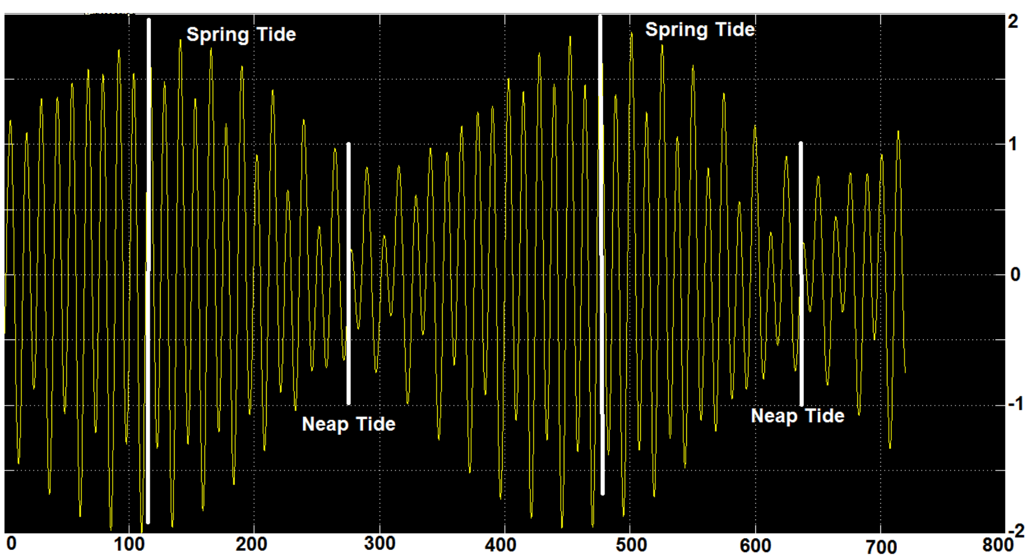

Figure 18 Tidal Range Puerto Refugio - 30 days Cycle

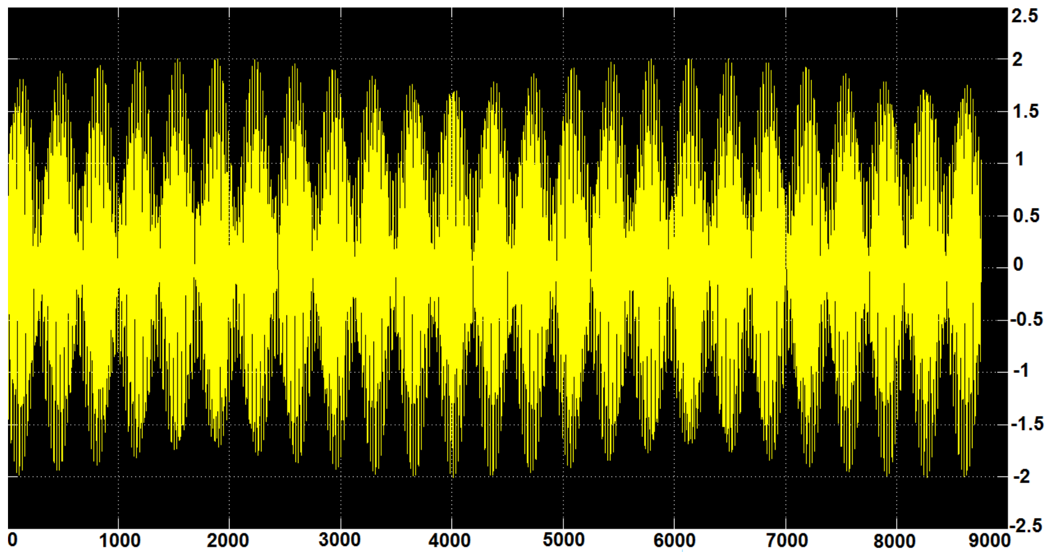

Figure 19 Tidal Range Puerto Refugio - Full year Cycle

Puerto Refugio exhibited a mean tidal range of 1.52 m and a mean maximum range of 3.97 m and having values as high as 4.02 m.

7.1.4. Bahia de los Angeles

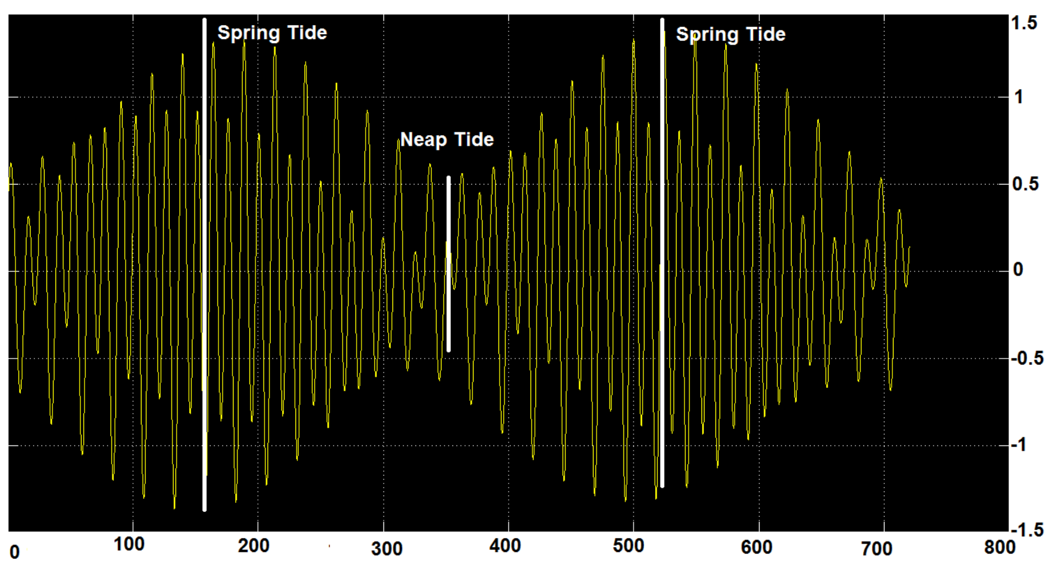

Figure 20 Tidal Range Bahia de los Angeles - 30 days Cycle

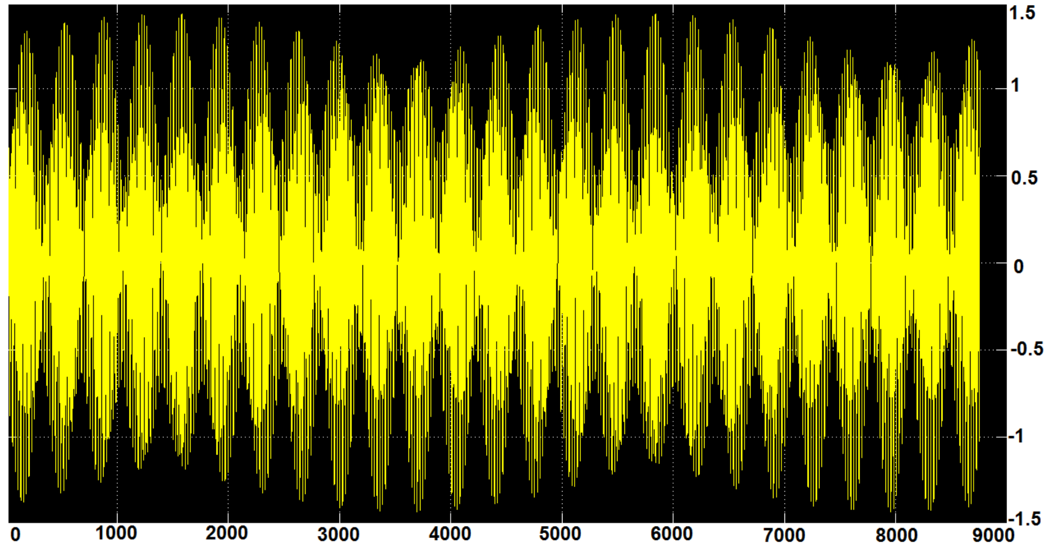

Figure 21 Tidal Range Bahia de los Angeles - Full year Cycle

Bahia de los Angeles is located in the state of Baja California Norte, and it is now for various touristic and adventure activities, such as rallies and camping. The maximum tidal range reached in this area is only 2.87 m.

7.1.5. Yavaros & Topolobampo

These two sites showed in the initial approach a high average tidal range (around 1 m), giving the possibility that higher tidal ranges where found. However, once the site-specific simulations were performed, the maximum values never surpassed 1.2 m.

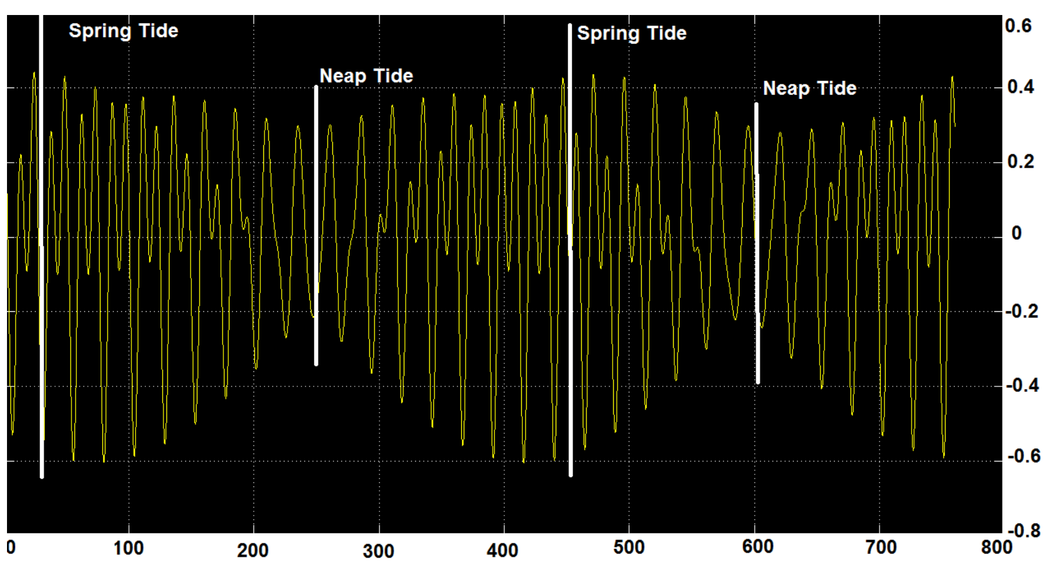

Figure 22 Tidal Range Yavaros - 30 days Cycle

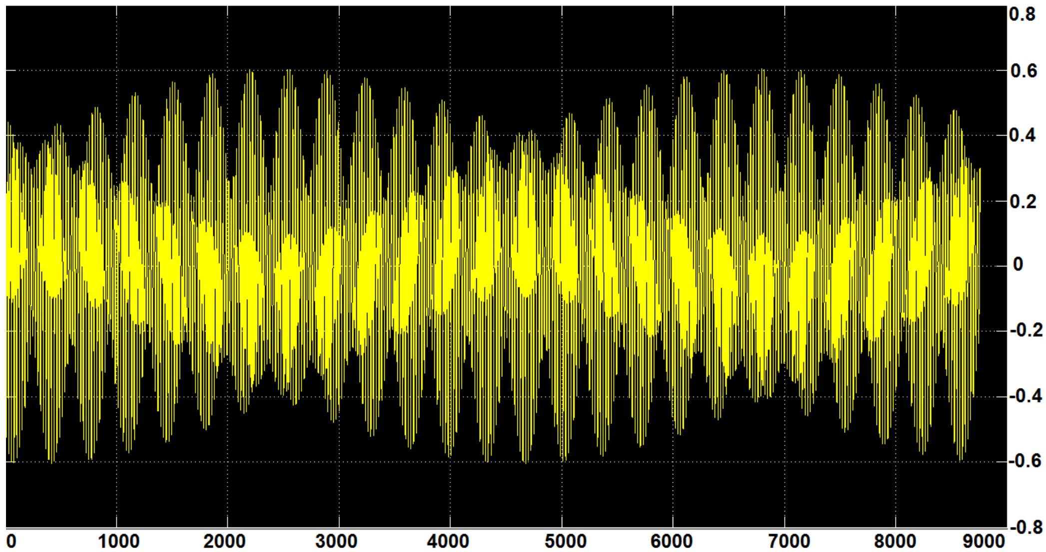

Figura 23 Tidal Range Yavaros - Full year Cycle

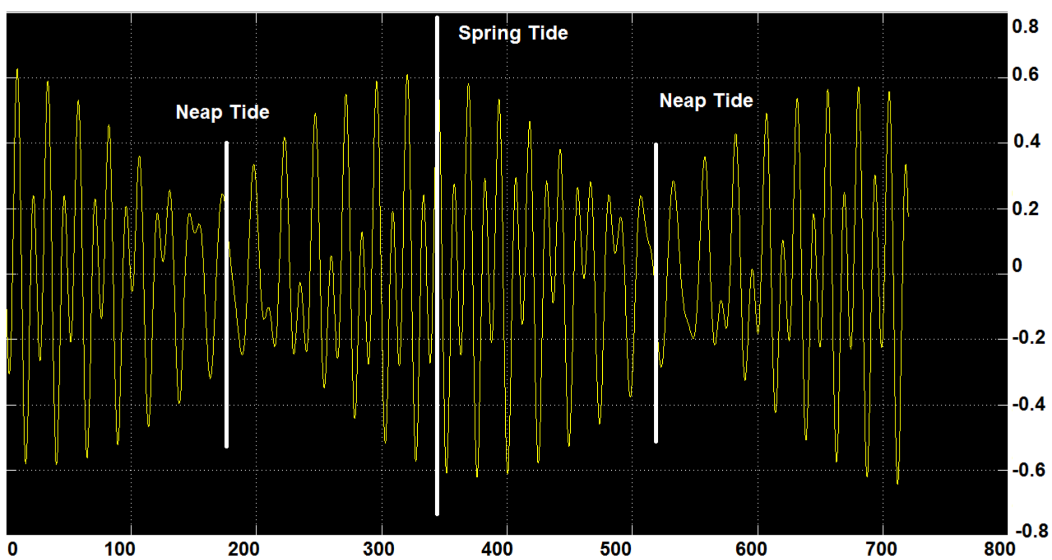

Figure 24 Tidal Range Topolobampo - 30 days Cycle

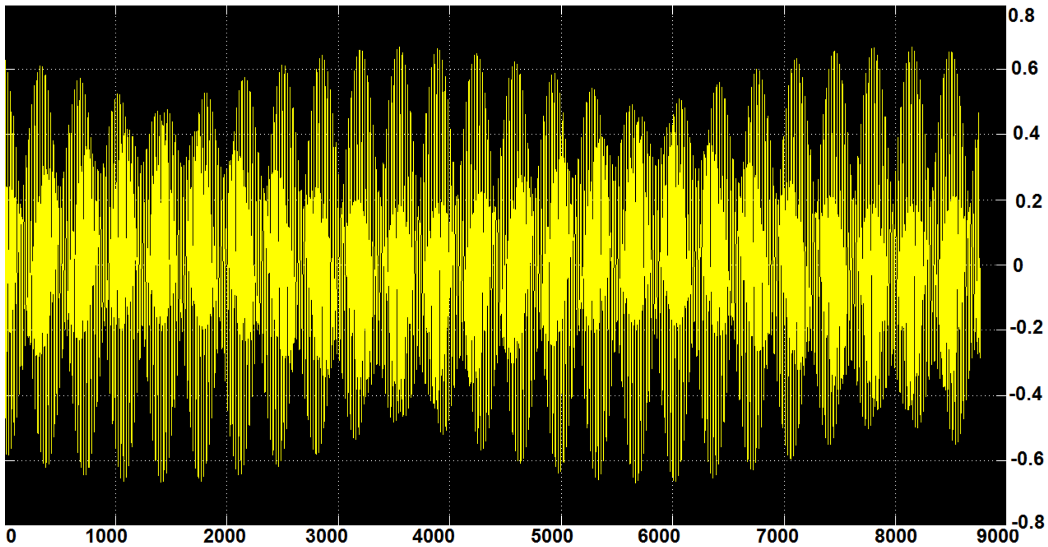

Figure 25 Tidal Range Topolobampo - Full year Cycle

Table 9 Maximun monthly tidal range values for the selected sites

Maximum Tidal Range (meters)						
	Puerto Peñasco	San Felipe	Puerto Refugio	Bahia de los Angeles	Yavaros	Topolobampo
Month 1	5.80	6.17	3.97	2.76	1.21	1.29
Month 2	5.67	6.16	3.95	2.85	1.18	1.33
Month 3	5.81	6.03	4.00	2.86	1.18	1.32
Month 4	5.78	6.14	3.98	2.77	1.21	1.28
Month 5	5.74	6.17	3.95	2.85	1.15	1.33
Month 6	5.81	6.02	4.02	2.86	1.20	1.33
Month 7	5.75	6.16	3.92	2.77	1.21	1.27
Month 8	5.75	6.14	3.99	2.85	1.16	1.33
Month 9	5.81	6.06	4.00	2.86	1.20	1.33
Month 10	5.78	6.15	3.93	2.79	1.21	1.26
Month 11	5.73	6.17	3.98	2.87	1.17	1.33
Month 12	5.80	6.07	4.01	2.85	1.19	1.33

Table 10 Average tidal range value for each location and each month

Average Tidal Range (meters)						
	Puerto Peñasco	San Felipe	Puerto Refugio	Bahia de los Angeles	Yavaros	Topolobampo
Month 1	2.28	2.44	1.51	1.04	0.42	0.46
Month 2	2.29	2.45	1.53	1.04	0.41	0.45
Month 3	2.30	2.44	1.52	1.04	0.42	0.45
Month 4	2.29	2.42	1.53	1.04	0.42	0.45
Month 5	2.29	2.42	1.53	1.06	0.42	0.45
Month 6	2.29	2.41	1.54	1.05	0.41	0.45
Month 7	2.27	2.40	1.53	1.05	0.41	0.45
Month 8	2.27	2.38	1.53	1.06	0.42	0.44
Month 9	2.26	2.38	1.53	1.06	0.41	0.45
Month 10	2.25	2.38	1.51	1.05	0.41	0.45
Month 11	2.23	2.40	1.51	1.05	0.42	0.45
Month 12	2.23	2.40	1.51	1.05	0.41	0.45

Table 11 Annual average values for selected locations

	Year Averages (Meters)		
	Max	Min	Average
Puerto Peñasco	5.77	0.0012	2.27
San Felipe	6.12	0.0016	2.41
Puerto Refugio	3.97	0.0009	1.52
Bahia de los Angeles	2.83	0.0003	1.05
Yavaros	1.19	0.0003	0.41
Topolobampo	1.31	0.0003	0.45

All the values in tables 9 to 11 were produced by mathematical simulations and these simulations where carried out using Matlab Simulink.

7.2. Tidal Stream Systems

For those systems using the kinetic energy of the tides, it was required to estimate the speed of the tidal currents in the evaluated area. As mentioned in the previous section, this study provides only a first approach, and whereas the values shown here are correct, the grid size prevents them from being accurate in a smaller scale. Let's not forget that current speed will increase in zones that might work as funnels, making area size an important parameter for current speed calculations.

Tidal Stream energy systems are regarded as more "ecologically friendly" as the Tidal Range systems for the main reason that no large construction blocking a section of the sea is needed and don't block regular flow. However, considering the fact that high speeds can be reached mostly by a resonating effect or by continuity, there is the concern that extracting too much of the current speed might disrupt this resonance and dramatically decrease the currents, moreover, it might have ecological impacts by disrupting the usual flows and transport mechanism.

This issue has been considered and studied theoretically. One of the suggest that the maximum extractable energy from tidal currents should not exceed 10% (Bryden, Melville, & Grinsted, 2004), lest risking reducing the speed to a disrupting level; in the EPRI report (2006) a value of 15% is used as maximum extractable energy.

While tidal stream turbines and wind turbines might seem similar at first glance, their source of energy and its behavior is quite different. Wind turbines obtain energy from the lower turbulent boundary layer of the atmosphere and slow down the wind directly behind them. However this slow wind "replenishes" its energy from air flows from the higher layers of the troposphere, whose width is around 16-18 km around the equator and 10 km around the poles. The same does not apply for tidal stream turbines. Tidal stream turbines are constraint in a limited volume of water, usually in depths no bigger than 100 m, therefore limiting the flows from where slowed-down currents could replenish their speed.

In other study, simulating a sea-loch or bay (Bryden, Melville, & Grinsted, 2004), the extraction of energy was considered to be 30% and showed no considerable reduction of speed or flow degradation. It is stated in this article that more than 30% of the energy could be extracted from locations such as sea-lochs, bays, fjords and other inlets or outlets. This point proves important for the area of the high Gulf of California where the Colorado River joins with the gulf.

7.2.1. Flow Speed Calculations

Flows in the whole area of the Gulf of California were calculated using the hydrodynamic model described before in the methodology section. The speeds obtained here are vectors with magnitude and direction. This is important because the direction of the flow will determine the location of the generators under water.

The speeds obtained here are depth-averaged speeds; this means that it is an average of all the speeds from the sea bed to the sea surface, being the speed at its lowest at the bottom. It has been estimated (EPRI, 2006) that the increase in currents speeds from seabed to surface follows a 1/10th power law, thus being possible to estimate any velocity at any depth, based only on a measured speed at a given depth. This would be expressed as follows:

$$u_z = u_0 \left(\frac{z}{z_0}\right)^{1/10}$$

Where u_z is the speed at a z depth and u_0 is the reference speed at reference depth z_0

This also means that the speed at the surface can be estimated from the average depth speed.

Considering the average depth speed:

$$\bar{u} = \frac{\int_{h_1}^{h_2} u\, dz}{\int_{h_1}^{h_2} dz} = \frac{\int_{h_1}^{h_2} u_0 \left(\frac{z}{z_0}\right)^{1/10} dz}{\int_{h_1}^{h_2} dz} = \frac{u_0 \left(\frac{1}{z_0}\right)^{1/10}}{h_2 - h_1} \left(\frac{10}{11}\right) \left({h_2}^{11/10} - {h_1}^{11/10}\right)$$

If the reference velocity is the surface velocity then

$h_2 = Channel\ Depth\ (D)$ $\qquad\qquad$ $h_1 = 0$

$$z_0 = reference\ depth = h_2\ at\ the\ surface$$

Therefore surface velocity is

$$\bar{u} = \frac{u_0 \left(\frac{1}{D}\right)^{1/10}}{D} \left(\frac{10}{11}\right) \left(D^{11/10} - 0^{11/10}\right) = u_0 \left(\frac{10}{11}\right) = 0.909 u_0$$

It is the possible to say that the average depth speed is 90.9% the surface speed and thus it is now possible to estimate this value and from it, estimate the value of any speed at any depth.

A first approach is based in observing the average speeds in the area of the Gulf; this would give an idea which sites might present high speed during the longest periods of time. For this a map showing the absolute value of the average speed's magnitude was created and shown here below:

It is notable that the maximum average speed is only 0.6 m/s; this due to the intermittence of the currents speeds. Maximum values in this model may reach up to 1 m/s in these areas, and even in some others where the speed distribution is less favorable for high speeds making the average value lower.

According to the some reports (Blunden & Bahaj, 2006; EMEC, 2009; EPRI, 2006), the minimum current speed for a tidal stream generation system to be feasible is 1 m/s; This severely reduces the potential sites for an energy generation system such as tidal current generators. However, let's not forget that current speed is inversely proportional to the area of the channel, and considering that the size of the grid used here is 5.5 km, it is really difficult to determine areas that might exhibit high speeds or even estimate correctly the speeds close to shores and channels.

Despite these two issues, the values here presented an important image of the behavior of currents in the Gulf and as mentioned before, a small increase in speed translates in considerable change in power; therefore some sites might still prove to be highly profitable when modeled with a higher resolution. Some sites, that were never before considered as potential, such as the southeast coast of the Gulf, can be seen on the image.

A first estimation for the kinetic energy in the region was obtained by calculating the mean absolute average depth speed during a period of a month. These results provide a quick look at potential sites for energy generation. It is important to remember once more, that since these are the mean velocities (and only in magnitude, no direction), the values do not represent maximum possible speeds rather than a tendency of distribution.

These simulations were also carried out considering 7 harmonic components

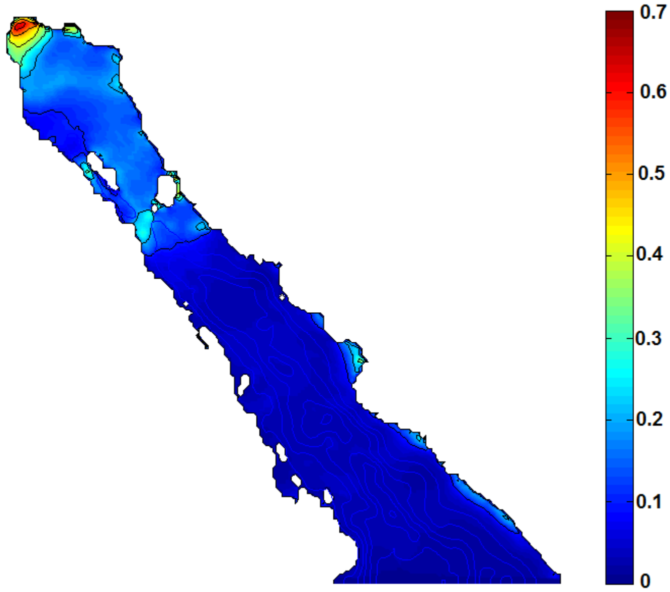

Figure 26 Monthly average speeds (magnitude) in the Gulf Of California

Here it can be seen once more that the highest values are located in the north part of the Gulf. However, some areas shown in light blue close to the coast in the southeast and next to some islands.

There is also the matter of the grid size. Since the grid size is 5.5 km, and as mentioned before, the speed increases with the reduction of the cross-sectional area of the canal, nothing smaller than greed size can be simulated. Also the bathymetry is bound to grid size, making it difficult to simulate the flow on close-to-shore terrain.

Still, a close up on the north part of the gulf reveals several points that should be considered.

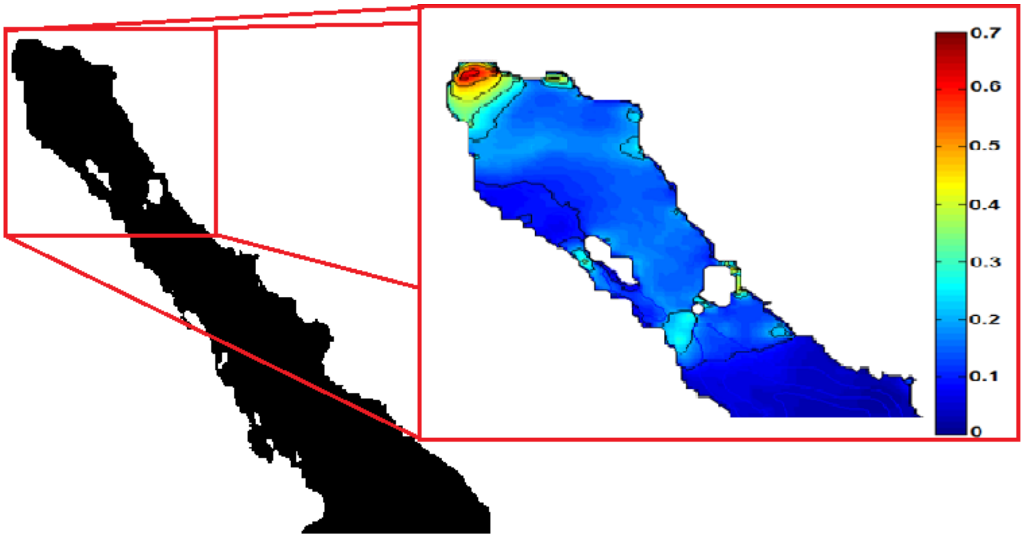

Figure 27 Close-up on average velocities in the north region of the Gulf of California

Here it can be seen that many areas show a mean speed of at least 0.3 m/s with some small parts displaying values between 0.45 and 0.7 m/s.

When analyzing the whole year, the values for the mean average speed didn't change much in respect to those of the month.

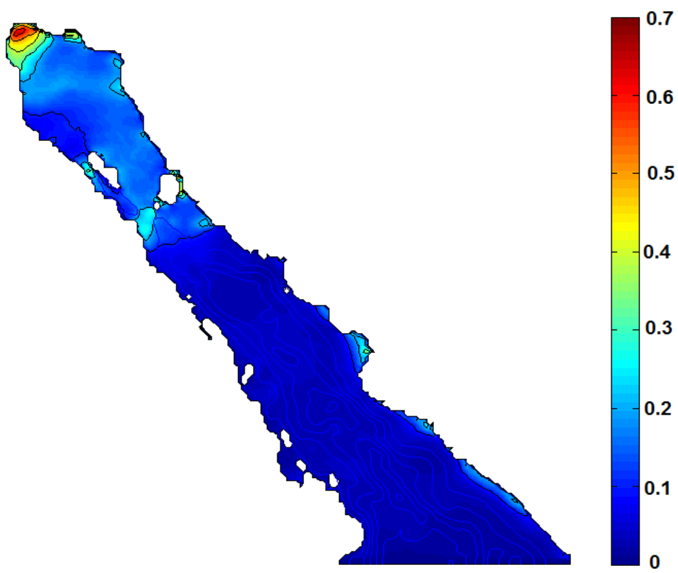

Figure 28 Average annual speeds (magnitude) in the Gulf Of California

The same pattern of distribution tendencies exhibited during the month is also exhibited throughout the year, thus indicating a steady pattern of velocities.

Now, since the values shown here are the depth average speed, it might also be of interest to know the speed at the surface of the sea. As stated before, the average speed is approximately 0.909 times the speed at the surface. This is important to know, to estimate more accurately the speed at the depth on which a tidal energy generator would be located. If it might as well seem as little difference between the average speed and the surface speed, let's not forget that the potential power of the currents is the cube of the speed, making a slight increment important.

Here, once more, the coast of Puerto Peñasco promises good potential for tidal stream energy generation.

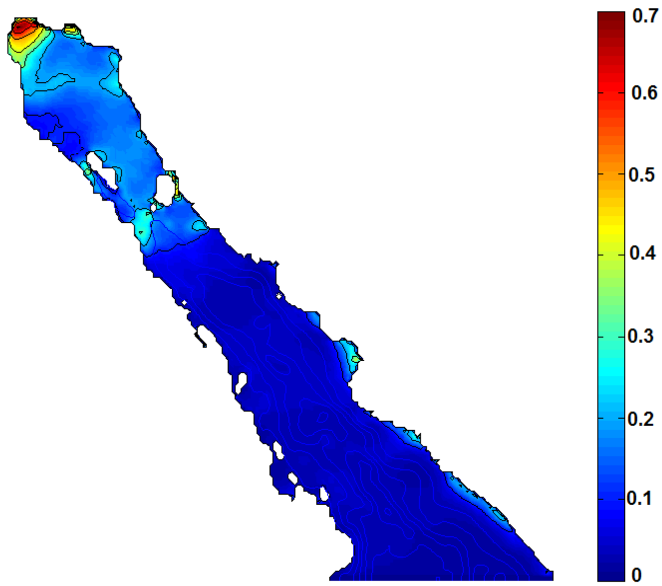

Figure 29 Average annual surface speed

So far only the averages have been presented here, but it is important to see the behavior of the currents during a 24 hours period considering both magnitude and direction. Following are a series of graphics that show the progress of the direction of the streams and their magnitude during a period of 24 hrs. This sequence shows how the tidal streams behave and their estimated magnitudes.

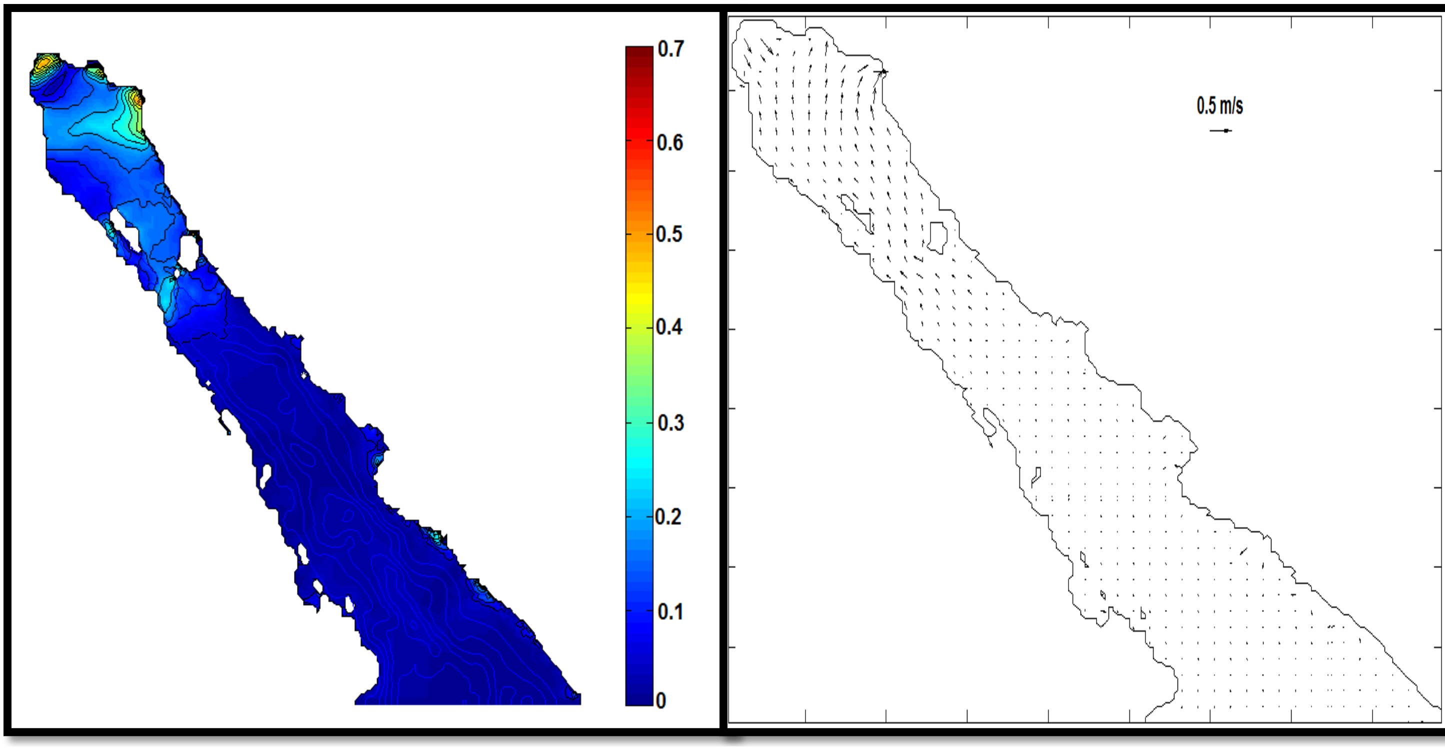

Figure 31 Development of tidal currents. Right: Direction; Left: Magnitude. (average depth velocities) Time = 9 hrs

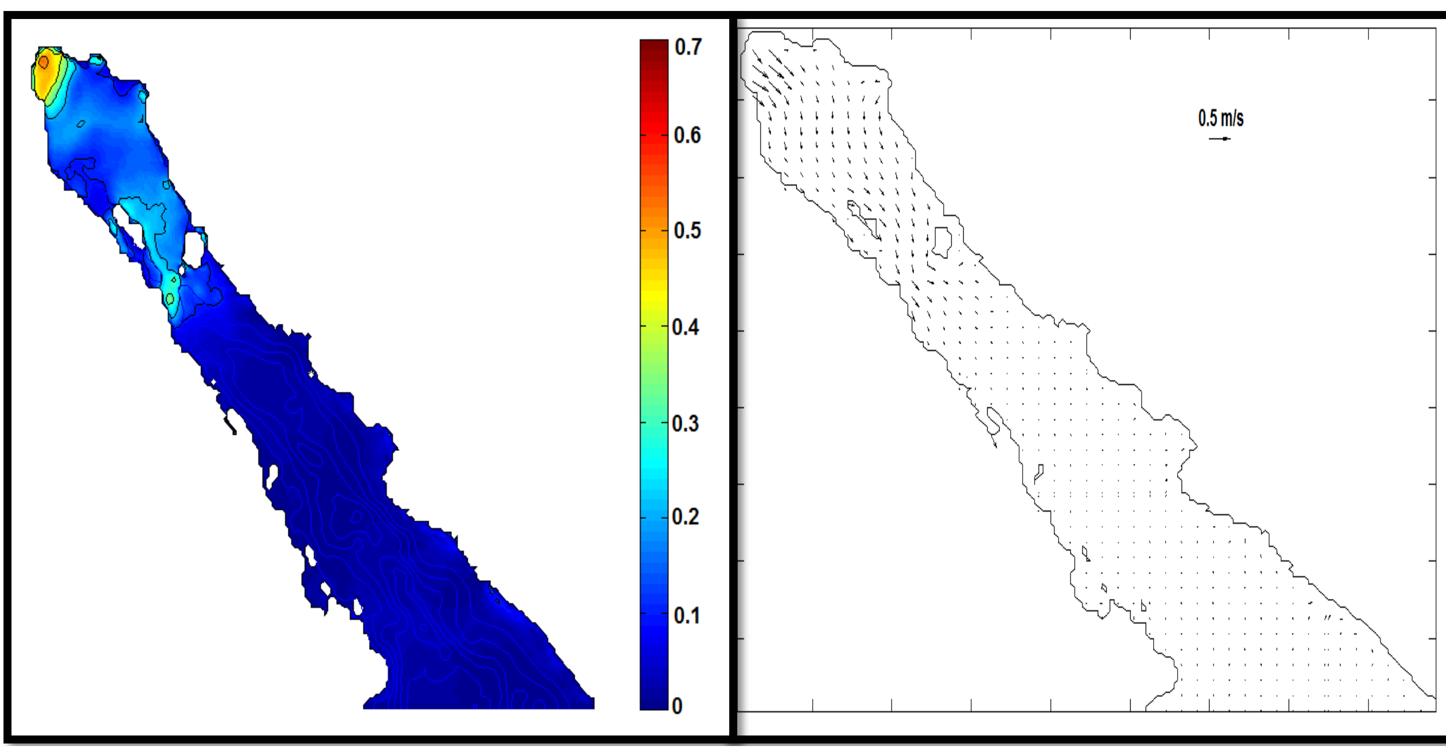

Figure 30 Development of tidal currents. Right: Direction; Left: Magnitude. (average depth velocities) Time = 3 hrs

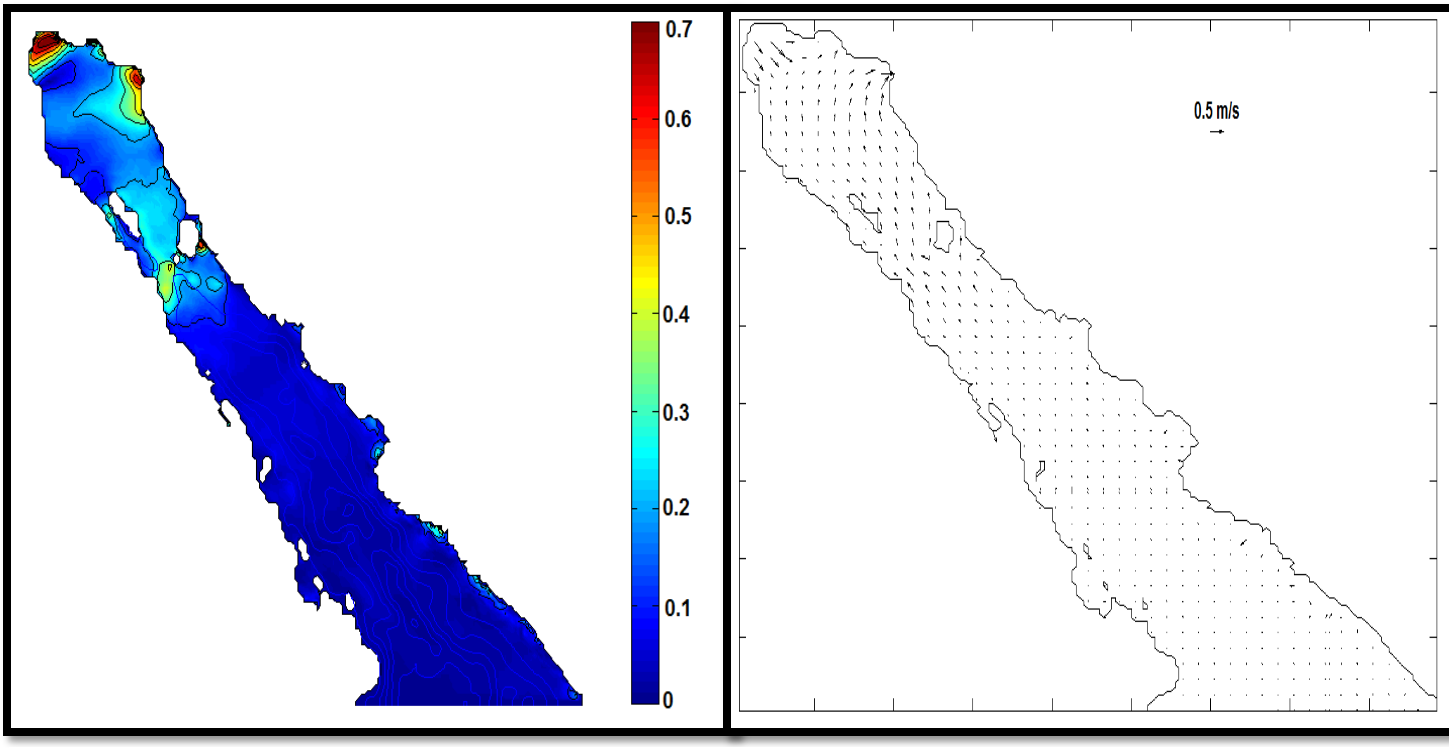

Figure 33 Development of tidal currents. Right: Direction; Left: Magnitude. (average depth velocities) Time = 21 hrs

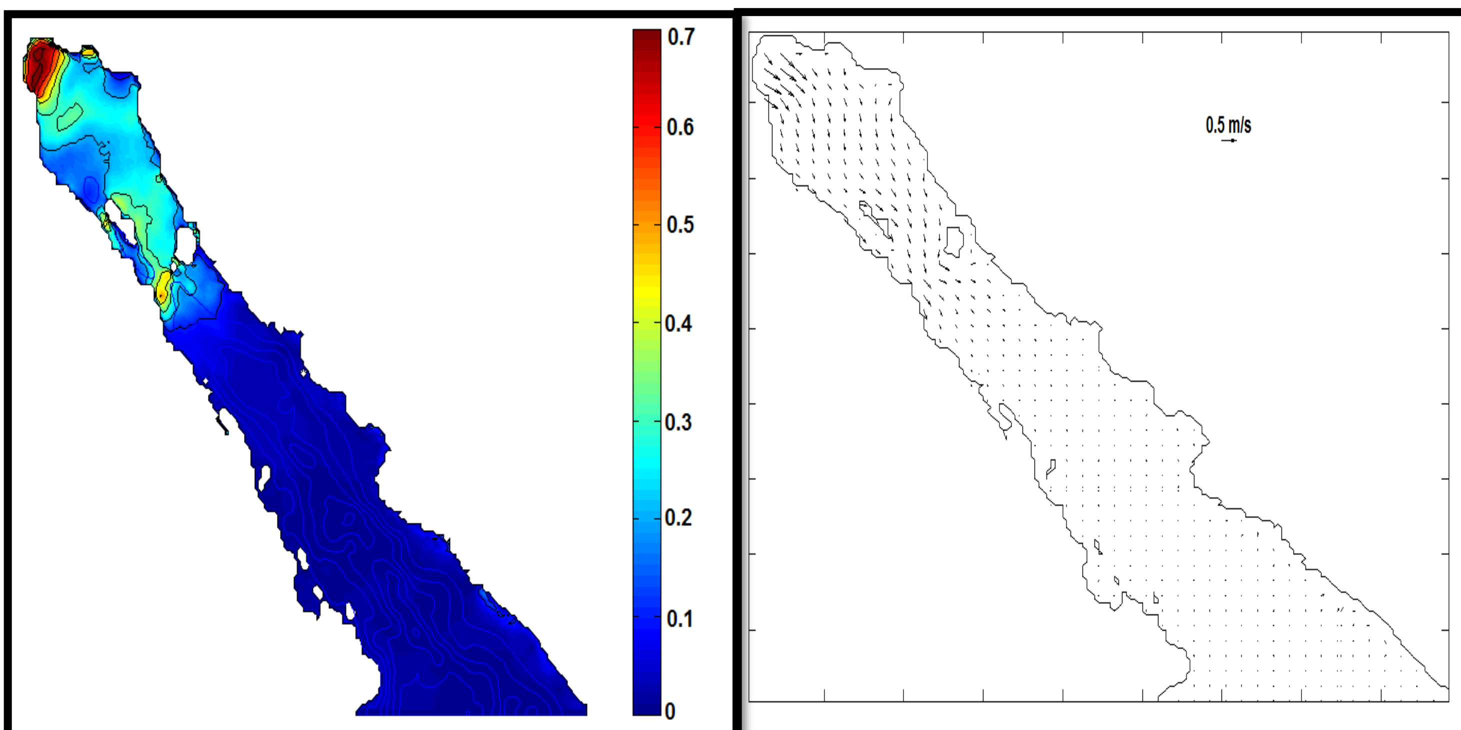

Figure 32 Development of tidal currents. Right: Direction; Left: Magnitude. (average depth velocities) Time = 15 hrs

The graphics shown here display the progress of the tidal phenomenon every 6 hours, where the movement of the water towards the sea, or ebb tide, is evident. This shows a correspondence with appreciated behavior in the tidal range plots. The movement towards inland (flood tide) happens between these 6 hours periods. The maximum speeds are reached mostly during the ebb tides (it is known from tidal theory that changes in the sea surface elevation and intensity of tidal currents are out of phase by 90°.).

It is also observed a convergence of the currents in the northeast part of the Gulf, close to Puerto Peñasco; whether this is of any advantage or disadvantage is still to be determined. Also important to notice is that that precise area is the location of a bay.

Now, comparing this sequence with the graphic of the mean speeds it is possible to determine which areas might be suitable for this kind of energy generation devices.

Another important calculation for this project is estimate the total energy available per area unit. This allows an easier understanding of the velocities in term of energy that can be compared with other types of energies.

As explained before, the density energy per area can be expressed as

$$P_D = \frac{1}{2}\rho v^3$$

And considering sea water density as $1026 \ {}^{kg}/_{m^3}$; also, as said before, the average depth speed is equal to a 0.909% of the surface speed; this means that the energy present in the surface should be expressed as:

$$\bar{u} = \frac{\int_{h_1}^{h_2} u^3 \, dz}{\int_{h_1}^{h_2} dz} = \frac{\int_{h_1}^{h_2} {u_0}^3 \left(\frac{z}{z_0}\right)^{3/10} \, dz}{\int_{h_1}^{h_2} dz} = \frac{{u_0}^3 \left(\frac{1}{z_0}\right)^{3/10}}{h_2 - h_1} \left(\frac{10}{13}\right) \left({h_2}^{13/10} - {h_1}^{13/10}\right) = {u_0}^3 \left(\frac{10}{13}\right)$$

Which equals= 0.769

Now rewriting the power equation we have:

$$P_D = \left(\frac{1}{2}\right)\left(1026\ \frac{kg}{m^3}\right)\left(\frac{v^3}{0.769}\right)$$

From here we obtained the mean energy density per square meter whose units are given in $W/_{m^2}$.

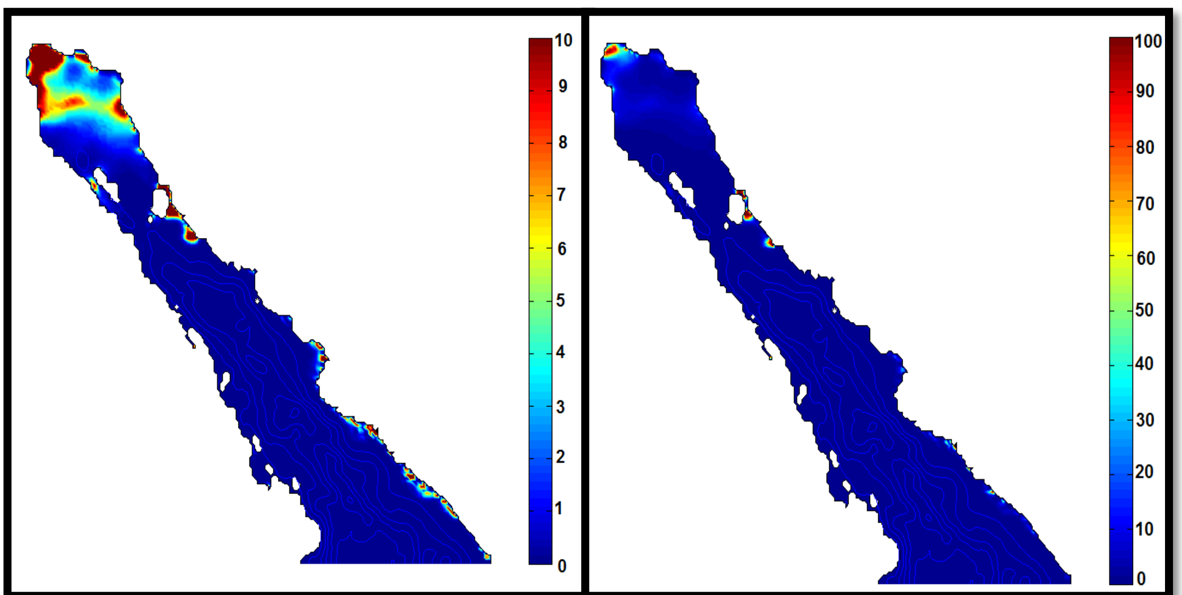

Figure 34 Energy density per square meter during flood tide (W/m^2). Left: Low scale density (1-10) red areas represent values 10 or higher; Right: High scale density (0-100)

As seen in figure 34, the highest energetic areas are found at the north part of the Gulf, the channel el Infiernillo and the southeast coast. However, the left image shows a low range (only to 10 W/m^2), once the range is increased only a few red areas are found (being red areas around 100 W/m^2), but still the same areas are highly energetic even though in a "reduced space". Let us not forget that every square in our matrix represents 5.5 km x 5.5 km, therefore, what might seem a small point in the map is in reality a huge region. The total area of the gulf is approximately 160,000 km^2.

A closer look to the red areas on the maps above reveals that they are even more energetic as it can be appreciated in fig. 35.

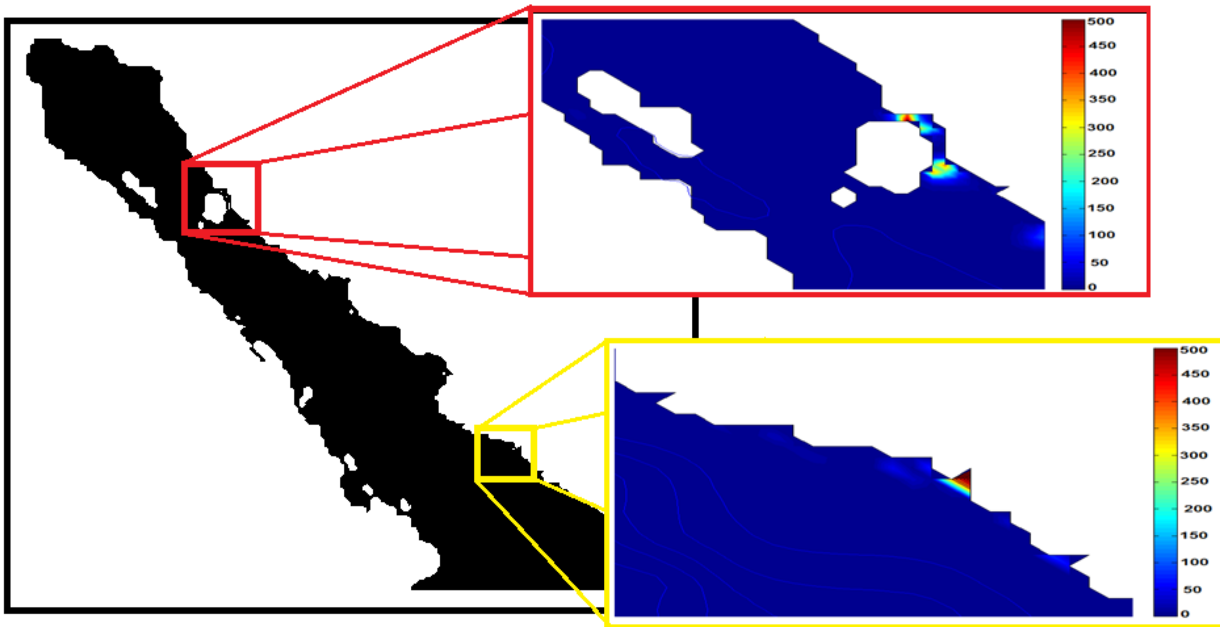

Figure 35 Close up to areas of interest. Left: West of Isla Tiburon, north of Gulf; Left: Coast of Sinaloa, southeast coast of the Gulf. Scale 500-0 W/m^2.

These images show only the values for a given moment which makes impossible to determine their reliability in terms of supply. For that purpose the mean year average energy density is calculated.

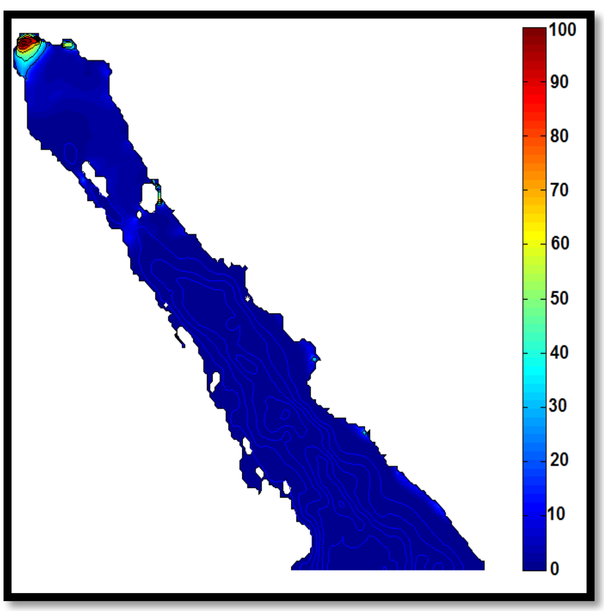

Figure 36 Mean annual Energy Density (W/m^2)

As with the previous mean speed graphics, this gives an idea as to what to expect in terms of supply throughout the year. Some areas that might appear to have low mean energy density can still be useable during certain hours of the day as shown on figures 34 and 35. For a deeper look into this, the daily behavior has been studied and shown in the next series of graphics.

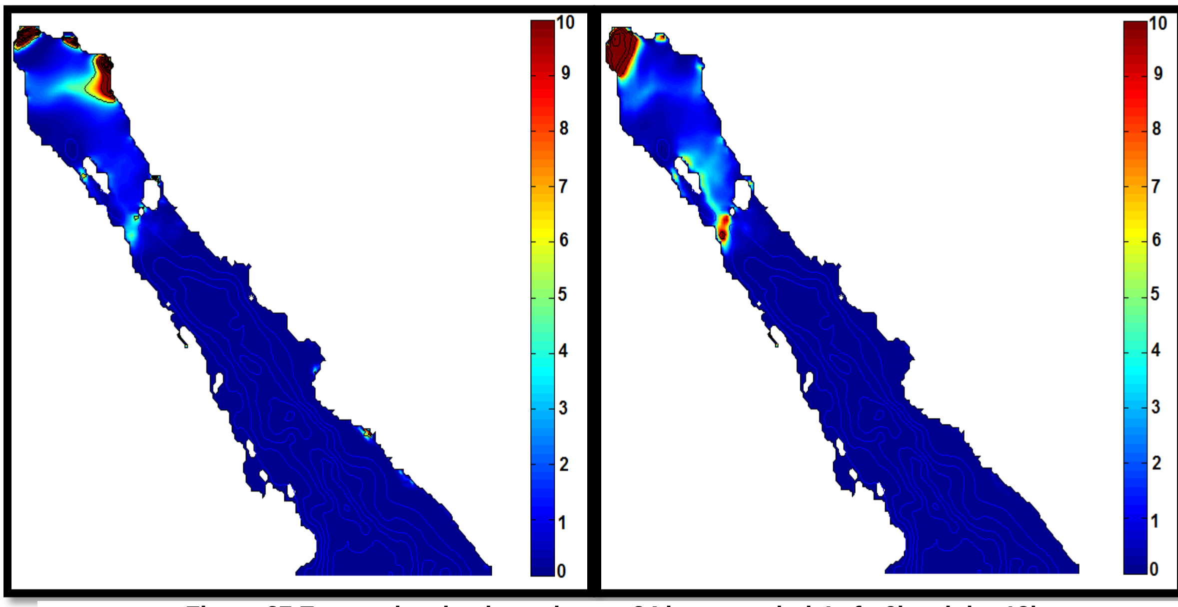

Figure 37 Energy density throughout a 24 hours period. Left: 6hr; right: 12hr

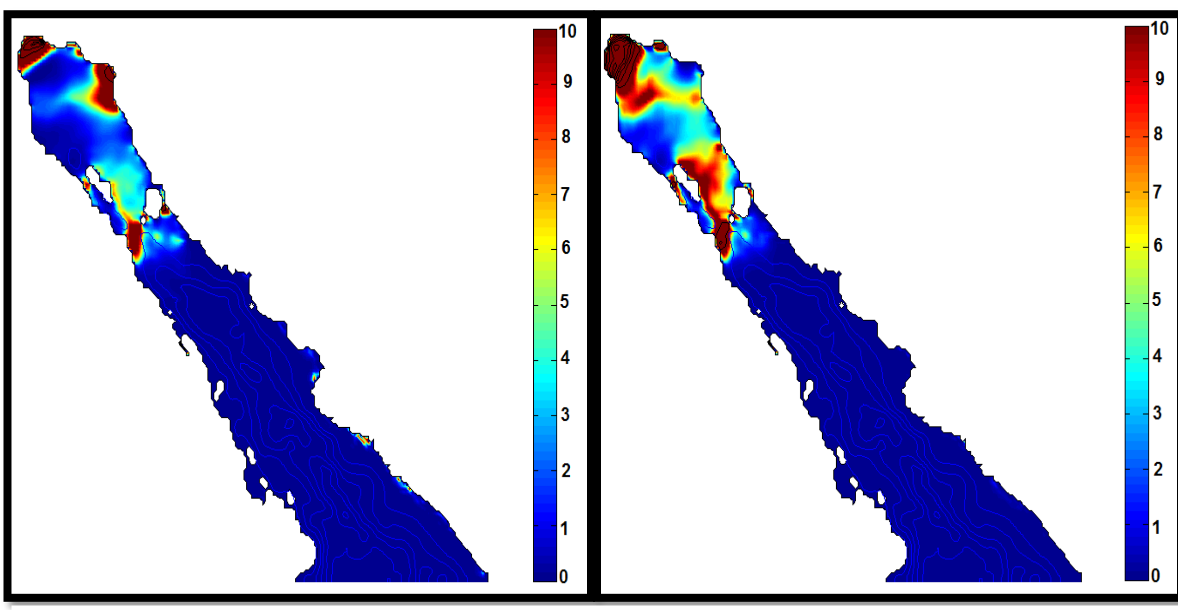

Figure 38 Energy density throughout a 24 hours period. Left: 18hr; right: 24hr

The range of the graphics has been given up to 10 W/m2 to make them more visually comprehensible and comparable between each other, but is important to mention that in every case, the red areas usually had in their centre values around 100-120 W/m2. In some others (at 24 hrs) the values even reached 500 W/m2 as was shown in figure 35.

VIII. DISCUSSIONS

The gulf presents several locations for tidal-based energy generation for both potential and kinetic energy. Most of these sites are found at the north and southeast coast of the Gulf.

8.1. THE MATHEMATICAL MODEL

In this study the whole area of the Gulf was analyzed in order to find suitable places for energy generation. Given the spread of the Gulf, a large size grid was used (5.5 km x 5.5 km) which allowed for the numerical calculation of potential and kinetic energy in the entire region. However, a grid this size shows its limitations too: features smaller than grid-size can't be displayed and thus, their effects on these phenomena cannot be modeled. As mentioned before, this leads to a reduction on values like speed and energy density which are directly related to channel size; another issue is that, since tides behave as Kelvin waves and Kelvin waves decrease exponentially as they get away from the coast, the tidal range values are an averaged value of the range at the coast and the value at 5.5 km from it; this decreases considerable the actual values at the coast.

Even at this scale though, when analyzed, certain spots within the Gulf showed interesting values for energy generation, some of them for barrage systems, some others for tidal stream systems and some others for both.

8.2 AREA SELECTION AND ANALYSIS TYPE.

Given the time given for this project, the scale had to be restricted to a regional analysis, or at Stage 1 according to the EMEC (2009). Further analysis would require a smaller grid size and more site-specific information. Nevertheless, certain features of more advanced stages were also included in this project: a 7 harmonic components regional study, a close up to sites with potential tidal ranges considering 3 harmonic components, average annual values for both tidal ranges and current speeds, information on protected areas and estimated values of energy density.

While the values might still change with a higher resolution grid, they still present an interesting image of the Gulf of California as a great source of energy. As a result of this analysis, some areas have already been identified as potential sites for energy generation.

8.3. DATA ANALYSIS AND SITE SELECTION.

All data obtained in the results section was studied and analyzed considering three main factors: Energy potential, geographic and environmental conditions. This list is not exhaustive due to the fact that at this scale, many geographical features might have been omitted which would lead to an increase in values such as current speed.

8.3.1. Tidal Range

8.3.1.1. San felipe and Puerto Peñasco

Both San Felipe and Puerto Peñasco present good conditions for a tidal barrage energy generation system. As mentioned before, there have been also some previous studies for these areas (Hiriart-Lebert G. , 2009; Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert, 2010). In these papers, tidal range systems are proposed for both areas, also including the Colorado River mouth. Unfortunately, for the cases of Puerto Peñasco and the Colorado River mouth, the potential areas are well within the natural protected area of the Upper Gulf of California (see Annex, figure 40) and San Felipe is still close to the buffer area of the same protected area. For further information on these areas and their tidal potential it is suggested to read: Hiriart-Lebert (2009) and Lopez Gonzales, Silva-Casarin, & Hiriart-Lebert (2010).

8.3.1.2. Puerto refugio

The bay of Puerto Refugio would provide an excellent location for a tidal barrage system if not for two main problems: Puerto Refugio is located in an island 25 km from the coast of the Baja California Peninsula and almost 65 km to the closest road (Carretera Federal 1); and is located within the Archipielago of San Lorenzo National Park, a natural protected area.

However, whether the ecosystem and the fauna in this protected area are affected by the facility itself would require further analysis and deeper ecological studies.

The total useable are for this project could be estimated between 1.7 to 0.8 Km^2, if useable at all.

Considering the distance and situation of the location, some other options may be useable, such as tidal current energy generators or the promising Gorlov Hydroturbine (Gorlov, 2001).

8.3.1.3. Bahia de los angeles

Bahia de los Angeles is located in the state of Baja California Norte, and it is now for various touristic and adventure activities, such as rallies and camping. While the values may not be as high as those in the North part of the Gulf, they are some of the few that can be found outside that area. Also it is located in the main land and roadways can be found nearby.

However, the maximum tidal range reached in this area is only 2.87 m which can present a problem when considering the size of the turbines. As stated in a paper by Hiriart-Lebert (2009), the hydraulic charge or the head in which they will operate will be very low compared to those in a hydroelectric station, and on the other hand, the diameter of the turbine cannot exceed the minimum depth of the sea level. It is also located within the area of the Archipielago de San Lorenzo, which means a deeper study on the impact of a tidal barrage instalation in the ecosystem of the area.

8.3.1.4. Yavaros and topolobampo

These two sites showed in the initial approach a high average tidal range (around 1 m), giving the possibility that higher tidal ranges where found. However, once the site-specific simulations were performed, the maximum values never surpassed 1.2 m. Still it is interesting to notice that the tidal range distribution is somewhat more uniform, making a smaller difference between neap and spring tides, thus generating a high average. It can also be possible that given the size of the model's grid and the location of the amplitude and phase points (Yavaros is 70 km north from where the actual tidal range was predicted by the model) the tidal range was underestimated or miscalculated.

The case of Topolobampo is similar to that of Yavaros. The amplitude and phase points were taken from Topolobampo, but the actual location, Isla de Altamura, is almost 100 km south of Topolobampo. In both cases, Yavaros and Topolobampo, the geography provides favorable characteristics for a tidal barrage system, being both a semi-closed bay with a natural barrage. Also, both locations are well connected to roads and human settlements (see Annex, figure 46).

From these considerations, the three main sites that strike as the most feasible, regardless of any other consideration but potential energy from a barrage system, are San Felipe, Puerto Peñasco and Puerto Refugio since they show tidal ranges of 6.17, 5.81 and 4.02 meters respectively. They are all also within the area of the Upper Gulf and Colorado River Delta protected area, which would practically leave them out of any possible project for tidal barrage energy systems, however, this will depend on the size and exact location of the system and will require deep ecological impact studies.

8.3.2. Tidal Stream

From this analysis the areas of interest in the Gulf are the Upper Part, (especially the river mouth of the Colorado and Puerto Peñasco), the channel between Isla Tiburon (el Infiernillo) and the east Coast of the State of Sonora, and some reduced areas of the southeast coast (near the city of Culiacan, Sinaloa).

In el Infiernillo channel and Puerto Peñasco, values around 500 W/m2 were found in periods of 12 hours, with decreases to 100 W/m^2. The area of the Delta also presented steady values of 100-150 W/m^2.

According to EPRI (2006), approximately 15% of the energy present in tidal streams could be extracted without having ecological impacts or affecting the resonance effects of the tides; this statement was based on Bryden’s studies (2004), where is also mentioned that in closed areas such as bays and fjords this limit might be increased to more than 30%.

If this numbers might seem relatively low compared to other renewable sources of energy, such as solar and wind energy, the efficiency for PV systems is currently no higher than 18% and while wind turbines can reach efficiencies up to 50%, due to the air’s low density, they require larger frontal areas to generate acceptable electrical outputs.

Another relevant observation is that, as stated by EMEC (2009), the values for tidal stream speeds from simulations with grids bigger than 3 km can be up 1.5 times lower than in reality in areas close to the coast or channels where speed can be dramatically increased by topographical features. A particular area deserves special attention in this matter: the strait between Isla Tiburon and the coast of Sonora. This area already exhibits a high energy density and speeds as high as 0.7 m/s at a 5.5 km grid-resolution. However, the actual size of the strait is 4 km at one of its ends and 2.7 km at the other with a regular width of 3.3 km across the whole channel, which would lead to believe that the actual speeds can reach higher values.

Some other areas are also lacking important distinctive features, as is the case of the Coast of Sinaloa, where a bay and the river outlet might change the values for tidal range and speed. A series of images showing the sites and their properties is shown in the Annex section.

A resume of the most interesting sites with their calculated values is shown in table 12.

Table 12 Potential sites for tidal current generators

	Maximum Speed (m/s)	Annual Average Speed (m/s)	Annual Average Energy Density (W/m^2)	Area (km^2)
Colorado River	0.8	0.65	180	600
Puerto Peñasco	0.8	0.4	100	159
Isla Tiburon	0.7	0.45	70	70
Isla de Altamura	0.6	0.35	60	288
Sinaloa (coast)	0.6	0.2	40	175

While the values for the areas here presented might seem quite big, let's not forget that the devices require certain spacing between each other and a certain depth to be located. A proposed spacing by the EMEC (2009) mentions that the spacing for tidal current devices should be 2.5 times de diameter of the device to the sides and 10 times in front of each other; this is:

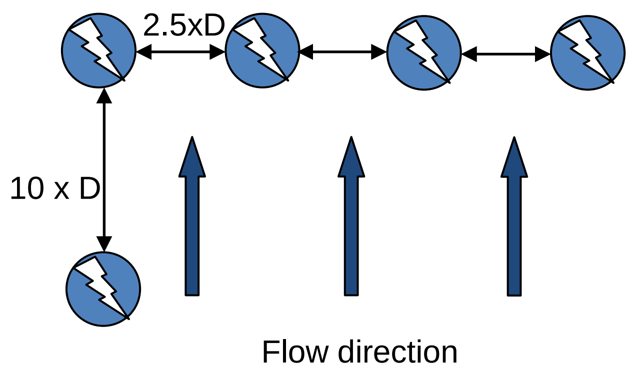

Figure 39 Spacing for tidal current generators

So, for a single square of the model, representing 5.5 km x 5.5 km, and a rotor with 1 meter diameter, this would mean 1570 x 500 turbines. This is a number that is quite certainly unpractical; however, it helps to show the magnitude and potential of this generation system.

Now, if we consider the energy density for Puerto Peñasco, which is a 100 W/m^2, and multiply it by the area of the grid-size square, we have a value of 3.025 GW, but let's remember the spacing of the turbines, which makes a large portion of the area unused, which means that from a total area of 30.25 km^2 we would have a total used area of 0.78 km^2, which would still translate in a 78.5 MW capacity.

While this number might seem impressive, there is still to consider that only between 10-15 % of this energy could be extracted, giving still around 7.85-11.8 MW. It can also be said that the region of Puerto Peñasco could provide 0.29-0.39 MW/km^2 of useable energy. This means 3.41 GWh/year per Km^2.

For the case of the Delta of the Colorado River, these values would be 180 W/m^2; once more considering the useable area the value for the capacity of a grid-size square is between 14.4-21.6 MW already considering the 10-15% extraction percentage. The total useable energy is 0.47-0.71 MW/km^2; this is 6.22 GWh/year per km^2.

A review with the potential sites and their most suitable approach is presented next:

Table 13 List of potential sites and their characteristics showing the suggested type of technology fur each case. * There are no feasible connection to settlements. [a]Area values are estimates based on potential useable area based on energy qualities. [b]Locality is an island.

	Barrage	Tidal Stream	Protected Area	Site Area (km^2)[a]	Closest settlement	Distance to closest settlement (km)
Colorado River's Delta	*X*		*X*	*1050*	*San felipe*	*50*
Puerto Peñasco (North)	*X*		*X*	*560*	*Puerto Peñasco*	*30*
Puerto Peñasco (South)		*X*		*159*	*Puerto Peñasco*	*30*
San Felipe	*X*		*Buffer area*	*18*	*San felipe*	*0*
Puerto Refugio[b]	*X*			*3.2*	*	*
Bahia de los Angeles	*X*		*X*	*27*	*Bahia de los Angeles*	*5*
Isla Tiburon		*X*		*70*	*Bahia Kino*	*37*
Isla de Altamura		*X*		*288*	*La Reforma*	*0*
Sinaloa (coast)		*X*		*175*	*Culiacan*	*45*

IX. CONCLUSIONS

The Gulf of California is a vast area with an enormous potential for energy generation, its geographical characteristics generate values of tidal range as high as 6 meters or more. Several sites present high average values of current speed, indicating, if not a big amount of energy, a steady one.

As it was shown, tidal energy in the Gulf of California can be predicted and estimated with a high degree of accuracy using mathematical models; this would allow planning energy systems accordingly. The estimations obtained by this project were in line with the recommendations made by the EMEC (2009) and EPRI (2006) reports, qualifying as Stage 1 analysis: Region study with a grid of approximately 5x5 km and use of at least four harmonic components.

The results have demonstrated that some areas outside the north of the Gulf can also be used for energy generation; these areas have the advantage to be closer to human settlements and to count with geographic conditions, such as bays and estuaries, suitable for tidal energy devices. However, the values obtained for tidal currents are too low to be considered useable for energy generation; the exact value considering smaller topographical features still has to be calculated.

Further analysis will be required in the potential sites, such as mathematical modeling with a smaller grid, possible with a 50 meter grid resolution to account for all the topographic features of the coast. Also the inclusion of more harmonic components EMEC (2009) recommends 20 for a full feasibility project) will be required as well as field survey to corroborate the results of the numerical analysis. However, thanks to the results of this work, the areas are now easily pin-pointed and delimited, bringing a tidal energy facility in Mexico one step closer.

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X. ANNEX

10.1. SITES LOCATIONS

Images of the potential sites showing closest cities, protected areas (if any) and approximate measures of distances.

Figure 40 Colorado River's Delta and Puerto Peñasco (North). Green line delimits natural protected area (Protected and Buffer areas)

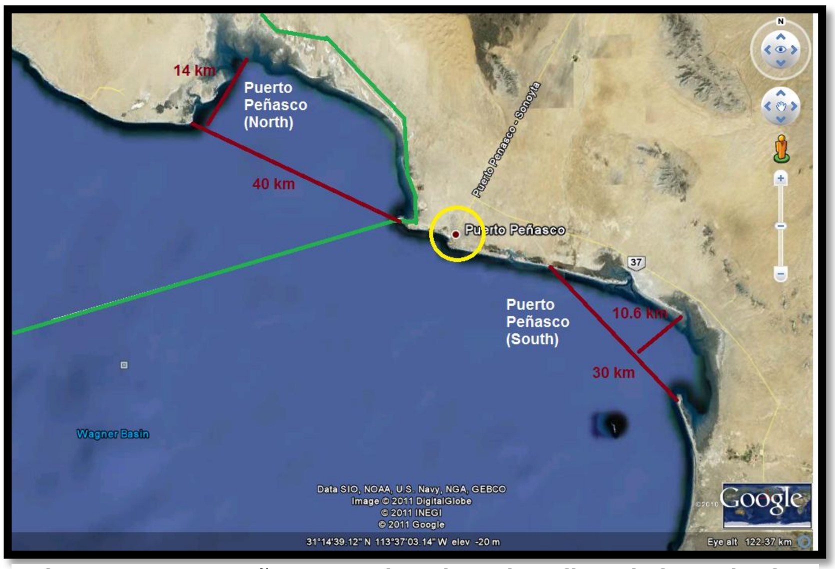

Figure 41 Puerto Peñasco, north and south. Yellow circle marks the city (settlement). Green Area delimits protected area

Figure 42 San Felipe. Yellow circle shows the Town of San Felipe

Figure 43 Puerto Refugio

Figure 44 Bahía de los Ángeles. Yellow circle indicates the town Bahia de Los Angeles. This is a tourist's village.

Figure 45 Isla Tiburón Channel

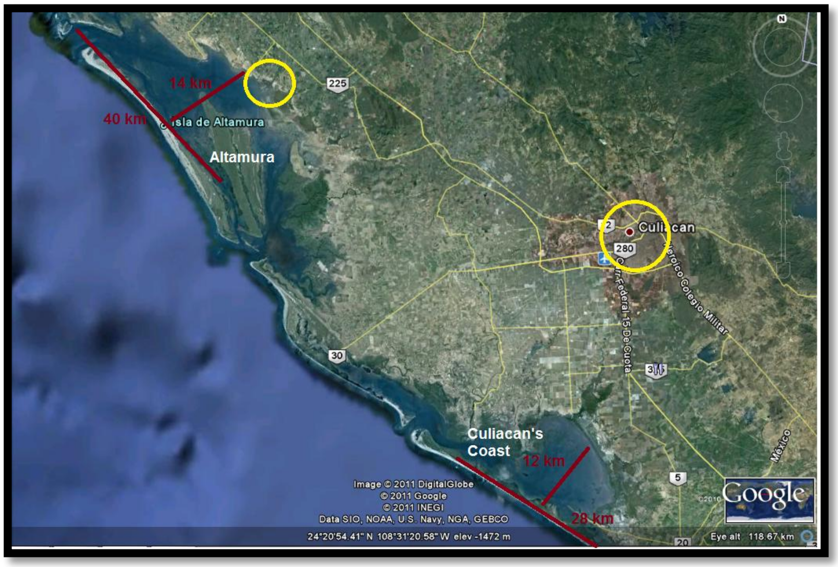

Figure 46 Isla de Altamura and Culiacán. Yellow Circles show the town of Reforma (north) and Culiacan (south).