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Preliminary Analysis of Potential for River Hydrokinetic Energy Technologies in the Amazon Basin

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Environment Department

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General Scope

The Inter-American Development Bank (IDB) produced this report for the Sustainable Energy for All Americas initiative. A team of experts on Amazon hydrology from the Universidade Federal do Amazonas (UFAM) based in Manaus, Amazonas, Brazil carried out the work. This report analyzes existing hydrological data and other available information in order to determine high-level feasibility for the deployment of River Hydrokinetic Energy technology in the Amazon River Basin. The investigation is based on an analysis of the ORE-HYBAM database (www.ore-hybam.org). Eight sites were chosen from the database and analyzed for velocity (water speed) and discharge data, while also considering existing Acoustic Doppler Current Profiler (ADCP) images.

The first part of the report provides an overview of the database and data used, as well as of the performed analysis. The second part (results) describes the analysis via graphs and tables of detailed information about the sites investigated. It includes maps with the geographic distribution of the sites and associated data, Google Earth images from each site with an analysis of the river section, and ADCP images. The annex includes graphs showing the results of discharge and velocity analysis.

Preliminary Analysis of Potential for River Hydrokinetic Energy Technologies in the Amazon Basin

Executive Summary

Background: RHK Potential and the Amazon Basin

River Hydrokinetic Energy (RHK) is an emerging clean technology sector in which electricity-generating turbines are placed directly in a river flow without a dam to retain water and create an artificial head or otherwise divert the course of the river. The sector has gathered increasing attention in recent years as a potential low-impact alternative to conventional dammed hydroelectricity. RHK is also an alternative to other conventional renewable energy and more traditional thermal technologies.

RHK technologies offer the potential for the provision of clean, renewable power for industrial centers and for remote riverside cities or communities such as those found in the Amazon Basin. There are approximately 10 million inhabitants[1] in the region, mostly concentrated in urban areas along the mainstream and its main tributaries. Population migration rates to the region are near 6% and are well above the national average for Amazon countries. Despite the large potential resources available, there has been limited desk-based and physical assessment of this emerging sector in the Amazon Basin and elsewhere in LAC to date.

As the world's major hydrological basin, the Amazon drainage basin covers more than 6,000,000 km^2 – almost 5% of the entire land area of Earth – and its average discharge is the greatest in the world (209,000 $m^3.s^{-1}$) (Molinier et al., 1996). Due to its size and position, the Amazon Basin includes a number of very different regions with various discharge regimes, which can be explored in terms of their potential for applying RHK technologies.

The Amazon Basin is shared by Brazil, Peru, Ecuador, Bolivia, Colombia, Venezuela and Guyana. More than half of the basin is located in Brazilian territory. The headwaters are located in the Andean portion of the basin, which is shared by Bolivia, Peru, Ecuador and Colombia. Most of the Amazon Basin does not exceed an altitude of 250 m, and the main humid zones are located below 100 m (Salati & Vose, 1984). These low altitudes produce a huge navigation area in the region.

[1] http://www.oas.org/dsd/events/english/documents/osde_8amazon.pdf

The Brazilian Amazon region holds more than half of the country's hydroelectric potential – in a country that already generates more than 80% of its electrical energy from hydroelectric sources. The construction of large-scale conventional hydroelectric facilities has been and continues to be considered in the Amazon Basin. However, these options have faced considerable opposition on social and environmental grounds. Large-scale facilities such as Santo Antonio (3,100 MW) and Jirau (3,300 MW) were both constructed in the Madeira River Basin. The 5,500 MW Belo Monte hydropower plant has been in the planning and consent phase for many years and has faced stern opposition. Paradoxically, despite this potential, the lowest rural electrification rates in the country are in the Amazonian states (less than 25%), while the national rate is 70%. Moreover, currently served demand centers do not have a reliable supply (Souza, 2012).

Even with the construction of these facilities, the electricity supply to the mostly rural areas in the Amazon region in Brazil will continue to be generated by isolated hydroelectric systems (for example, dams like Balbina, Samuel, Curua-Una and Coaracy-Nunes). They will be complemented by conventional fossil-fuel burning thermo-electrical units. In light of this, alternative options such as energy efficiency programs and new and renewable sources are being given increasing consideration. In this context, RHK is an important sustainable and potentially low environmental impact alternative for urban and semi-urban areas in the Amazon region.

Data Used for RHK Survey in the Amazon

Di Lascio and Barreto (2009) conducted previous work in Brazil that analyzed the potential for the deployment of sustainable energy technologies, including RHK, at some sites in Amazonia. The general conclusion was that the velocity intensity at the studied sites was not strong enough for the specific technology under development at a Brazilian university at the time. The studied sites were located in the highest regions of some small river catchments in the Brazilian Amazon. The analysis did not include larger river catchments – the focus of this report – due to a lack of data.

In this report, the ORE-HYBAM database (www.ore-hybam.org) is a source of data used to provide a preliminary analysis of the feasibility of RHK technology in selected locations throughout the Amazonian regions of Brazil, Peru and Ecuador. Bolivia is also given limited consideration. ORE-HYBAM is an environmental observatory that includes several hydrology research groups in LAC, particularly in Amazonia. The ORE-HYBAM initiative was launched in 2003 to monitor and analyze hydrological systems and sedimentation transport in the Amazon River Basin. The project incorporates hydrographic measurements taken since 1995. Although the data is relevant and extremely useful, it still falls short of what is required for the longer-term development of RHK in the Amazon Basin. More investigation is required and recommended.

Data Processing and Analysis for RHK

This report performs an analysis of the ORE-HYBAM database, and it identifies a total of 54 sites with data that can be analyzed for RHK purposes (Figure 1). From this group, 20 sites were identified as having geomorphological and hydrological characteristics potentially suitable for a future RHK initiative (other sites beyond this initial screening and outside the scope of this report will exist). Of these 20 sites, several did not possess sufficient data for further study. Of the 20 sites, 8 sites (Table 1) were chosen that had the necessary availability and quality of data to perform a first analysis. These sites are distributed as follows: Brazil (3), Peru (3) and Ecuador (2). Investigations were also carried out at sites in Bolivia, but the limitations of existing agreements between the Bolivian Government and the ORE-HYBAM database prohibit further analysis at this time.

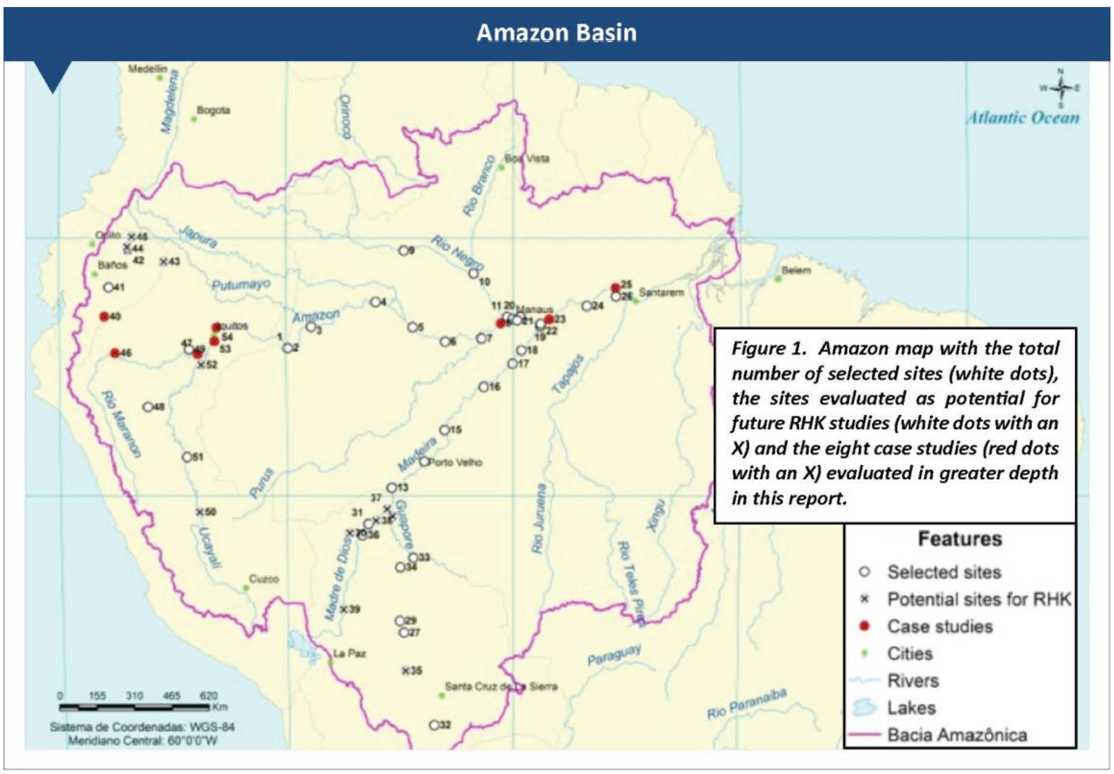


Figure 1. Amazon map with the total number of selected sites (white dots), the sites evaluated as potential for future RHK studies (white dots with an X) and the eight case studies (red dots with an X) evaluated in greater depth in this report.

Table 1. Summary of key characteristics determined at each site. Average Discharge (AVR Q), Power potential per 1000m^2 (Pp) under mean water speed, conditions at the whole river section, population at urban sites near the investigated river section and estimated distance from that point to the nearest electric grid.

Station Name - Country	AVR Q ($m^3.s^{-1}$)	Pp (MW)	Nearest Pop. (inhab.)	Estimated distance to the grid (km)
Bellavista - PE	6,758	9	>15,000*	<10
Borja - PE	5,085	12	≈1,000	<25
Itacoatiara - BR	162,535	17	96,000	<10
Manacapuru - BR	105,781	18	92,996	<10
Óbidos - BR	181,645	13	50,317	<10
San Regis - PE	16,817	14	≈1,000	NI
Santiago - EC	1,616	6	9,150	NI
Tamshiyacu - PE	29,182	18	8,000	<10

Note. *NI = N**ot Identified. The distance to the grid was estimated using the mean distance to the nearest city served by a thermic source.**

In this study, data was used to derive high-level feasibility of a theoretical RHK system over the course of at least one (but in some cases several) year(s). It should be noted that the MW power figures presented are over a river surface area of 1000m^2, which represents a tiny fraction of the surface area and therefore power available at these locations. From the total number of listed ORE-HYBAM sites (hydrometric stations), 54 were chosen taking into account important geomorphological indicators (local and regional slope, channel conditions with high and homogeneous velocities, etc.). These favorable characteristics were then associated with proximity to an electric demand center that can be investigated as a potential future energy beneficiary. The availability of hydrological data, especially ADCP (Acoustic Doppler Current Profiler)[2] measurements and data, was a final key consideration.

The specific hydrological data of interest used here was: i) ADCP measurements yielding information on river current velocity, turbulence intensity, depth, and bathymetry and ii) historical discharge measurements. This data was used to conduct the following high-level analysis:

[2] ADCP is a standard piece of equipment that gathers hydrological data and can present this in the form of Doppler transects images with color-coded water velocities and other features. It works by using the Doppler effect to transmit sound at a fixed frequency and listen to the echoes returning from sound scatters in the water (RD Instruments, 1989).

a) Historical discharge measurement data was combined with ADCP imagery in order to estimate river current velocity and therefore overall energy availability and theoretical energy capture of RHK systems at the selected sites;

b) Data was extracted from each ADCP measurement image, relating to river current velocities, depths, and the variation of these factors throughout the annual hydrological cycle;

c) For each ADCP file analyzed, two areas from each section were selected: those containing faster water velocities and those with slower water velocities. The root mean cubed was taken over each area for each measurement and plotted against the mean discharge. The relationship between discharge and water speed was calculated for each area.

Results from the Eight Case Studies

As indicated above, eight sites were selected as case study sites based on the data available. All eight sites are potentially suited to the eventual siting of an RHK demonstrator or commercial project. Most of these sites have significant electric demand centers nearby. The estimated power that can be generated by a single turbine at five of the sites is greater than 1 MW – with potential for much larger arrays. It should be noted that the MW power figures presented are over a river surface area of $1000m^2$, which represents a tiny fraction of the surface area and therefore power available in these locations. Considering a local mean water speed of between 1.5 and 2 $m.s^{-1}$ as a limit of technical and commercial viability, conditions are good to excellent at almost all of the sites during six to seven months of the year, whereas there is less generation during the remainder of the year.

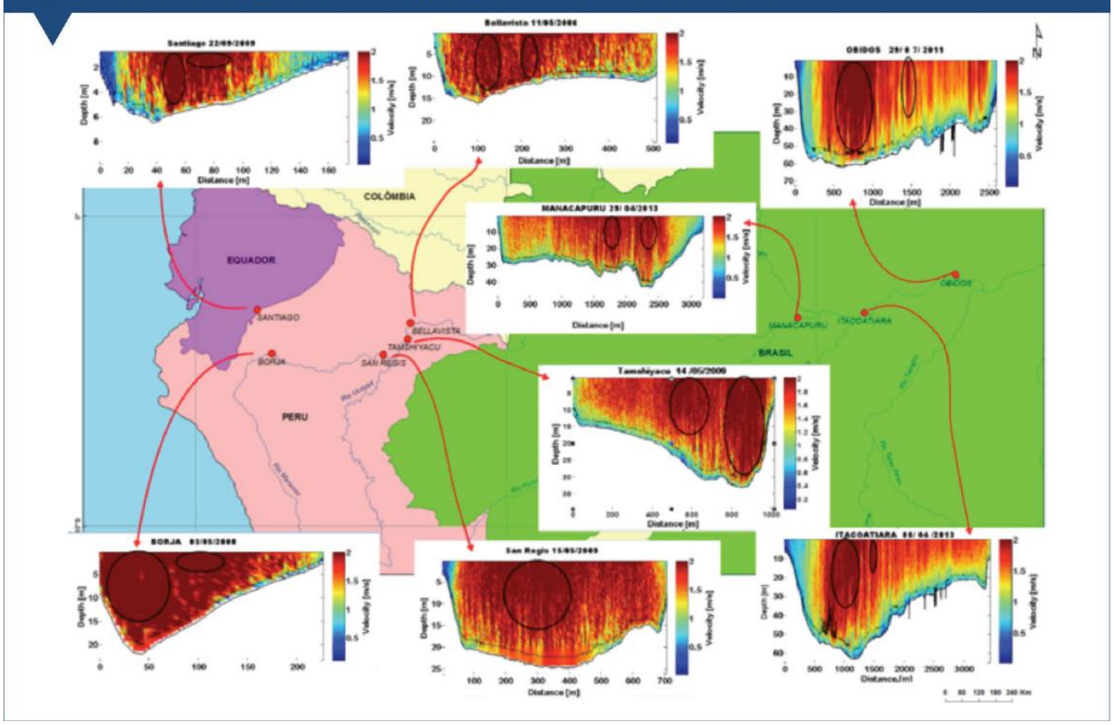
Current velocities above 2 $m.s^{-1}$ (Table 2) were used in the analysis of the monthly data from each station. The results took into account all the years shown for each station in Figure 1. Discharge versus velocities graphs at different periods of the year (fast and slow current) were generated and then used to calculate the base discharge values (Base Q). The data from each site was used to calculate the number of days with velocities greater than the range of 1.5 to 2 $m.s^{-1}$. The results showed that even in Borja, where the discharge was the lowest of all sites surveyed, there were an average of 312 days that had current velocities above 2 $m.s^{-1}$. In contrast, current velocities at the higher discharge sites, such as Óbidos, were in the range of 1.5 to 2 $m.s^{-1}$ (classified as 'good conditions') during almost half of the year. The site with the least attractive conditions is Bellavista, where even with a Base Q of 10,000 $m^3.s^{-1}$, the current velocities were in the 'good conditions' range for only an average of 37 days per year.

Table 2. **Base flows and the number of days where discharge conditions produced current velocities greater than 2 m.s^{-1}.**

Station Name	Base Q (m^3.s^{-1})	No. Days/Year (Q > Base Q)
Manacapuru	120,000	172
Itacoatiara	160,000	211
Óbidos	180,000	195
Borja	2,500	312
San Regis	13,000	269
Tamshiyacu	30,000	178
Bellavista	10,000	37
Santiago	900	309

The ADCP images (see Report, Annex 1) from each site were used to indicate (with the color scale) the regions with velocities greater than 2 m.s^{-1}. Additionally, a discharge versus velocity (in %) relationship was derived and analyzed using a 95% confidence bound. That basic and initial analysis indicated two sites, Borja and Santiago, both in Peru, with a linear trend. The stations of Óbidos, Itacoatiara, Tamshiyacu, San Regis and Borja had velocities greater than 2 m.s^{-1} more than 20% of time.

Figure 2. ADCP image samples from sites in Brazil, Peru and Ecuador.



The results indicate that for the maximum values, all the sites had water speeds (WS) greater or equal to 2.0 $m.s^{-1}$ during at least one point in the annual hydrological cycle. For the mean values, except at Manacapuru, all the sites had water speeds (WS) greater than 1.5 $m.s^{-1}$. These results, using the local mean river level annual variability, led to estimate the “natural” Power Potential (Pp) to be generated at each site (Table 3). Using a water surface of 1,000m^2 at each river transect, Borja had the greatest power potential, along with the sites of Óbidos, Itacoatiara, Manacapuru and Tamshiyacu, which also appeared to be promising. More details on this data analysis, including the relationship between velocity, discharge, and seasonal variability, are included in the report’s annex.

Table 3. Maximum and mean water speed ($m.s^{-1}$) and power potential (MW) for each site studied, using an area of 1,000m^2 at each transect.

Station Name	Max WS ($m.s^{-1}$)	Mean WS ($m.s^{-1}$)	Pp (MW) - Max WS	Pp (MW) - Mean WS
Bellavista - PE	2.2	1.5	13	9
Borja – PE	3.6	2.4	17	12
Itacoatiara - BR	2.2	1.5	24	17
Manacapuru - BR	2.0	1.4	26	18
Óbidos - BR	2.5	1.7	19	13
San Regis - PE	2.4	1.7	20	14
Santiago - EC	2.8	2.2	7	6
Tamshiyacu - PE	3.0	2.0	28	18

It is important to begin to characterize the nature and frequency of extreme events such as floods, droughts, and large changes in depth as these have an important impact on potential project design and operation. To start the process, the historical average discharge was calculated at each of the eight sites. These values made it possible to identify how different the sites are in terms of the volume of water transported by rivers. Further details on this analytical process are included in Annex 1 and 7 (the latter has supplementary images).

The seasonal variability of water discharge was also analyzed, and data was grouped using the monthly mean, maximum and minimum values (Annex 2). Such analysis made it possible to identify the general hydrological regime at each station (Figures 8A to 8H).

The results about the discharge occurrence (in %) at each station during an “average” year identified different behaviors for the investigated sites, which can be seen in Annex 3, Figures 9A to 9H.

Using the ADCP images from each station, two ensembles of data were obtained and used to create the figures in Annex 4 (Figures 10A to 10H): data from the fastest and slowest parts of the section. There is not always ADCP data from a specific month, and thus it was not possible to represent all the months at some stations (e.g. Óbidos, where there was no data for August and September).

The 'fast' and 'slow' velocity areas of each ADCP image were analyzed to obtain the frequency of velocity occurrence (in percentage) and to acquire data that generates Figures 11A to 11G in Annex 5.

Taking into account the objectives of this study and the above-referenced analysis, a summary of the results is detailed below:

- At Óbidos, for a range of 1.5 to 2.5 $m.s^{-1}$, the percentage of occurrence is greater than 20%. For that specific range, the total percentage of occurrence is greater than 60% over the year. The lowest velocities remain around 0.2 $m.s^{-1}$, 35% of the time. Values near 0.6 $m.s^{-1}$ occur only 10% of the time.

  Preliminary Classification: Good – Excellent. Strong potential for almost year-round generation. Capacity factors in the range of 50% - 80%. Large-scale turbines and arrays possible.

- At Manacapuru, the variability at the fast part ranges from 1 $m.s^{-1}$ (less than 10% of time) to 2.25 $m.s^{-1}$ (almost 10% of the time). Velocities reached between 1.5 and 2 $m.s^{-1}$ almost 40% of the time. For the slower part, the range is very broad (between 0.1 $m.s^{-1}$ and 1 $m.s^{-1}$), and stays between 0.3 and 0.9 $m.s^{-1}$ more than 50% of the time.

  Preliminary Classification: Good. Potential for steady generation during 50% of the year. Capacity factors in the range of 40% - 60% or more. Large scale turbines and arrays possible.

- At Itacoatiara, the behavior for the fastest part showed two peaks of occurrence, one with values greater than 1 $m.s^{-1}$ and less than 1.5 $m.s^{-1}$ with 10% of occurrence. The other peak is represented by a curve with velocities between 1.7 $m.s^{-1}$ and almost 2.4 $m.s^{-1}$ with almost 40% occurrence.

  Preliminary Classification: Good - Excellent. Year-round resource with potential for generation at or close to full power for 50% of the year, from February to September. Capacity factors in the range of 50%-80%. Large-scale turbines and arrays possible.

- At Tamshiyacu, the percentage of occurrence is greater, as with Óbidos. The difference is that the curve here reveals more percentage of occurrence for velocities near 1 $m.s^{-1}$. At Óbidos, that percentage of occurrence is greater for values near 3.0 $m.s^{-1}$, whereas velocities at Tamshiyacu range from 1 $m.s^{-1}$ to 3.5 $m.s^{-1}$ (higher than the peak of 3 $m.s^{-1}$ found at Óbidos). Velocities in the slower part range from 0.4 to 0.7 $m.s^{-1}$ more than 50% of the time.

  Preliminary Classification: Good – Excellent. Potential for steady generation from January to June. Capacity factors in the range of 50% - 80%. Medium to large-scale turbines and arrays possible.

- At San Regis, velocities at the fastest are greater than 2 $m.s^{-1}$ more than 60% of the time. The slower part had velocities concentrated near 0.4 $m.s^{-1}$ more than 60% of the time. The range is from 0.2 $m.s^{-1}$ to 1 $m.s^{-1}$.

  Preliminary Classification: Good - Excellent. Strong potential generation during a significant part of the year. Capacity factors in the range of 40% - 60% or potentially greater.

- At Bellavista, velocities at the fastest part of the section remain near 1.5 $m.s^{-1}$ almost 50% of the time. For the slower part, the range is from 0.2 $m.s^{-1}$ to close 1 $m.s^{-1}$, however more than 50% of the time it stays between 0.4 and 0.6 $m.s^{-1}$.

  Preliminary Classification: Poor - Average. Generation is possible for a large portion of year. Frequency of sufficient velocities appears to be below what would be required for commercial viability.

- At Borja, the fastest part revealed very interesting behavior, with a range of between 1 $m.s^{-1}$ and, at times, 4 $m.s^{-1}$. More than 60% of the time, velocities are higher than 2 $m.s^{-1}$, and more than 20% of the time they are above 3.5 $m.s^{-1}$. Velocities in the slower part are higher than 0.4 $m.s^{-1}$ more than 50% of the time.

  Preliminary Classification: Good – Excellent. Strong potential for much of the year. Potentially challenging in terms of varying velocities throughout the year.

- At Santiago, the fastest part is represented by a parabolic curve with velocities between 2 $m.s^{-1}$ and 2.5 $m.s^{-1}$ more than 40% of the time. For the slower part, velocities stay between 0.4 $m.s^{-1}$ and 0.6 $m.s^{-1}$ more than 40% of the time.

  Preliminary Classification: Average - Good. Strong potential for generation for at least 50% of the year.

Summary of Activities

The analysis carried out in the preparation of this report made it possible to:

- Evaluate data from Brazil, Ecuador and Peru - accessible through the ORE-HYBAM database;
- Compare water discharge and water velocity during different periods of different years in order to theoretically explore and verify the capacity of some river sections to produce electricity using RHK technology during an "average year;
- Identify high-potential sites to be explored for potential future deployment of an RHK pilot and future commercial projects;
- Develop case studies from 8 of the 54 total investigated sites, which indicate, in hydrological terms, that Brazil, Peru and Ecuador have variable but generally very favorable conditions for RHK technology;
- Perform a brief analysis of some aspects of the hydrology of the Amazon Basin as well as make observations on extreme events;
- Investigate the proximity of the RHK resource analyzed to an electric demand center.

Conclusion and Recommendations

There are extremely powerful RHK resources, close to electric demand centers, in the Amazon Basin of Brazil, Peru and Ecuador (which are also likely to be found in other countries). Thus, the authors of this report endorse the preliminary feasibility of RHK as a hereto untapped renewable energy option for the region. Application of RHK technology on a multi-megawatt and potentially multi-gigawatt scale could have a significant positive impact on the region and should thus be further investigated and supported. RHK potentially enables the provision of renewable energy while also allowing rivers to remain open for the transport of goods and services, thereby preserving existing regional transport links that would otherwise be destroyed by the construction of a conventional dammed hydropower project.

This report shows that existing available hydrological data is highly useful – physical measurements of current speed and depth can be linked to existing data thereby providing an assessment of the potential energy yield. The number of ORE-HYBAM hydrological stations with available data limited the scope of this report but more sites with strong potential likely exist.

Further investigation should be financed to build on the results of this report, both in terms of desk-based analysis and on-site investigation. The results of this report highlight the differences that exist between different sites. The sites, although linked, are not homogenous. It is also important to continue to characterize the nature and frequency of extreme events such as floods, droughts, and large changes in depth as these have a significant impact on potential project design and operation.

The authors recommend a more detailed study and physical assessment that also considers the environmental and social impacts of RHK deployment at each of the specific selected locations, as well as suggested mitigation measures.

Information gathered for these purposes will also have cross-functionality with other lines of hydrological and environmental investigation.

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Preliminary Analysis of Potential for River Hydrokinetic Energy Technologies in the Amazon Basin

1. Introduction

River Hydrokinetic Energy (RHK) is an emerging clean technology sector in which electricity-generating turbines are placed directly in a river flow without a dam to retain water and create an artificial head or otherwise divert the course of the river. The sector has gathered increasing attention over recent years as a potential low-impact alternative to conventional dammed hydroelectricity. The sector, which has undoubted significant potential throughout the Latin America and the Caribbean (LAC) region, is now approaching maturity with the first demonstrator arrays planned for construction soon.

RHK technologies can potentially provide clean, renewable power for remote riverside cities, communities and industrial centers. Many of these are significantly or wholly dependent on conventional thermal generation using expensive and polluting fuel that is imported from elsewhere. Facilitating the future deployment of RHK technologies in LAC is an ideal fit with two of the three pillars of the Sustainable Energy for All Initiative, namely, ensuring universal access to electricity and doubling the global installed capacity of renewable energy.

Di Lascio and Barreto (2009) conducted previous work in Brazil to evaluate the energy sector possibilities in Amazonia for RHK. They analyzed the development of sustainable energy as well as the hydrokinetic option for some sites. The general conclusion was that the velocity intensity at the studied sites was not strong enough for the specific technology under development at a Brazilian university. The studied sites were located in some highest areas of small catchment in the Brazilian Amazon. They did not investigate the big rivers because their RHK technologies had some limitations, and also because they did not have access to hydrological information that could provide them with a clear idea of the velocity distribution in space and time under the same section.

Therefore, resource assessment for this emerging sector in LAC has been limited to date. An in-depth resource assessment program is required to catalyze the development of the sector. However, existing hydrological data, gathered primarily for sedimentation analysis, is valuable in determining high-level energy potential and individual project feasibility.

In this report, the ORE-HYBAM database (www.ore-hybam.org) was used as a source of data to be screened and refined to provide an estimate of the annual energy yield of an RHK array. ORE-HYBAM is an environmental observatory that includes several hydrology research groups in LAC, particularly in Amazonia. The ORE-HYBAM initiative was launched in 2003 to monitor and analyze hydrological systems and sedimentation transport in the Amazon River Basin. The project incorporates hydrographic measurements taken since 1995. This information will serve to highlight the potential that RHK offers for clean, distributed generation in selected high-potential locations throughout the Amazonian region of Brazil, Peru, Ecuador and Bolivia.

2. Objectives

The main objective of this report is to present the results from an analysis of existing ORE-HYBAM hydrological data for RHK uses.

Data was used to determine possible sites in Amazonia (Figure 1) for future energy production of a theoretical RHK system over the course of at least one, but ideally several, year(s).

Amazon Basin

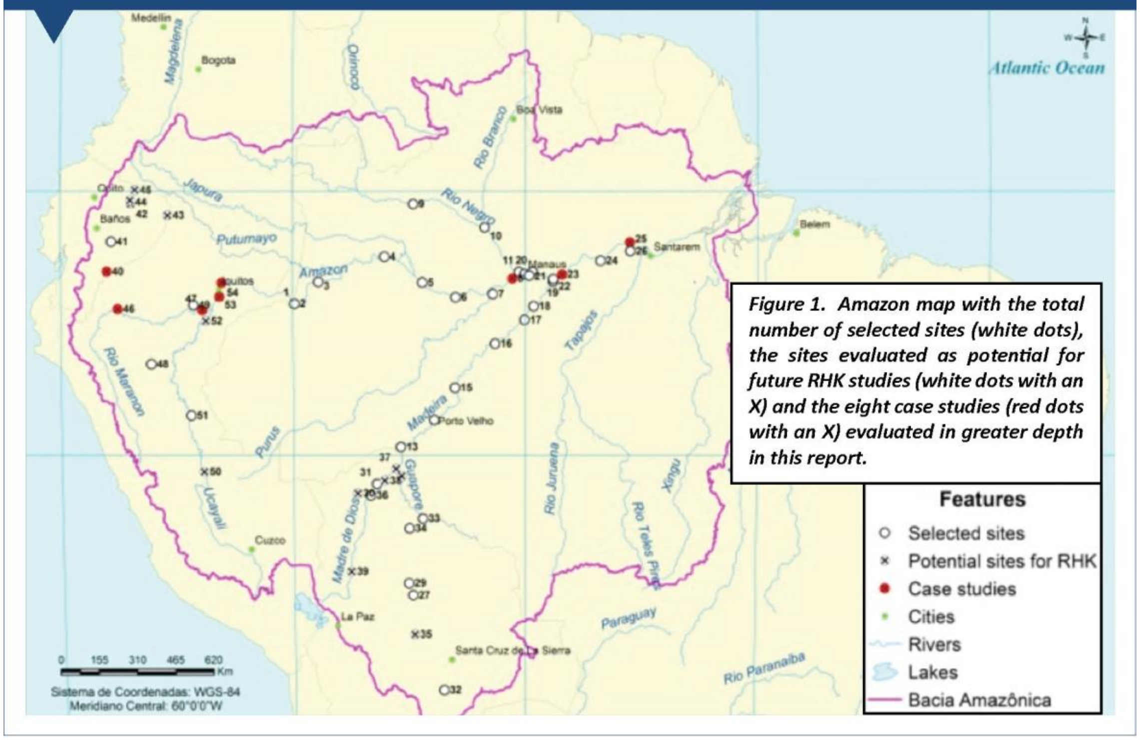


Figure 1. Amazon map with the total number of selected sites (white dots), the sites evaluated as potential for future RHK studies (white dots with an X) and the eight case studies (red dots with an X) evaluated in greater depth in this report.

3. Materials and Methods

3.1. About the data

The main sources of data is the ORE-HYBAM data set (www.ore-hybam.org), which includesmore than 200 stations across the entire Amazon Basin. This research was made possible by the privileged access that the group of consultants had to the database as well as their knowledge of the sites and the hydrology of the Amazon region in general. Of the total number of sites (hydrometric stations), 54 were chosen, taking into account important geomorphological indicators (of where high velocities were expected) associated with possible cities to be investigated as future energy beneficiaries. Sites were also considered that had hydrometric stations with ADCP (Acoustic Doppler Current Profiler) data that could be useful for the demands of this report.

ADCP is a device that generates Doppler images over river transects identifying velocities and other water features (RD Instruments, 1989). It uses the Doppler effect transmitting sound trough the water at a fixed frequency. It also listens to the echoes returning from sound scatters generated by suspended particles in the water. This sound reflection or “backscatter” is used by the ADCP to calculate the water velocity and discharge. To do this, a software divides the river section into several virtual cells, each one with a pre-defined area, configured by the user according to the environmental conditions. The device also identifies the river bottom profile, depth measurements, as well as length, current direction and backscatter signal values determination. With specific computer software, it is possible to see the acquisition procedure in real time. It is also possible to use raw data to be processed doing statistics with it to compare ADCP data with other parameters obtained over the section. Additional information about ADCP techniques and data corrections can be found at Simpson & Oltman (1993) and Callède et al. (2000). Information about the use of ADCP in Amazonia can be obtained at Filizola et al. (2009) and at Filizola and Guyot (2004).

In addition to the data, there is another factor that limited the research -the existence of legal instruments that prohibit the publishing or use of all data without official authorization. In order to obtain official authorization, a bureaucratic procedure is required, which is very time consuming and therefore not useful for this kind of report.

Preliminary data processing was carried out at some sites where little data was available. This was done due to the proximity of possible important energy consumer centers. Sites such as Jatuarana and Careiro (near the city of Manaus), and Iracema and Santarém (near the city of Santarém), where identified as important for future initiatives.

Of the 54 sites, 17% are located in Peru, 11% in Ecuador, 24% in Bolivia and 37% in Brazil (Table 1). The following station information was analyzed: the period of existing data in the database set, the amount of ADCP data with high water velocity (greater than 1.5 to 2 m/s) indications, the number of ADCP transects, and the volume of data in megabytes.

Taking the period of data into account, the existence of well-distributed measurements over the years was used as criterion to reselect stations in a more restrictive manner. The stations with the most complete data set were selected (ADCP data from January to December). For those stations, the number of ADCP measurements and the number of existing transects were used as additional criteria. As a result, 1,283 ADCP measurements were analyzed for the sites indicated in Table 1. That means that 6,062 transect or 54,296 Mb of data were processed for the objectives of this report.

The specific hydrological data of interest used here were: i) instantaneous Acoustic Doppler Current Profiler (ADCP) measurements yielding information on river current velocity, turbulence intensity, depth, and bathymetry and ii) historical discharge measurements.

Table 1. ORE-HYBAM Database Inventory tested for River Hydrokinetic Energy (RHK). Station names in bold indicate the group of 20 stations with potential and those with an asterisk (*) are the more detailed "case studies" in this report. Source: www.ore-hybam.org.

Country	River	Station Name (Fig.1 ID)	Latitude (º)	Longitude (º)	Data Period (Yrs)	# ADCP Measuements	# ADCP Transects	Data Volume (MB)
BRAZIL	Solimões	Nazareth (1)	-4.27182	-69.94238	1995-2011	11	46	91
		Tabatinga (2)	-4.26847	-69.94331	1995-2013	10	48	1147
		São Paulo de Olivença (3)	-3.44317	-68.91317	1995-2013	9	33	232
		Fonte Boa (4)	-2.48517	-66.06730	1995-2013	5	17	788
		Tefé (5)	-3.46770	-64.43655	1995-2013	8	28	430
		Itapéua (6)	-4.02377	-63.00283	1995-2012	32	149	2140
		Beruri (7)	-3.89882	-61.39170	2009-2012	33	133	1690
		Manacapuru * (8)	***-3.31192***	***-60.55345***	***1995-2012***	***76***	***281***	***8376***
	Negro	Serrinha (9)	-0.48194	-64.82889	1996-1998	2	8	55
		Moura (10)	-1.37283	-61.74685	1996-1998	3	11	21
		Paricatuba (11)	-3.05923	-60.26551	1995-2012	42	127	1864
		Manaus (12)	-3.13739	-60.02796	1994-2012	7	9	42
	Madeira	Abunã (13)	-9.70883	-65.36893	1995-2013	4	19	179
		Porto Velho (14)	-8.68630	-63.92328	1995-2013	12	54	739
		Humaitá (15)	-7.46316	-63.02600	1995-2013	13	61	924
		Manicoré (16)	-5.78420	-61.29950	1995-2013	10	55	751
		Fazenda Vista Alegre (17)	-4.88544	-60.03039	1995-2013	13	48	655
		Borba (18)	-4.36377	-59.64352	1994-2013	37	118	1423
		Foz Madeira (19)	-3.43146	-58.79665	1995-2012	35	117	1710

Country	River	Station Name (Fig.1 ID)	Latitude (º)	Longitude (º)	Data Period (Yrs)	# ADCP Measuements	# ADCP Transects	Data Volume (MB)
	Amazonas	Jatuarana (20)	-3.05379	-59.67869	1997-2012	4	14	266
		Careiro (21)	-3.19697	-59.83152	2010-2013	4	18	173
		Iracema (22)	-3.32877	-58.79180	2004	1	3	573
		Itacoatiara * (23)	***-3.15550***	***-58.41103***	***1994-2013***	***66***	***234***	***6,963***
		Parintins (24)	-2.63379	-56.75268	1996-2010	19	53	911
		Obidos * (25)	***-1.93275***	***-55.49444***	***1995-2013***	***67***	***528***	***9,708***
		Santarém (26)	-2.27083	-55.47639	2001-2003	6	8	96
BOLIVIA	Mamore	Camiaco (27)	-15.33444	-64.86556	2005-2011	15	63	ND
		Guayaramirim (28)	**-10.81242**	**-65.34298**	**1997-2011**	**25**	**101**	**ND**
		Los Puentes (29)	-14.88505	-65.03754	2005-2010	13	48	ND
	Madre de Dios	**El Sena (30)**	**-11.47018**	**-67.23681**	**2003-2011**	**18**	**86**	**ND**
		Miraflores (31)	-11.10772	-66.41114	1997-2005	17	76	ND
	Grande	Paraiso (32)	-18.94130	-63.53000	2002-2011	16	65	ND
	Guapore	Principe da Beira (33)	-12.42667	-64.42528	2005-2009	8	31	ND
		Puerto Siles (34)	-12.80433	-65.00322	2005-2011	14	67	ND
	Ichilo	**Puerto Varador (35)**	**-16.83167**	**-64.79972**	**2002-2011**	**24**	**142**	**ND**
	Beni	Peñas Amarillas (36)	-11.54876	-66.67365	2002-2011	20	75	ND
		Cachuela Esperanza (37)	**-10.53742**	**-65.58463**	**2002-2011**	**23**	**96**	**ND**
		Riberalta (38)	**-10.99444**	**-66.07533**	**2001-2011**	**28**	**116**	**ND**
		Rurrenabaque (39)	**-14.44097**	**-67.53508**	**1999-2011**	**39**	**170**	**ND**

Country	River	Station Name (Fig.1 ID)	Latitude (º)	Longitude (º)	Data Period (Yrs)	# ADCP Measuements	# ADCP Transects	Data Volume (MB)
ECUADOR	Santiago	***Santiago * (40)***	***-3.05100***	***-78.01305***	***2001-2010***	***28***	***136***	***270***
	Pastaza	La Unión (41)	-1.91410	-77.82575	2001-2004	12	33	55
	Napo	**Francisco de Orellana (42)**	**-0.47330**	**-76.98250**	**2001-2010**	**48**	**232**	**671**
		Nuevo Rocafuerte (43)	**-0.91689**	**-75.39639**	**2001-2011**	**34**	**135**	**872**
	Coca	**San Sebastián (44)**	**-0.34290**	**-77.00680**	**2001-2011**	**31**	**170**	**360**
	Aguarico	**Nueva Loja (45)**	**0.04400**	**-76.80830**	**2001-2011**	**23**	**124**	**197**
PERU	Marañón	***Borja * (46)***	***-4.47039***	***-77.54828***	***2003-2012***	***28***	***195***	***496***
		San Regis * (47)	***-4.51338***	***-73.90678***	***2003-2012***	***50***	***330***	***2,007***
	Huallaga	Chazuta (48)	-6.56889	-76.11353	2003-2012	20	117	236
	Tigre	Nueva York (49)	-4.32136	-74.29490	2006-2009	10	57	260
	Ucayali	**Lagarto (50)**	**-10.65344**	**-73.86863**	**2003-2012**	**34**	**152**	**724**
		Pucallpa (51)	-8.51400	-74.40467	2001-2012	11	46	346
		Requena (52)	**-4.92868**	**-73.76549**	**2002-2012**	**54**	**348**	**8**
	Amazonas	***Tamshiyacu * (53)***	***-4.00665***	***-73.16948***	***2002-2012***	***79***	***472***	***5,325***
	Napo	***Bellavista * (54)***	***-3.47904***	***-73.07707***	***2001-2012***	***32***	***159***	***523***

3.2. Data analysis

The data indicated in Table 1 was used in the following ways:

- Historical discharge measurement data was combined with ADCP images in order to estimate overall energy availability and the theoretical energy capture of RHK systems at the selected sites.
- Each ADCP measurement image and data was used to extract information on river current velocities, depths and the variation of these factors throughout the annual hydrological cycle.
- Two areas were chosen from each ADCP image and the fastest and the slowest parts were identified. The root mean cubed was taken over each area for each measurement and plotted against the mean discharge. A relationship between discharge and water speed was calculated for each area.
- In this process, certain conditions were taken into account, (e.g. where the discharge measurements were taken -- site conditions), and there was discussion of the validity of extrapolating results from a small number of velocity measurements at each site.
- Using the interannual variability of river current velocities, an analysis was conducted on the impact of the seasonal variation of discharge flow rates on current velocities and depth, throughout the year.

3.3. Other analyzed topics

To complete the report and finalize the analysis with more additional information, a brief summary of the Amazon River system is provided. Additional comments are also included on unique aspects of energy in Amazonia and their relationship to certain socioeconomic topics, such as the United Nations HDI-M. The Human Development Index per Municipality (HDI-M) is a composite index that measures three indicators of human development considered by the United Nations Development Program: longevity, education, and revenue. A scale of zero (0) to one (1) is used, with values closest to one indicating higher human development levels at that site/location. This is an important reflection of socioeconomic conditions for energy consumption in the Amazon region. Some research in Brazil has analyzed the relationship between HDI-M and energy consumption. This report uses that kind of work to present a view on the matter, focusing on the sites studied here. When possible, additional 'project enabling' factors potentially impacting project viability were defined and described (electricity consumption, breakdown of local electricity generation, population, power demand and others that may become relevant). An overview of the conditions during flooding, drought, or other extreme events was also provided.

4. Results

4.1. An Overview of Amazon Hydrology

As the world's major hydrological basin, the Amazon drainage basin covers more than 6,000,000 km^2 -- almost 5% of the Earth's entire landmass. Its average discharge is the greatest in the world (209,000 $m^3.s^{-1}$) (Molinier et al., 1996). Due to its size and its position astride the equator, the Amazon Basin includes very different regions with various discharge regimes.

Temperatures within the basin range from negative values (at the summits of the Andes Mountains) to near 40 °C (in the lowland plain areas), and there is a strong precipitation gradient that ranges from 200 to 6,000 $mm/year^{-1}$ (with an average of 2,400 $mm/year^{-1}$). The Inter-Tropical Convergence Zone controls the equatorial climate in Amazonia, and some recent dramatic events such as the 2005 and 2010 droughts and the 2009 and 2012 floods show that it is insufficient to analyze only the mean annual discharge. It is also important to pay attention to extreme values. Several research groups analyzed extreme events, and most of them concluded that the confluence of climatic events in the Pacific and North Atlantic Oceans was the most important factor that gave rise to such extreme situations.

Brazil, Peru, Ecuador, Bolivia, Colombia, Venezuela and Guyana share the Amazon basin. More than half of this basin is located in Brazilian territory. The headwaters are located in the Andean portion of the basin, which is shared by Bolivia, Peru, Ecuador and Colombia. Human density in the Amazon Basin is very low and people are concentrated in urban centers. In the entire basin, there are five cities with more than one million inhabitants and three cities with more than 300,000. However, despite the high proportion of the population living in urban areas, the economy of the region is still primarily dependent on the extraction of exportable minerals, oils, and forest products. The only exception is the contribution made by the industrial park located in the city of Manaus.

Most of the Amazon Basin does not exceed an altitude of 250 m, and the main humid zones are located below 100 m (Salati & Vose 1984). The ports located in Iquitos, on the Amazon River (Peru), and Porto Velho, on the Madeira River (Brazil), receive ships that travel more than 3,500 km on the rivers. Not all the rivers of the Amazon Basin are navigable by commercial ships, although it is estimated that more than 40,000 crafts of various types navigate the waterways within the basin (UNEP, 2004).

Even with a huge potential for navigation, frequent flooding, and droughts, local governments are still planning to build large hydroelectric dams in the Amazon region. Such infrastructure was not envisioned to solve the energy problem for local populations, but as a source for the big and faraway consumer centers that have a significant and growing demand. In this context, RHK is an important sustainable alternative to the urban areas in the Amazon region.

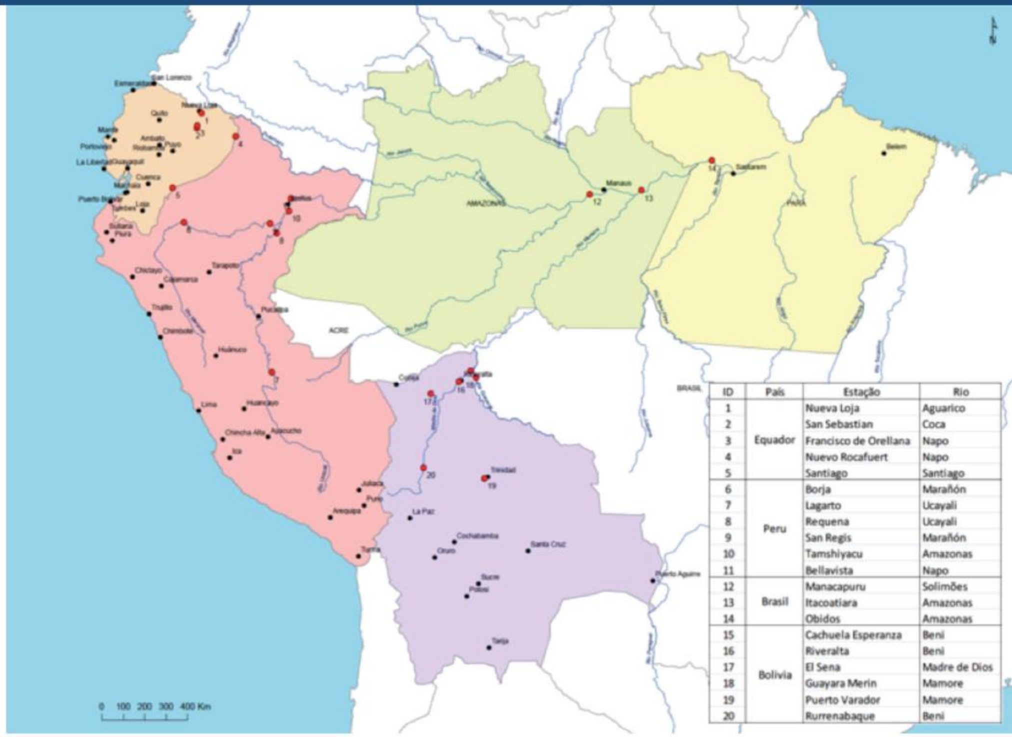
4.2. Potential hydrological sites for future RHK studies

Using the station data indicated in Table 1, river velocities were analyzed in more detail, especially at the sites with more than 24 ADCP measurements. The sites of El Sena (Madre de Dios River) and Cachuela Esperanza (Beni River) were the exceptions, as they had fewer than 24 measurements due to their locations. The minimum number of measurements used is 24 because in the database this number coincided with data distribution from January to December, when taking into account the whole period of available data from each station. Using that criteria, 20 stations were selected as potential sites for further exploration. From those 20 stations/sites, 8 of them were found to have enough data to be explored further. Moreover, the 8 sites are located in areas with a high potential for future RHK projects.

Thus, for the 20 sites indicated in Table 1 in bold lettering (Figure 2 shows their distribution), there is data on water velocities in good conditions for RHK investigations. However database limitations hindered more in-depth research. Those points can be studied further in the future through additional measurements. Those limitations include, for example, the amount of data generated each month of a year (with ADCP raw data) on the historical record of each station (Table 2). As shown in Table 2 of the database, August and September are the months with the least amount of data available, followed by January.

Using all of the data, 8 of the stations were chosen for more in-depth study. The most important city near the stations was also taken into consideration in the study (Figure 2). Relevant data was also determined by which cities had existing data, whether there was ADCP data as well, and whether there were HDI-M registered by an official national statistics authority.

Figure 2. The 20 sites (red dots) with RHK potential, initially analyzed in this report. The black dots are important urban centers as energy consumers in the region. Source: ORE-HYBAM website.



ID	País	Estação	Rio
1	Equador	Nueva Loja	Aguarico
2		San Sebastian	Coca
3		Francisco de Orellana	Napo
4		Nuevo Rocafuert	Napo
5		Santiago	Santiago
6	Peru	Borja	Marañón
7		Lagarto	Ucayali
8		Requena	Ucayali
9		San Regis	Marañón
10		Tamshiyacu	Amazonas
11		Bellavista	Napo
12	Brasil	Manacapuru	Solimões
13		Itacoatiara	Amazonas
14		Obidos	Amazonas
15	Bolivia	Cachuela Esperanza	Beni
16		Riveralta	Beni
17		El Sena	Madre de Dios
18		Guayara Merin	Mamore
19		Puerto Varador	Mamore
20		Rurrenabaque	Beni

Table 2. Number of times each station has data in a specific month with current velocities in good conditions for RHK purposes. Bolivian stations were not considered because of lack of access to raw data.

	Station Name	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
BRAZIL	Manacapuru	3	9	10	6	11	6	6	13	6	4	12	8
	Itacoatiara	3	3	5	4	5	6	5	4	5	6	6	4
	Óbidos	1	1	6	1	5	6	4	1	1	6	5	5
PERU	Borja	0	2	3	3	2	1	2	0	1	1	0	2
	San Regis	2	3	1	4	4	3	1	3	2	5	2	1
	Lagarto	1	0	4	1	2	1	2	1	0	0	1	1
	Requena	1	4	2	4	4	3	1	3	2	3	1	1
	Tamshiyacu	1	4	1	3	6	2	3	5	2	3	3	1
	Bellavista	1	4	1	4	3	2	1	1	1	2	4	1
ECUADOR	Santiago	4	3	1	3	3	1	3	0	3	2	1	1
	Francisco de Orellana	1	5	3	1	3	6	3	0	0	4	3	4
	San Sebastián	1	4	2	1	3	7	3	0	0	2	3	4
	Nuevo Rocafuerte	0	2	2	1	0	7	4	0	0	3	2	3
	Nueva Loja	0	3	1	1	2	5	2	0	0	3	1	3

During the analysis of each station's monthly data, considering current velocities greater than 2 $m.s^{-1}$, the total number of stations decreased. Only eight of them have a discharge condition that produces velocities above 2 $m.s^{-1}$ for more than 30 days per year (Table 3). Table 3 shows results for all the periods of years shown for each station in Table 1. Graphs of discharge versus velocities at different periods of the year (high and slow current) were generated and based upon this, the base discharge values (Base Q) were calculated. With this information for each site, the days with velocities that meet the necessary conditions were used to calculate an average for the period of data used. The results show that even in Borja, the Base Q is the lowest, having an average of 312 days with current velocities above 2 $m.s^{-1}$. In contrast, at the higher discharge sites, such as Óbidos, the current velocities are in good condition for almost half of the year. Of those eight stations, Bellavista had the worst conditions. Even with a Base Q of 10.000 $m^3.s^{-1}$, the current velocities are only good for an average of 37 days per year. Stations marked with "NS" indicate that the data was insignificant for the purposes of this report.

Table 3. Analysis of the number of days when discharge conditions produced current velocities greater than 2 m/s.

Station Name	Base Q ($m^3.s^{-1}$)	No. Days/Year (Q > Base Q)
Manacapuru	120,000	172
Itacoatiara	160,000	211
Óbidos	180,000	195
Borja	2,500	312
San Regis	13.000	269
Lagarto	- NS	- NS
Requena	- NS	- NS
Tamshiyacu	30,000	178
Bellavista	10,000	37
Santiago	900	309
Francisco de Orellana	- NS	- NS
San Sebastián	- NS	- NS
Nuevo Rocafuerte	- NS	- NS
Nueva Loja	- NS	- NS

Obs. **NS** = Data with No Significance to this study

4.3. The hydrological conditions for RHK on the case studied

Taking into account all of the data examined from the ORE-HYBAM database, ADCP images were first used to indicate the sites to be further explored. For this procedure, six stations (with an NS) from Table 3 were eliminated. The eight remaining sites were chosen for more detailed investigation.

4.3.1. The sites and the ADCP image sample descriptions

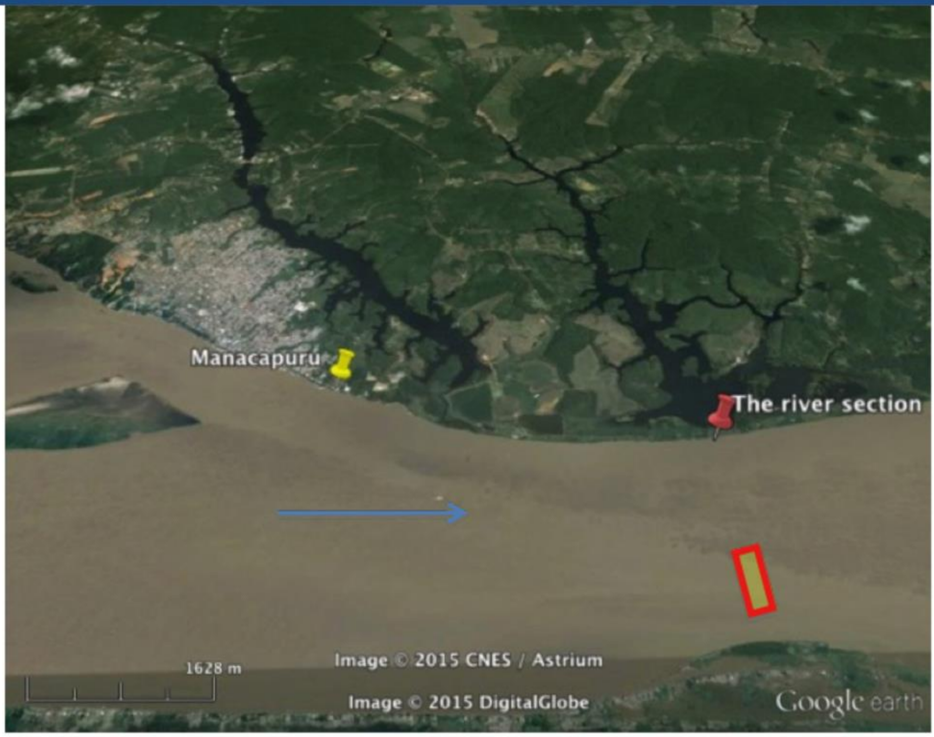
At each site, the ADCP images (Figure 3 and Annex 1) were used to indicate the color scale of the regions with velocities greater than 2 $m.s^{-1}$. An initial relationship between discharge and percentage of velocity greater than 2 $m.s^{-1}$ was also analyzed using a 95% confidence bound. For that initial basic analysis, Borja and Santiago, both in Peru, indicated a linear trend. The Óbidos, Itacoatiara, Tamshiyacu, San Regis, and Borja stations had velocities greater than 2 $m.s^{-1}$ more than 20% of the time.

The Óbidos site (Plate 1) is located on the Amazon River in Brazil, almost 700 km from the river mouth. The river section is approximately 2,500 meters wide and almost 70 meters at its maximum depth (Annex 1, Figure 7A). In some transect parts, even near the bottom, water velocities can reach more than 1.5 $m.s^{-1}$. The site location is quite near the city of the same name (less than 5 km away), which is a municipality in Pará, located at the narrowest and swiftest part of the Amazon River, and home to 50,317 inhabitants.

Plate 1. The station at the site of Óbidos (yellow pin). The red rectangle indicates approximately the region with high water speed in the section. The blue arrow indicates the current direction. Source: Google Earth.

The Manacapuru site (Plate 2), located on the Solimões River in Brazil, has a river section that is 3,000 meters wide and that reaches a maximum depth of almost 40 meters. Velocities are very diffused under the river transection, but high velocities were found in two areas (Annex 1, Figure 7B). The site (river section) is less than 10 km from the city of Manacapuru (and to the electric grid), which has 92,996 inhabitants.

Plate 2. The station at the site of Manacapuru. The red rectangle indicates approximately the region with high water speed in the section. The blue arrow indicates the current direction. Source: Google Earth.



The site of Itacoatiara (Plate 3), located on the Amazon River in Brazil, just below the Madeira River mouth, is almost 60 meters deep at the low waters (Annex 1, Figure 7C) and can reach a depth of 110 meters in high waters. This river section is more than 3,500 meters wide. Water speed can sometimes reach 2 $m.s^{-1}$, but only near the thalweg region. Itacoatiara has almost 96,000 inhabitants and is the second most economically important city in the State of Amazonas. The river section is less them 5 km from the city and from the electric grid. The city is connected to Manaus, which isthe state capital, by road (176 km).

Plate 3. The station at the Itacoatiara site. The red rectangle indicates the region in that section that has high water speed. The blue arrow indicates the current direction. Source: Google Earth.

The Tamshiyacu (Plate 4) section is located on the Amazonas River in Peru in front of the city of the same name. The section is almost 1,000 meters wide and 35 meters deep in the thalweg region (Figure 7D). Water speed can reach 2 $m.s^{-1}$ near this transect region. The city has a population of about 8,000 and is situated about 30 km upstream from the city of Iquitos (about an hour away by speedboat).

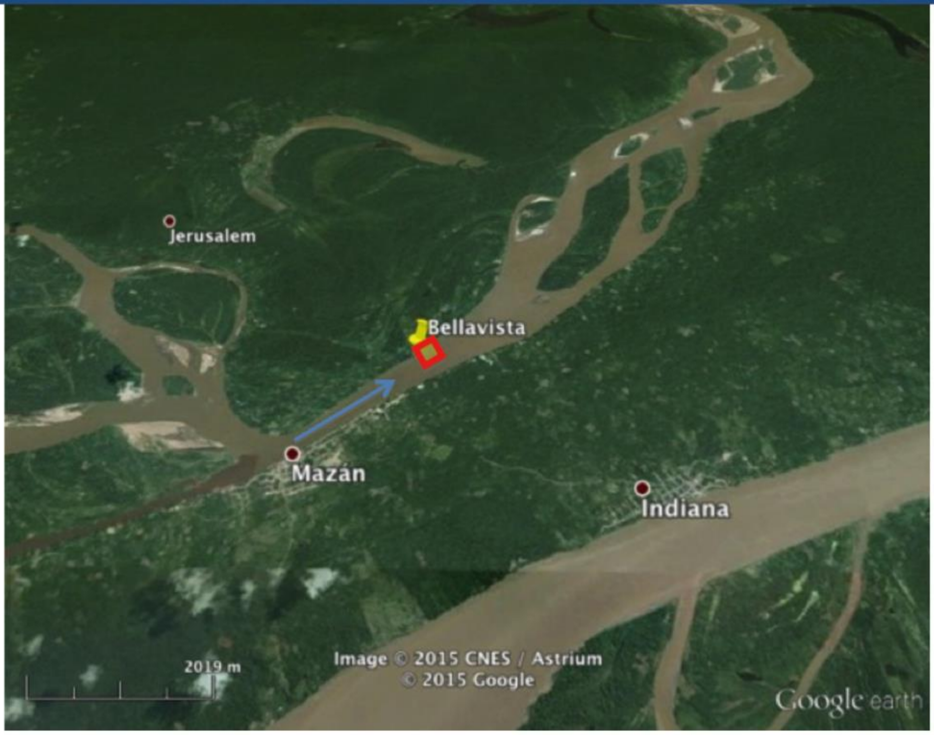
Plate 4. The station at the Tamshiyacu site. The red rectangle indicates the region in the section with high water speed. The blue arrow indicates the current direction. Source: Google Earth.

San Regis (Plate 5), on the Marañon River in Peru, has a section that is almost 700 km wide and 25 meters deep. High velocities are very well distributed under the section, which is formed in a "U" shape (Figure 7E). The village of San Regis is very small and isolated from a city with a more widespread electric grid.

Plate 5. The station at the San Regis site. The red rectangle indicates approximately the region in the section with high water speed. The blue arrow indicates the current direction. Source: Google Earth.

Bellavista (Plate 6) is another ORE-HYBAM station, but it is situated on the Napo River. The river section at the site is almost 500 meters wide and between 10 and 15 meters deep. High velocities are more concentrated at the deepest part of the section (Figure 7F). The site has no special urban area, but is close (less than 5 km) to the grid of Mazán (3,626 inhabitants) and Indiana (13,369 inhabitants). For both of these small cities, tourism (of the Amazon rainforest) is the most important element of their economies. It is important to note that "near the grid" sometimes means thermic and isolated electricity infrastructure, which is not connected to a national grid.

Plate 6. The station at the Bellavista site. The red rectangle indicates approximately the region with high water speed in the section. The blue arrow indicates the current direction. Source: Google Earth.

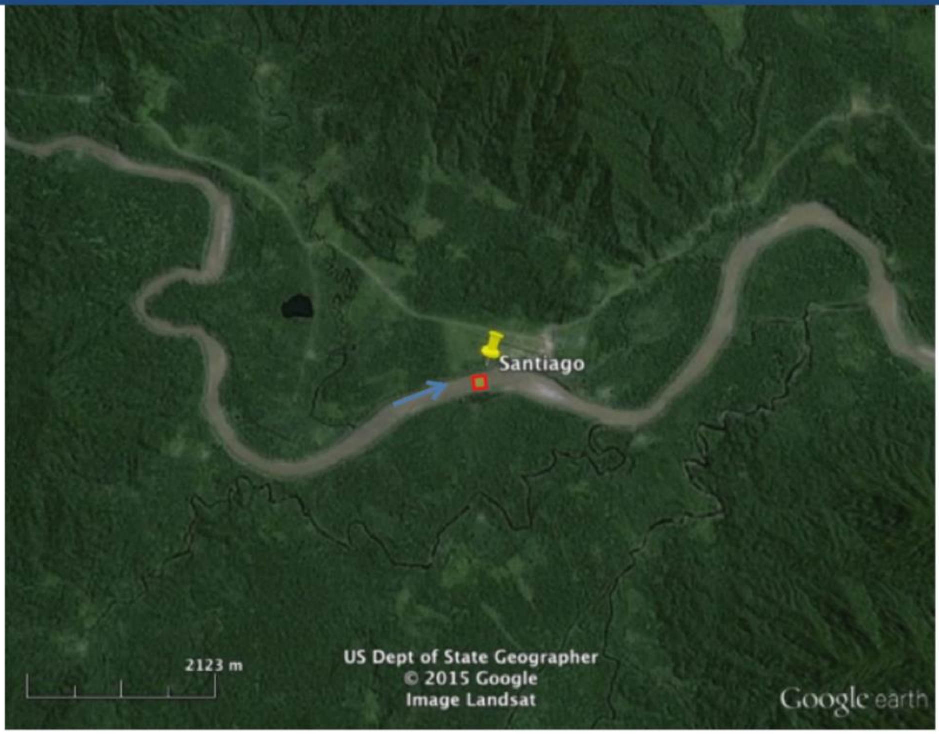


The next site is Borja (Plate 7), which is located on the Marañon River after it runs through the Andes Mountains. The ADCP transect image shown in Figure 7G indicates high water speeds in almost the entire river section. The width at this site is about 250 meters and the maximum depth can reach 20 meters with a very well defined thalweg at one specific riverside. The site is very isolated and the nearest village is more than 20 km away. Moreover, because the section is located in the high/low altitudes of the Andes, there are hills that complicate accessibility.

Plate 7. The station at the Borja site. The red rectangle indicates approximately the region with high water speed in the section. The blue arrow indicates the current direction. Source: Google Earth.

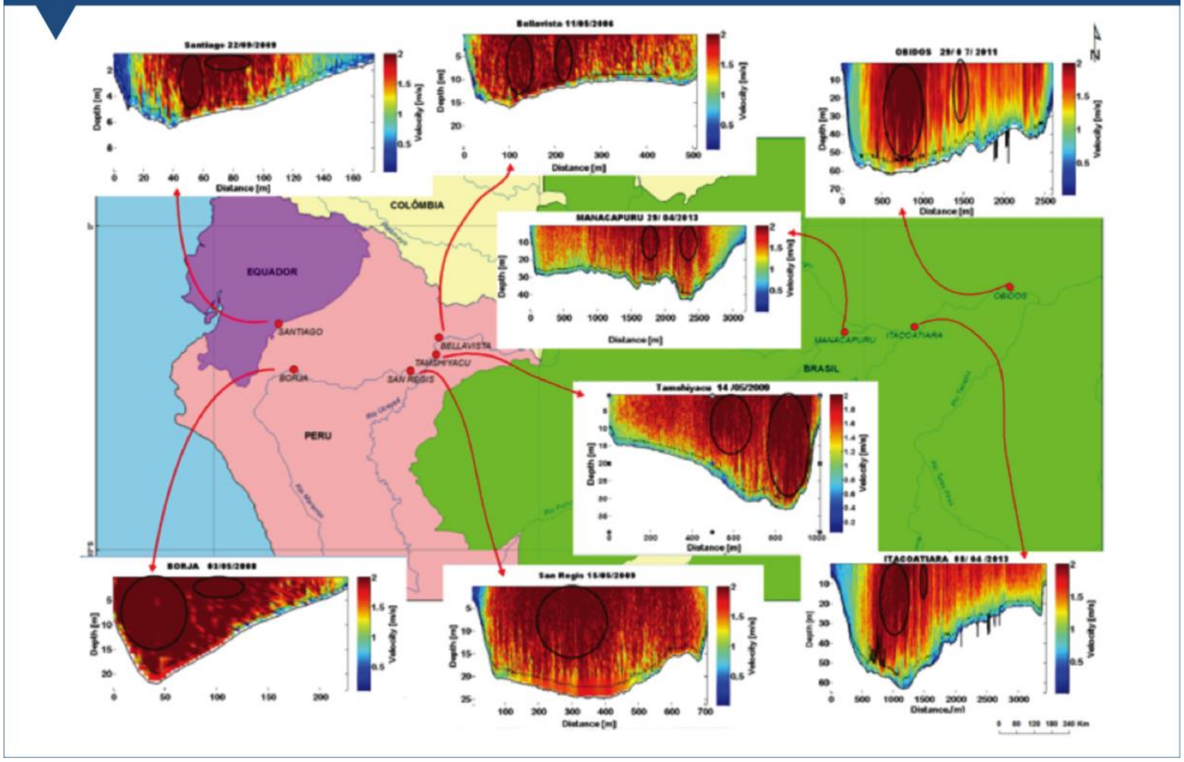
The final site to be presented here is Santiago (plate 8), on Rio Santiago in Ecuador. This site is near the small mountainous village of Santiago, with close to 9,150 inhabitants. The river section is almost 200 meters wide and less than 8 meters deep (Figure 7H). During high waters it can reach greater depths, but there was no available data on very high waters. The high water speed areas are more concentrated near the middle of the section, not exactly under the thalweg.

Plate 8. The station at the Santiago site. The red rectangle indicates approximately the region with high water speed in the section. The blue arrow indicates the current direction. Source: Google Earth.



In Figure 3, each river section can be spatially connected with its corresponding ADCP image on a map of the investigated sites in the region. The most noteworthy aspect is the distribution of strong velocity areas in each river section, which are more diffused over the section at Peruvian sites than those in Ecuador and Brazil. At the fastest area of each studied site in Figure 2, the maximum water speed was calculated using information from the database (Table 4).

Figure 3. ADCP image samples at their sites in Brazil, Peru and Ecuador.



The results indicate that for the maximum values, all the sites had water speeds (WS) greater or equal to 2.0 $m.s^{-1}$. For the mean values, except at Manacapuru, all the sites had water speeds (WS) greater than 1.5 $m.s^{-1}$. And even for Manacapuru, the value was also significant and close to the reference water speed. These results were used to calculate the Power Potential (Pp) to be generated for RHK technology at each site (Table 4), considering a water surface of $1000m^2$. For this, the most promising potential site under consideration is Borja and then Óbidos, Itacoatiara, Manacapuru, and Tamshiyacu are also promising. This report includes further data analysis in order to supplement this information and provide more details on the velocities and discharge relationship and seasonal variability (see Annexes).

Table 4. Maximum and mean water speed and power potential for each studied site

Station Name	Max WS ($m.s^{-1}$)	Mean WS ($m.s^{-1}$)	Pp (MW) - Max WS	Pp (MW) - Mean WS
Bellavista - PE	2.2	1.5	13	9
Borja - PE	3.6	2.4	17	12
Itacoatiara - BR	2.2	1.5	24	17
Manacapuru - BR	2.0	1.4	26	18
Óbidos - BR	2.5	1.7	19	13
San Regis - PE	2.4	1.7	20	14
Santiago - EC	2.8	2.2	7	6
Tamshiyacu - PE	3.0	2.0	28	18

4.3.2. The mean discharge at each site

For the sites with ADCP figures and where the initial velocity against discharge relationship has been studied, the historical average discharge was calculated. These values (Table 4) illustrate how different the 8 sites are in terms of the volume of water transported by the rivers. This difference exists due to the site positions in the basin. Normally, the higher the discharge, the closer the site is to the mouth of the Amazon River. Another important value for the focus of this report is the historic river level seasonal variability. These values, shown in Table 5, were also calculated for each site. The final number comes from the maximum values obtained from the time series for each year's seasonal variation. It is noteworthy that for the high upstream part of the Amazon River (e.g. Tamshiyacu), the RLSV values are almost the same as those calculated for Óbidos (7.8 meters), which is very far downstream on the river. However, not far from Óbidos, at Manacapuru and Itacoatiara, the RLSV values were higher than 11 meters. This is a consequence of the hydrological regime from rivers like the Madeira and the Trombetas, and is also associated with a possible sea tidal influence.

Table 5. Historical Average (AVR) Discharge and the historical River Level Seasonal Variability (RLSV) at each investigated site.

Station Name	AVR Q (m3/s)	RLSV (cm)
Óbidos - BR	181,645	780
Itacoatiara - BR	162,535	1136
Manacapuru - BR	105,781	1333
Tamshiyacu - PE	29,182	943
San Regis - PE	16,817	855
Bellavista - PE	6,758	604
Borja – PE	5,085	490
Santiago - EC	1,616	258

4.3.3. Discharge seasonal variation

This section includes the results from historical data for each station. The data was grouped using the monthly mean, maximum, and minimum values (Annex 2), identifying the general hydrological regime at each station (Figures 8A to 8H). Using the transition between months 6 (June) and 7 (July) as a reference, the following is noted:

- Óbidos, Manacapuru and Itacoatiara have almost the same behavior for the mean curve. The high discharge period occurs between months 6 and 7.
- The Óbidos curves for minimum and maximum are different than those from Manacapuru and Itacoatiara;
- Tamshiyacu and San Regis have a very similar regime, especially for the mean curves. The high discharge period occurs between months 4 and 5.
- Borja and Santiago both have regimes that differ from each other and also from the others. The regime in Borja varies and has a homogeneous mean and minimum values; there were higher values during the period of March until June. For Santiago, the homogeneity for mean and minimum values was well marked. High discharges were signaled by rivers with “monsoonal behavior” (Latrubesse et al., 2005), where the high peak occurs at a very isolated and marked time of the year – June, in this case.
- At Bellavista, the high discharge period is different from the others, even when comparing the maximum, minimum, and mean curves. Using the mean curve, it is possible to identify the high water discharges between months 6 and 7.

With regard to the ratio between the minimum and maximum discharge (here called RQ) in high water periods, the sites can be divided into the following three site groupings: stations with an RQ greater than 70% (Óbidos, Manacapuru and Itacoatiara), those with an RQ below 70% but greater than 40% (Tamshiyacu, San Regis and Bellavista), and those with an RQ below 10% (Santiago and Borja). This parameter marks the percentage of the maximum discharge that can be reached as a minimum value in high water periods. Thus, the three Brazilian stations have the closest variation of discharge values.

4.3.4. Discharge distribution (% of occurrence)

This section covers the results from the discharge percentage of occurrence at each station during an "average" year. The result of this graphics analysis (Annex 3, Figures 9A to 9H) led to the identification of different behavior at the investigated sites.

A simple and inverse parabolic curve was revealed for the stations of Borja, San Regis, Bellavista, and Santiago (Figures 9E to 9H). Values from these stations are as follows:

- At San Regis, the most frequent discharge values (30% of the time) are those close to 20,000 $m^3.s^{-1}$.
- At Bellavista, the most frequent discharge values (70% of the time) are those close to 10,000 $m^3.s^{-1}$.
- At Borja, the most frequent discharge values (between 65 to 60% of the time) are those close to 7,000 $m^3.s^{-1}$.
- At Santiago, the most frequent discharge values (80% of the time) are those close to 5,000 $m^3.s^{-1}$.

For the Manacapuru and Tamshiyacu stations, Figures 9B and 9D show a very similar curve (with two peaks of percentage of occurrence), but higher discharge values are more frequent in Tamshiyacu than in Manacapuru. Otherwise, the discharge values in Manacapuru are more than double those in Tamshiyacu. At Itacoatiara (Figure 9C), there was no parabolic behavior. The relationship is almost linear, revealing that higher discharge normally occurs more than 35 % of the time, with a trend of positive proportionality. This can be explained by the water inputs from the Madeira River. This important tributary empties its waters into the Amazon River very near to Itacoatiara (upstream) and in a different timeframe as well. At Óbidos (Figure 9A), behavior differs from the other sites and reveals a tendency to harmonize different contributions from several important tributaries, such as the Negro, Madeira, Nhamundá and Trombetas. Otherwise, there is a peak on the curve that indicates that discharge between 250,000 and 270,000 $m^3.s^{-1}$ occurs more than 20% of the time.

4.3.5. Velocity seasonal variability

This section presents the annual velocity[3] variability at each studied site. Using the ADCP images of each station, two data sets were used to develop Figures 10A to 10H (in Annex 4): data from the fastest and slowest parts of the section. There is not always data from ADCP in a specific month, and therefore it was impossible to represent all the months at some stations, e.g. Óbidos, where there was no data from August and September.

The high velocity limit for the fast data was 3 or 3.5 (only at Borja) $m.s^{-1}$. For the slowest data it was 1 $m.s^{-1}$.

The results showed that:

- Velocities at Óbidos, Manacapuru, Itacoatiara, Tamshiyacu, Borja, and Santiago varied between 1.5 to 2 $m.s^{-1}$, occasionally higher, from January until July. The slower part is very different, and the trend reveals diminished values during the same period. Santiago, San Regis, Itacoatiara, and Manacapuru seem to be the sites with more regular velocities and with less variation in the first semester of an “average” year.

- For the other sites, things seem to be more erratic, without well-defined trends and no regularity for the velocities in the fast parts.

- The slowest parts normally indicate values below 0.6 $m.s^{-1}$, and during a few months the only exceptions were Bellavista and Tamshiyacu. Those stations had velocities near 0.8 $m.s^{-1}$ during 1 to 3 months.

4.3.6. Velocity distribution (% of occurrence)

This section presents and analyzes the percentage of velocities occurrence at the above-mentioned sites. The fastest and slowest parts of the ADCP images were also examined to obtain data for figures 11A to 11G in Annex 5.
The results revealed that:

- At Óbidos, there was a range of 1.5 to 2.5 $m.s^{-1}$, where the percentage of occurrence is greater than 20% for its specific range with a total percentage of

[3] For this report velocity and water speed are considered synonymous.

occurrence greater than 60% over the year. The slowest velocities are around 0.2 $m.s^{-1}$, 35% of the time. Values near 0.6 $m.s^{-1}$ occur only 10% of the time.

- At Manacapuru, the variability at the fast part ranges from 1 $m.s^{-1}$ (less than 10% of the time) to 2.25 $m.s^{-1}$ (almost 10% of the time). Otherwise, velocities reached between 1.5 and 2 $m.s^{-1}$ almost 40% of the time . For the slower part, the range is quite broad (between 0.1 $m.s^{-1}$ and 1 $m.s^{-1}$), and remains between 0.3 and 0.9 $m.s^{-1}$ more than 50% of the time.
- At Itacoatiara, the behavior for the fastest part showed two peaks of occurrence, one with values greater than 1 $m.s^{-1}$ and less than 1.5 $m.s^{-1}$, with 10% of occurrence. The other peak is represented by a curve with velocities between 1.7 $m.s^{-1}$ and almost 2.4 $m.s^{-1}$, with almost 40% of occurrence.
- At Tamshiyacu, the percentage of occurrence is higher, such as at Óbidos. The difference is that the curve here reveals more percentage of occurrence for velocities near 1 $m.s^{-1}$. At Óbidos, that percentage of occurrence is higher for values near 3.0 $m.s^{-1}$. Otherwise, at Tamshiyacu velocities range from 1 $m.s^{-1}$ to3.5 $m.s^{-1}$ and not to 3 $m.s^{-1}$, as occurs at Óbidos. For the slower part, more than 50% of the time the velocity ranges from 0.4 to 0.7 $m.s^{-1}$.
- At San Regis, velocities at the fastest part are greater than 2 $m.s^{-1}$ more than 60% of time. The slower part had velocities around 0.4 $m.s^{-1}$ more than 60% of time, with a total range of 0.2 $m.s^{-1}$ to 1 $m.s^{-1}$.
- At Bellavista, velocities at the fastest part of the section remained near 1.5 $m.s^{-1}$ almost 50% of the time. The range for the slower part goes from 0.2 $m.s^{-1}$ to almost 1 $m.s^{-1}$, but more than 50% of the time it stays between 0.4 and 0.6 $m.s^{-1}$.
- At Borja, the fastest part revealed very interesting behavior, with a range between 1 $m.s^{-1}$ and at times, 4 $m.s^{-1}$. More than 60% of time the velocities were greater than 2 $m.s^{-1}$ and more than 20% of the time they were above 3.5 $m.s^{-1}$. For the slower part, more than 50% of time velocities remained above 0.4 $m.s^{-1}$.
- At Santiago, the fastest parts are represented by a parabolic curve that showed velocities between 2 $m.s^{-1}$ and 2.5 $m.s^{-1}$ more than 40% of the time. For the slower part, velocities remained between 0.4 $m.s^{-1}$ and 0.6 $m.s^{-1}$ more than 40% of time.

4.3.7. Relationship between discharge and velocity (faster and slower periods)

Finally, the last area studied from hydrological data from the ORE-HYBAM database is the relationship between discharge and velocity for the fastest and slowest parts (Annex 6, Figures 12A to 12H). The slowest parts revealed a very poor relationship between velocity and discharge, meaning that at slower parts velocities normally remained below 0.5 $m.s^{-1}$. Moreover, the graphs indicate that even with an augmentation of discharge, at the slower part, velocity range variations are small. In contrast, for the fastest parts, there was a linear correlation for all sites. The R^2 varies from 0.8 to 0.9, indicating that high velocities are explained 80% to 90% of the time by a discharge variability with positive proportionality.

The trend line is indicated by the letter "b" of the equation: y=ax+b, where y=velocity and x=discharge, shows where velocities tend to be greater with stronger discharge. The closer "b" is to 0 (zero), the tendency is for more stable velocities against the discharge augmentation. Thus, we divided the investigated sites into four classes: 1) Óbidos with b<0.5 (0.15); 2) Itacoatiara, Bellavista and Tamshiyacu with 0.5<b<0.6; 3) Manacapuru, Borja and San Regis with 0.6<b<1.0 and 4) Santiago with b>1 The letter "b" can also be used here as the minimum theoretical velocity that may be admitted at each station.

4.4. Extreme hydrologic events in Amazonia

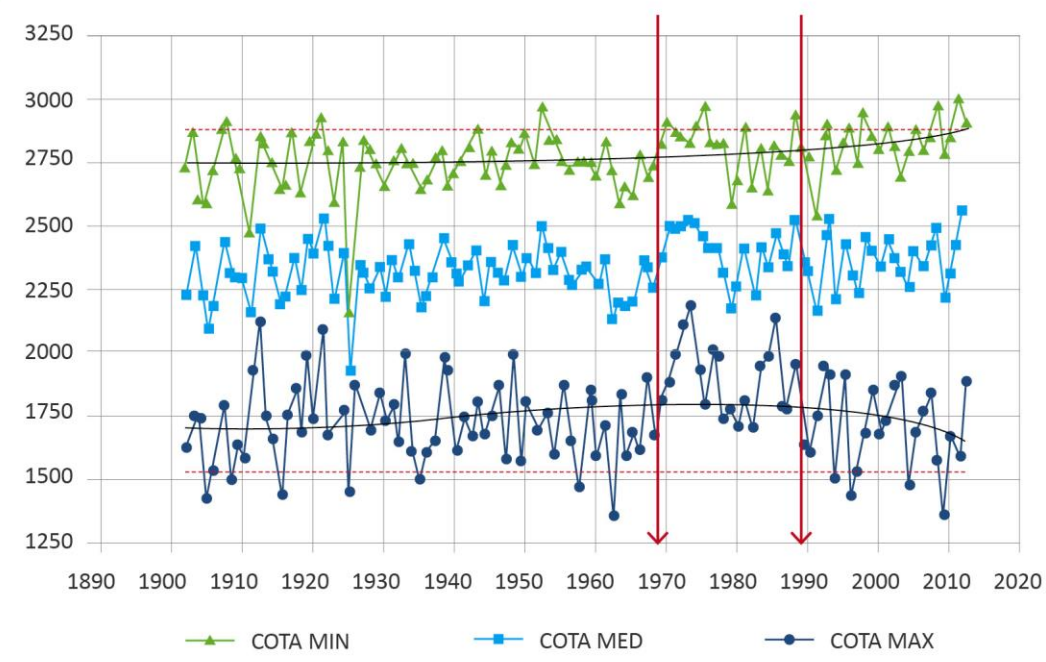
Several papers published recently revealed a trend in increased extreme hydrological events in the Amazon region. Most of these kinds of events have been reported more frequently in the Amazon region during the last decade (Marengo et al 2011, 2012, 2013, Espinoza et al 2011, Satyamurty et al 2013). According to these papers, abundant rainfall, especially in the western Amazon, has caused intense floods along the river's main channel, affecting human and natural systems (Marengo et al 2012, 2013, Espinoza et al 2013). Some of the conclusions of the scientific community identify an association with a possible intensification of the hydrological cycle in western Amazon detected since the beginning of the 1990s. This kind of behavior is characterized mainly by an increase in rainfall in the western part of the basin (Espinoza et al 2009a, Lavado et al 2012, Gloor et al 2013).

Some of the intense rainfall and subsequent floods (Figure 4) were also associated with La Niña events (e.g. 1989, 1999, 2009, 2011 and 2012) and characterized by an abundant moisture transport flux from the tropical North Atlantic and the Caribbean Sea toward the northwestern Amazon and a maintenance of the monsoon flux over this region (Espinoza et al 2012, 2013). Moreover, intense rainfall in the central Amazonia region, with the associated extreme floods, has also been related to an anomalously southward migration of the Atlantic ITCZ, in relation to warm conditions in the tropical South Atlantic sea surface temperature (SST). This phenomena was observed in 2009 (Marengo et al 2012, 2013), with important hydrological consequences, such as the highest river level ever observed, but not the highest discharge ever recorded at Óbidos, the reference station for the Amazon Basin (Filizola et al., 2014).

The flood of 2012, which set a record during the last 50 years, was related to both La Niña and warm conditions in the tropical South Atlantic (Marengo et al 2013, Espinoza et al

2013). And in the 2013/2014 austral Summer (December–March), the Madeira river basin in southwestern Amazon experienced historical rainfall and flooding, while no robust SST anomalies were observed in El Niño regions and in the tropical Atlantic Ocean. This means that until now the system that controls the most recent extreme hydrological events is still under evaluation by the scientific community. Monitoring systems over the Amazon exist in Brazil and Peru, and they currently have the capability to send alerts with almost 3 months of anticipation.

Figure 4. The minimum (blue line), mean (red line), and maximum (green line), river levels (Cota) at Manaus since the year 1902 with the indication of changes (red arrows) in trends (black lines) for the years 1970 and 1990.



4.5. Socioeconomic aspects and energy

The quality of life of the population in the Amazon River Basin, based on indicators such as basic sanitation (provisioning of water, sanitary exhaustion and garbage collection) and incomes, is characterized by an accentuated lack of infrastructure and social investments. These factors make the North region (e.g. in Brazil) less favored than the average situation of the other regions in South America. The situation in the Amazon region in Peru and Ecuador is similar to that of Brazil.

The economic contribution of the Amazon River Basin to each country that comprises it is relatively modest, compared to the more developed regions in each country. With the exception of Brazil, no other Amazonian country has a city with a population over one million and with an economy that is strong enough to be considered a very high-energy consumer.

The hydroelectric potential of Latin American countries comes partially from snow melt from glaciers in the Andes and because of the existence of large river basins, whose rivers provide great electricity-generating potential. However, much of this potential has not been tapped, as is the case in Brazil, for example, which uses only one third of this potential. Each country has different reasons for the greater or lesser use of hydroelectric power. Bolivia and Peru, for example, have large gas reserves and use a subsidy policy to maintain energy produced from this source cheaper than that produced by hydroelectric power plants.

In Brazil, the potential used until now was that located closest to the load centers. With the demand for growth, it was necessary to expand the hydroelectric frontier to the remotest regions from the load center. That was the case in the Amazon Basin, especially during the 1980s, but is even true today with the recently built large hydropower plants of Santo Antonio (3,100 MW) and Jirau (3,300 MW), both in the Madeira River Basin, and also with the 5,500 MW Belo Monte Project under construction in the Xingu River Basin. Both the Xingu and Madeira are Amazon River tributaries.

The supply of electric energy in the Amazon Region of Brazil, to some specific areas, is generated by isolated hydroelectric systems (the Balbina, Samuel, Curua-Una and Coaracy-Nunes dams) and complemented by fuel-burning thermo-electrical centers. The northern Brazilian connection with the NE, SE, S and CO system is under construction through the Tucuruí Hydroelectric Dam, with a transmission line (1,000 MW) between Venezuela and the Balbina Hydroelectric Dam planned for the future. In general, medium and small villages in Amazonia have difficulties receiving service from a cheaper energy source and system interruptions of the service supply are common.

According to Tolmasquim (2011), the current president of the Brazilian EPE (Energy Planning Enterprise), despite the complexity of the Amazon region, it is possible to build hydropower plants in a sustainable way in the region. However, this process will be slow and the plants will be built in an unconventional way. Therefore, contracting other types of projects in order to ensure a security of supply is required.

The Amazon was designated as a strategic energy region, especially in Brazil, where the region harbors half the country's hydropower generation potential. More than 80% of the energy produced in Brazil originates from hydropower. Probably no other country has such hydroelectric dependence. Although this is generally regarded as a huge competitive advantage, it does have some negative repercussions. The need to expand this Brazilian model to Peru and other countries in the continental Amazon was signaled by Matt Finer and Clinton N. Jenkins (2012), who analyzed the proliferation of hydroelectric dams in the Andean Amazon and the implications for Andes-Amazon connectivity. Based on their analysis, there are plans to build 79 new hydropower plants in Peru, 60 in Ecuador, and 10 in Bolivia.

Two key features of the Amazon Rivers give rise to caution for logical reasons, especially: water volume and slope. Firstly, after the exit of the Andean region, the lowland rivers have a huge volume of water, but low natural slope. Secondly, those rivers have a significant difference in volume between the ebb and flow periods (Pinto, 2006).

Even with the cited precautions, the Amazon region undoubtedly has a sufficient magnitude of energy resources to meet the domestic needs and even those of other regions. Brazil has done this since the 1980s. However, paradoxically, Amazonian states have the lowest rural electrification rates in the country (less than 25%), while the national rate is 70%. Moreover, the currently served centers do not have a very reliable supply (Souza, 2012). This augments the trend toward the development of alternative sources that can meet the local needs of the Amazon region and do so with minimal environmental impact.

In Brazil, energy prices for distributors are set at auction. For the sake of comparison, at the last auction in December 2014 of plants to be built in Brazil by 2018, the price of hydropower reached US$ 30 per MWh and thermal reached about US$ 48 per MWh. For industrial and domestic uses, the big hydropower plants have a final price that is lower than other sources (Table 6). However, in a region like the Amazon, with its low Human Development Indexes, hydropower plant projects must take into account the environmental impact, local population development, and sustainability. According to Andrade et al., 2002 (Figure 5a), in developing countries with an HDI greater than 0.8, energy consumption (in tons of oil equivalent) it is normally greater than 1.2. For intermediate developed countries (HDI between 0.5 and 0.8), energy consumption falls between 0.5 and 1.2. In the case of the Brazilian Amazon states, the HDI is normally between 0.75 and 0.78, and with the exception of Pará, consumption is between 900 and 1,500 kWh/inhab/year (Figure 5b). But the same figure reveals that energy consumption in Brazil shows a logical growing and linear trend in the direction of the more economically developed states. This means that the more economically developed a state is, the greater the energy demands. In this curve, it is important to point out that the Amazonian states (red dots) have a higher HDI than those states in the NE Brazilian region (which normally suffer from drought problems).

Table 6. Final (average) electricity price in Brazil for industrial consumption by source in US$ per MWh. Source: FIRJAN Report (2011), with data from the Brazilian National Electric Energy Agency (ANEEL).

Energy Source	AVG Price (US$/MWh)
Big hydropower plants	30
Medium hydropower plants	53
Small hydropower plants	57
Eolic power plants	36
Thermal power plants (nuclear)	60
Thermal power plants (coal)	118
Thermal power plants (biomass)	122
Thermal power plants (natural gas)	127
Thermal power plants (oil)	242

Figure 5a. Graph showing relationship between energy consumption in tons of oil equivalent and the HDI. Source: Andrade et al., 2002

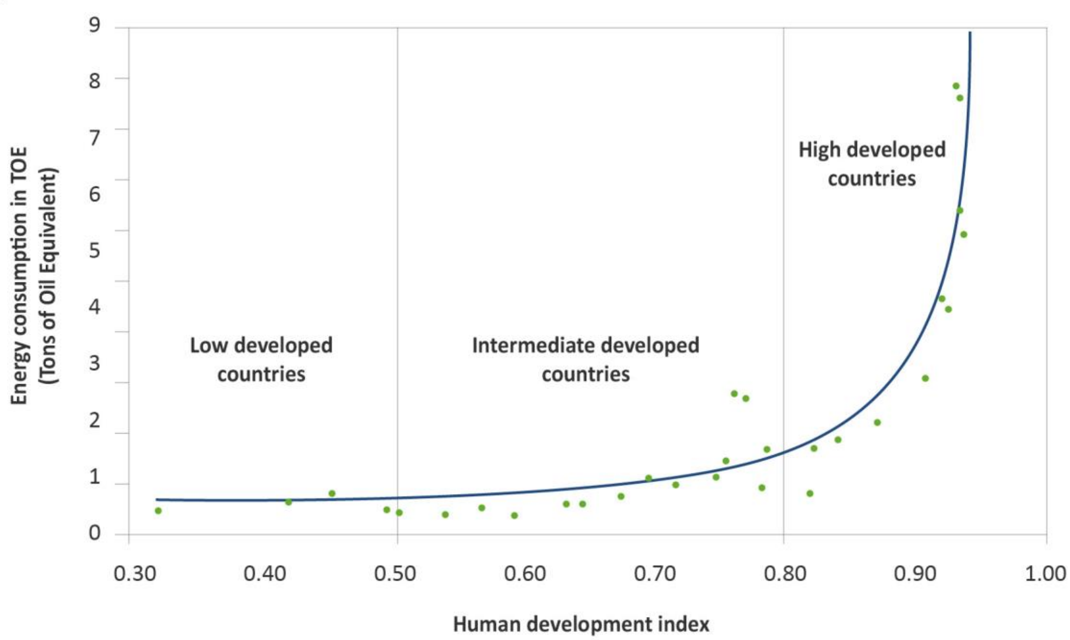


Figure 5b. Relationship between energy consumption and HDI per state in Brazil. The red circle indicates the Amazonian States (AM, RR, RO, AP, TO) with consumption between 700 and 1700kWh/hab.year (ano). The only exception is Pará (PA) State. Source: Silva & Guimarães, 2012.

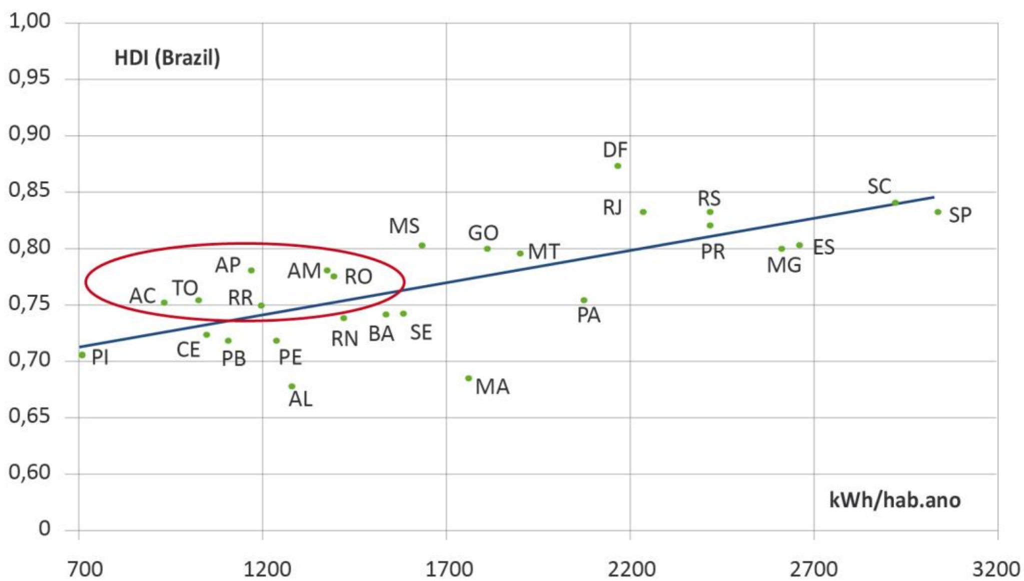


Figure 6 shows the trends in energy use (kg of oil equivalent per year) from 2005 until 2011 for Brazil, Peru, and Ecuador. Peru revealed an interesting and growing trend, especially after 2008. Brazil and Ecuador also had trends indicating growth, although they were more modest than in Peru.

Figure 6. The energy use evolution between the years 2005 and 2011 for Brazil, Peru and Ecuador. Source: World Bank database.

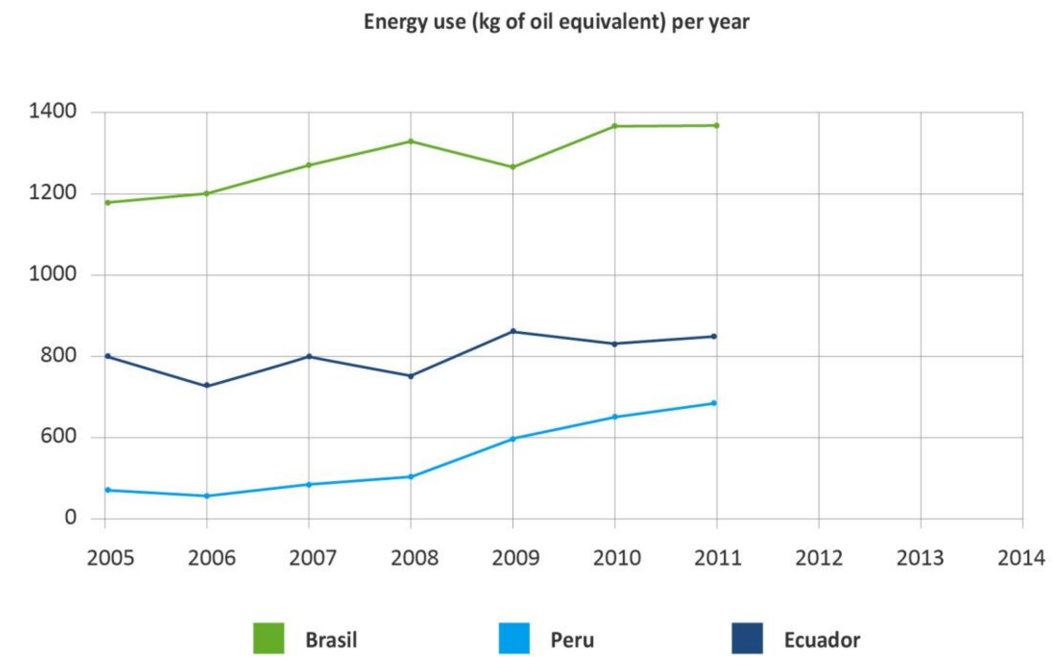


Figure 5b shows general energy consumption behavior and the HDI for Brazilian states. If this behavior is similar in Peru and Ecuador, and considering the HDI values shown in Figure 7, Ecuador and Brazil could be viewed as the most important markets for an initial RHK energy production project.

As a development indicator, the electricity infrastructure capacity building in Peru is lower than the limit when compared with the one determined by Silva & Guimarães (2012) in Figure 5b. With the trend for a growing demand, Peru should be potentiality explored for that as well.

Given the HDI analysis, the observations made on Peru, and the geomorphological and hydrological general view, the Bolivian Amazon seems to be a potential area as well. Although no data was authorized to be used in this report, indirect information from the accessible data supports such a view.

5. Summary of activities

The analysis carried out in the preparation of this report made it possible to:

- Analyze data from Brazil, Ecuador and Peru - accessible through the ORE-HYBAM database;
- Compare water discharge and water velocity during different periods of different years in order to theoretically explore and verify the capacity of some river sections to produce electricity using RHK technology during a “normal” year;
- Identify high-potential sites to be explored for potential future deployment of an RHK pilot and future commercial projects;
- Establish case studies from 8 of the 54 total investigated sites, which were used to identify, in hydrological terms, that Brazil, Peru and Ecuador have variable but generally very favorable conditions for RHK technology;
- Conduct a brief analysis of some aspects of the hydrology of the Amazon Basin as well as comment on extreme events; and
- Investigate the proximity of the RHK resource analyzed to an electrical demand center.

6. Conclusion and recommendations

There are extremely strong RHK resources close to electric demand centers in the Amazonian Basin of Brazil, Peru and Ecuador. Therefore, the authors of this report endorse the preliminary feasibility of RHK as a hereto untapped renewable energy option for the region. Application of RHK technology on a multi-megawatt and potentially multi-gigawatt scale could have significant positive impact in the region and as such should be further investigated and supported. RHK potentially enables the provision of renewable power while also allowing rivers to remain open for the transport of goods and services, thereby preserving existing regional transport links that would otherwise be destroyed by the construction of a conventional dammed hydropower project.

This report shows that current, available hydrological data is highly useful – physical measurements of current speed and depth can be linked to existing data thereby providing an assessment of the potential energy yield. The scope of this report was limited by the number of ORE-HYBAM hydrological stations with available data. Outside of this limitation, many more sites with strong potential likely exist.

Significant further investigation should be financed to build on the results of this report, both in terms of research and on-site investigation. The results of this report highlight the differences that exist between different sites. Although they are linked, the sites are not homogenous. It is also important to continue to characterize the nature and frequency of extreme events such as floods, droughts, and big changes in depth as these have an important impact on potential project design and operation.

The authors recommend a more detailed program of study and physical assessment that also considers the environmental and social impact of RHK deployment at each of the specific selected locations as well as suggested mitigation measures.

Information gathered for these purposes also has cross-functionality with other lines of hydrological and environmental investigation.

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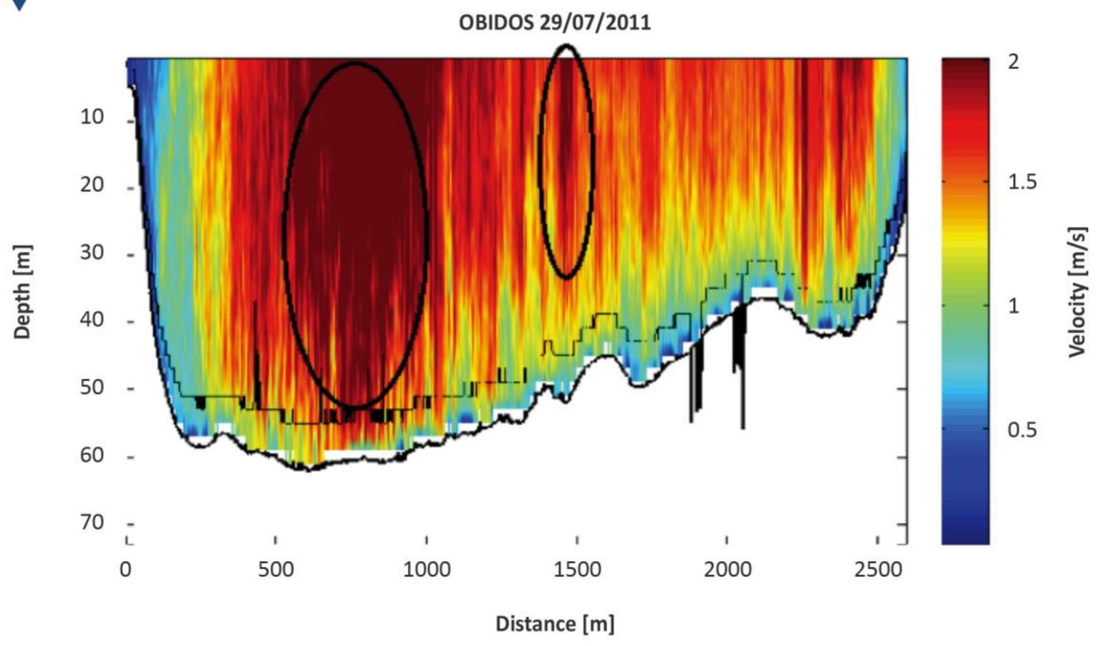
8. Annexes

Annex 1 – ADCP images and interval of confidence for the use of velocities percentage of occurrence against discharge

Figure 7A.



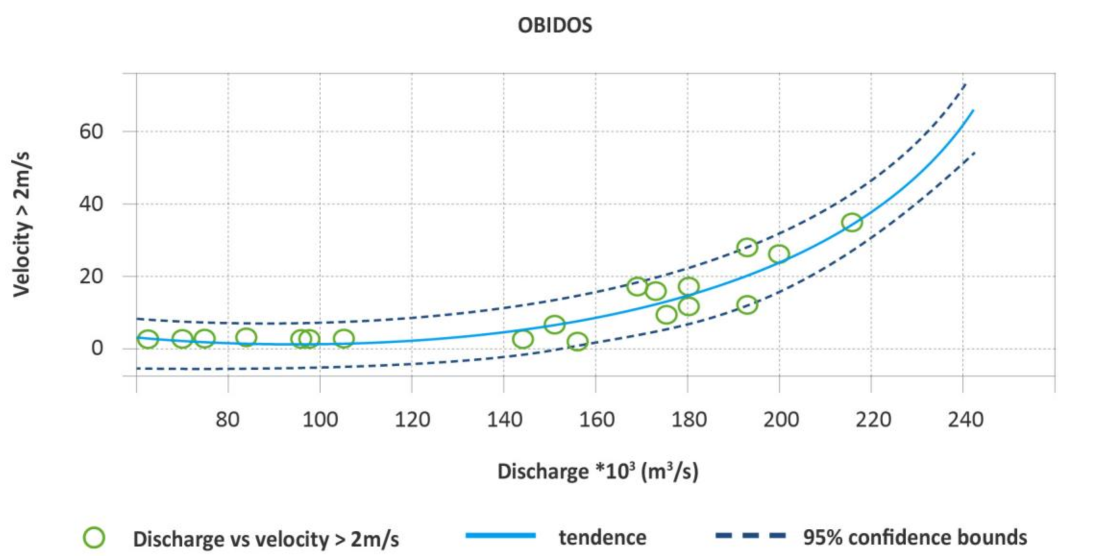
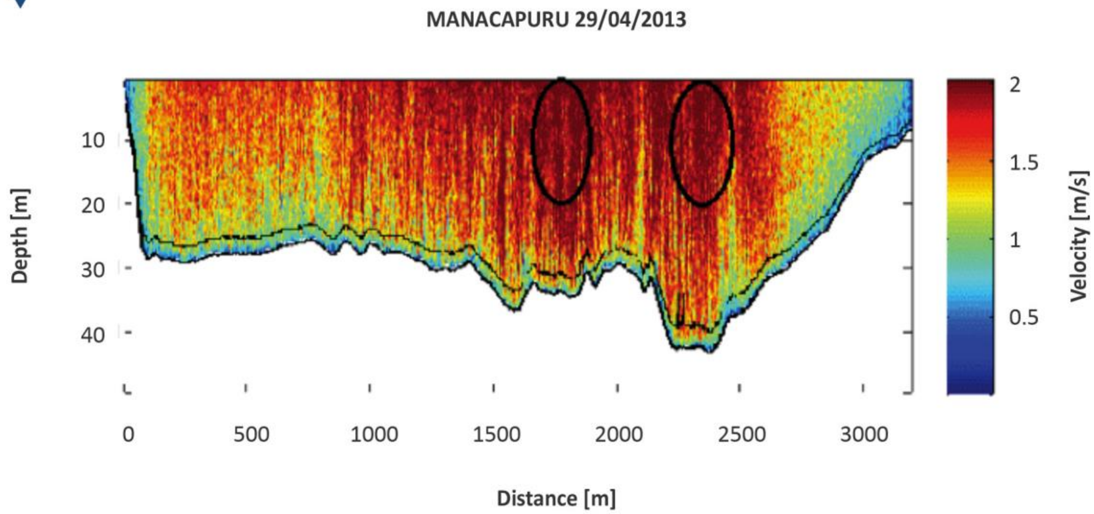


Figure 7B.


MANACAPURU 29/04/2013
Depth [m]
10
20
30
40
0
500
1000
1500
2000
2500
3000
Distance [m]
2
1.5
1
0.5
Velocity [m/s]

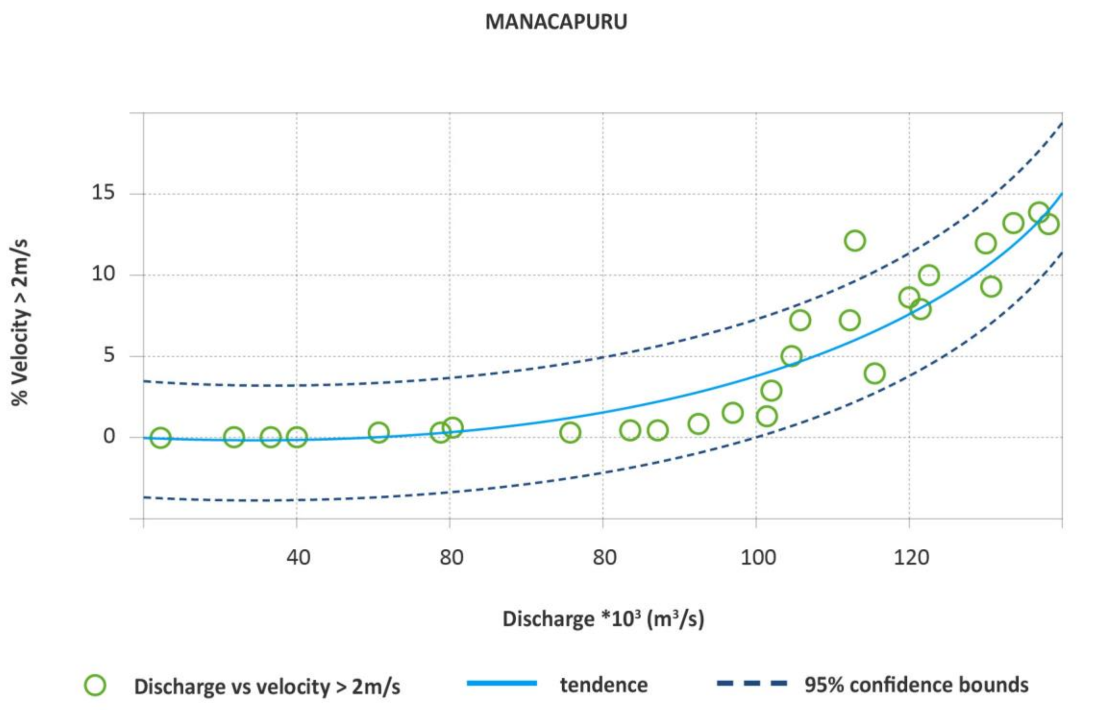
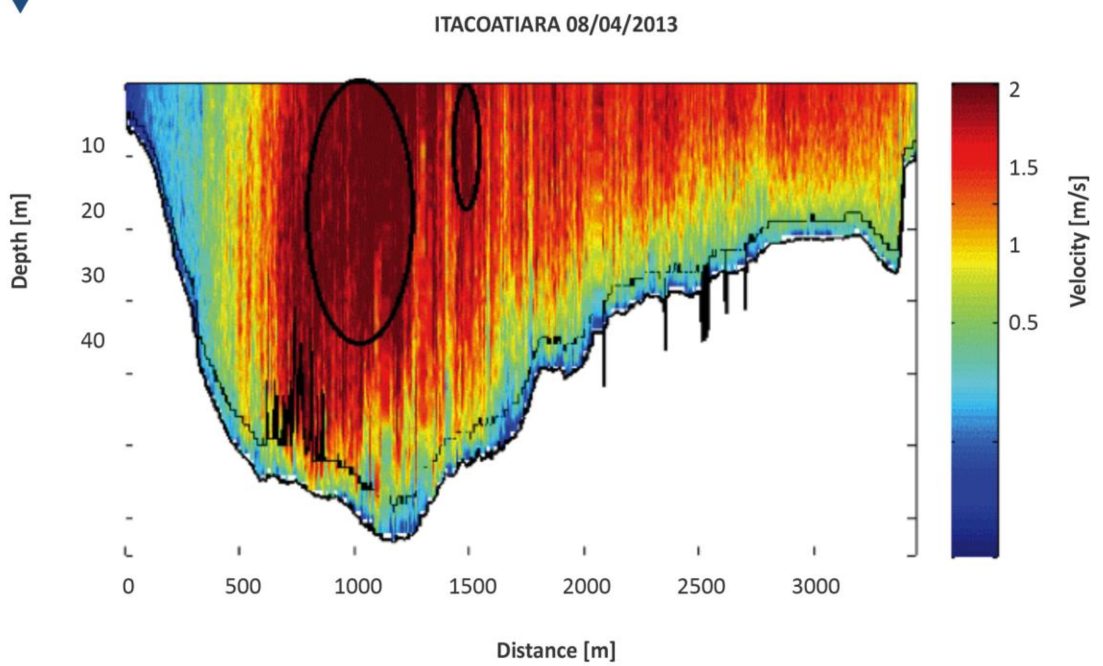

MANACAPURU
% Velocity > 2m/s
15
10
5
0
40
80
80
100
120
Discharge *10³ (m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Figure 7C.


ITACOATIARA 08/04/2013
Depth [m]
10
20
30
40
0
500
1000
1500
2000
2500
3000
Distance [m]
2
1.5
1
0.5
Velocity [m/s]

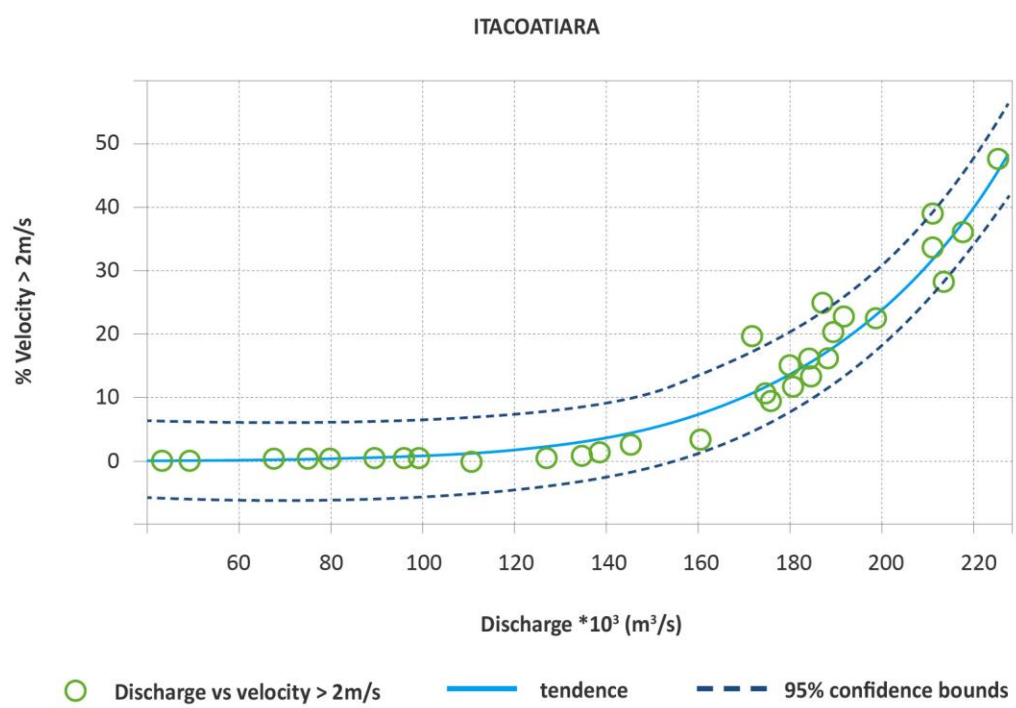
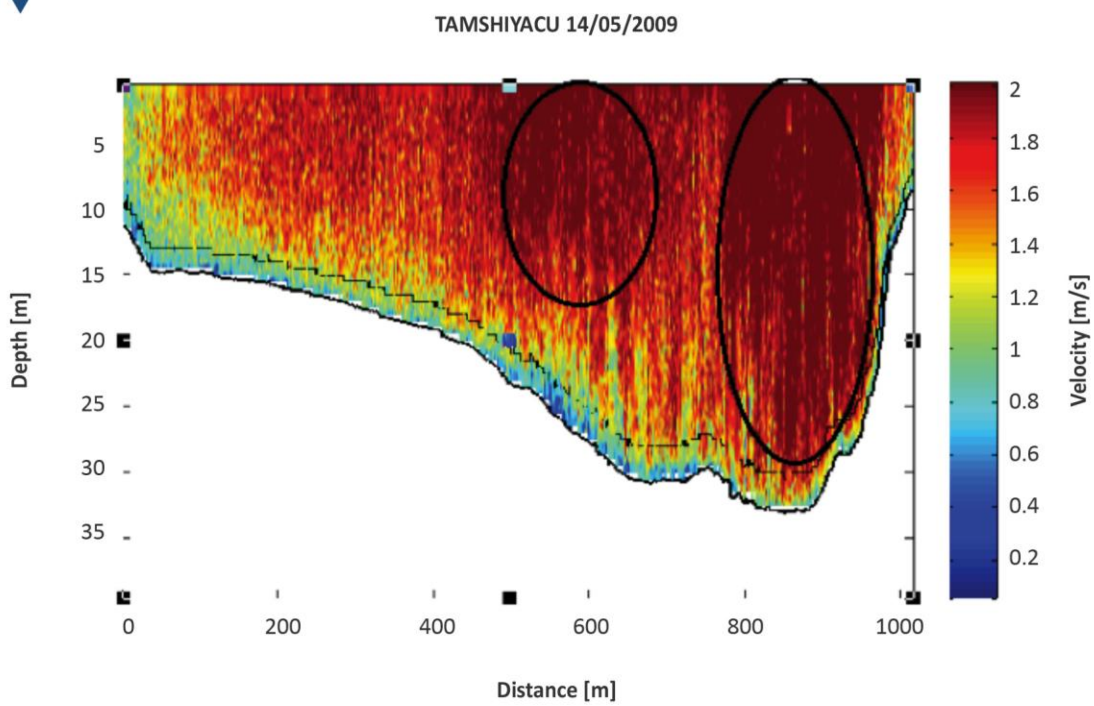

ITACOATIARA
% Velocity > 2m/s
50
40
30
20
10
0
60
80
100
120
140
160
180
200
220
Discharge *10³ (m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Figure 7D.


TAMSHIYACU 14/05/2009
Depth [m]
5
10
15
20
25
30
35
0
200
400
600
800
1000
Distance [m]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Velocity [m/s]

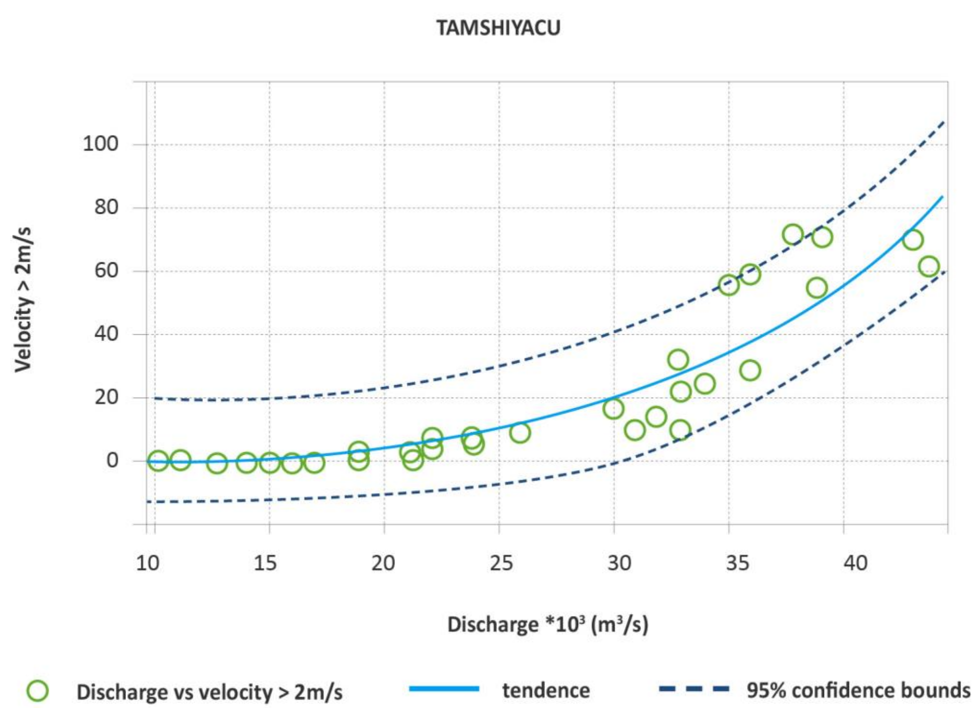
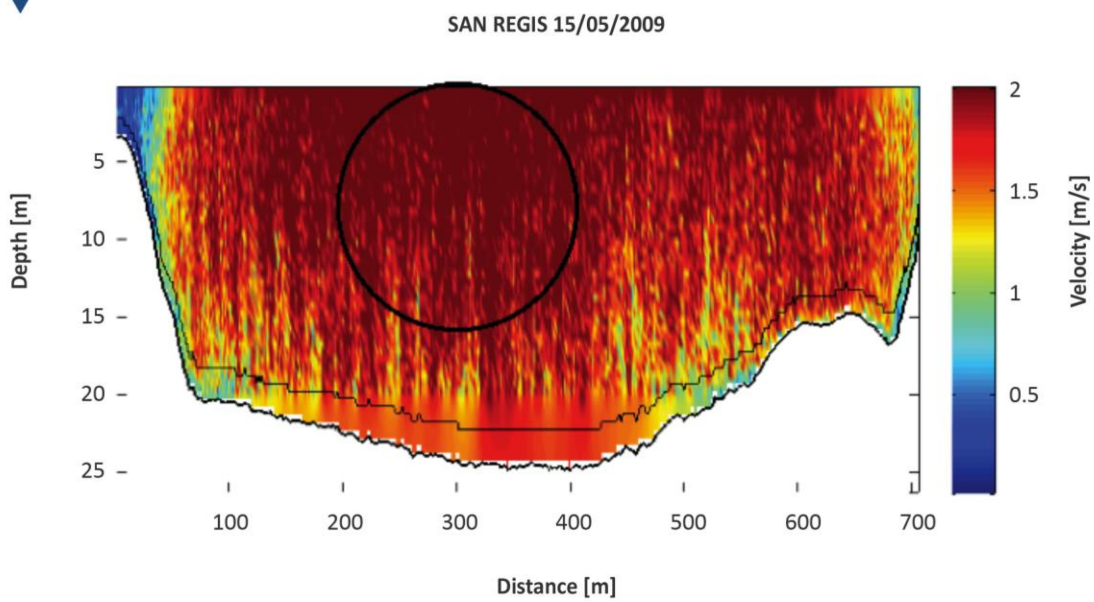

TAMSHIYACU
Velocity > 2m/s
100
80
60
40
20
0
10
15
20
25
30
35
40
Discharge *10³ (m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Figure 7E.


SAN REGIS 15/05/2009
Depth [m]
5
10
15
20
25
100
200
300
400
500
600
700
Distance [m]
2
1.5
1
0.5
Velocity [m/s]

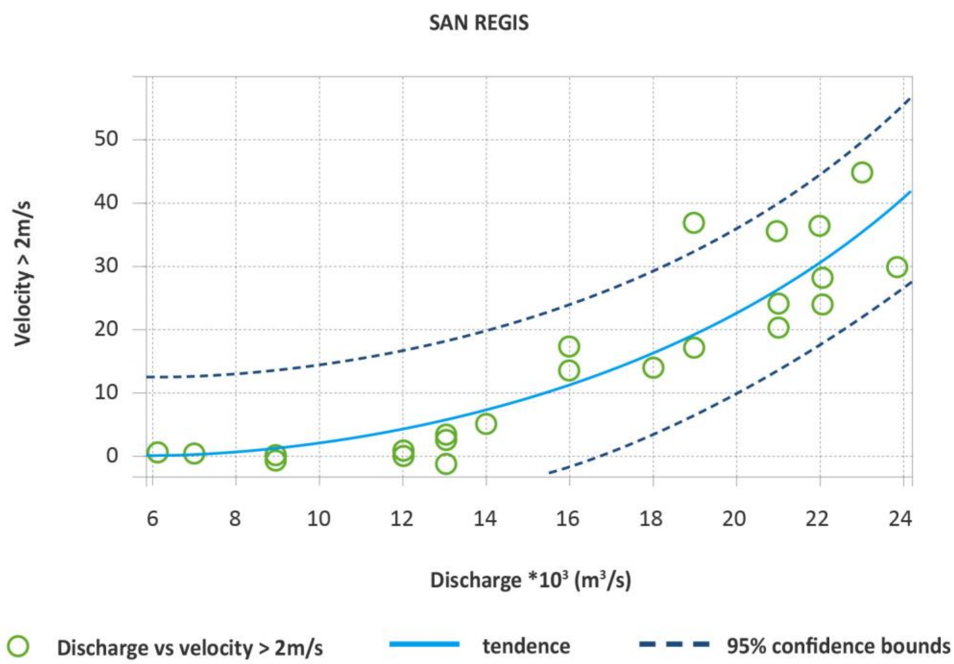
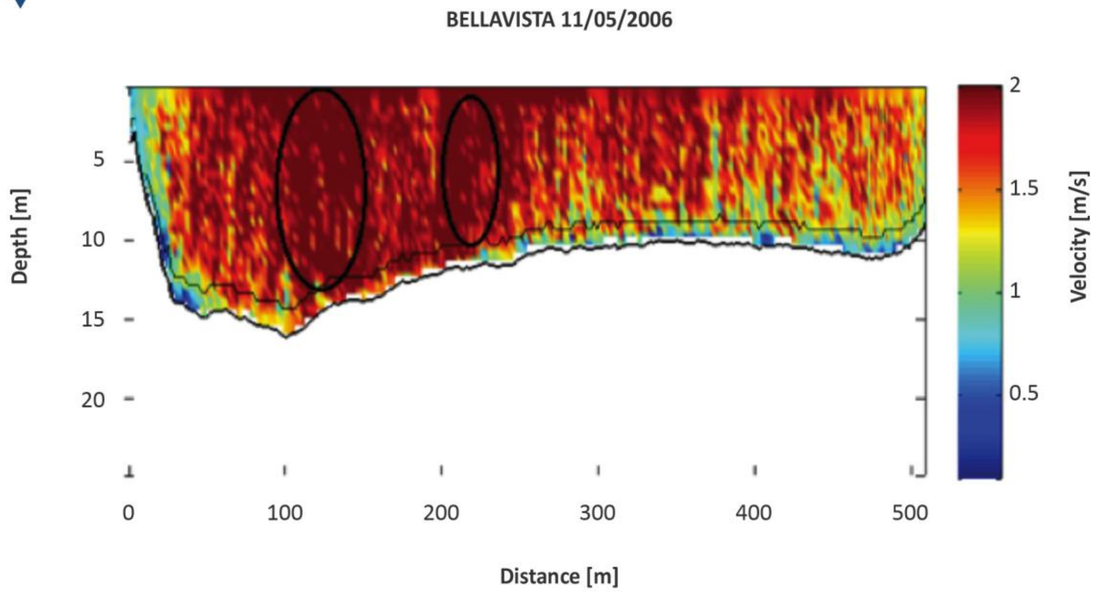

SAN REGIS
Velocity > 2m/s
50
40
30
20
10
0
6
8
10
12
14
16
18
20
22
24
Discharge *10³ (m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Figure 7F.


BELLAVISTA 11/05/2006
Depth [m]
5
10
15
20
0
100
200
300
400
500
Distance [m]
2
1.5
1
0.5
Velocity [m/s]

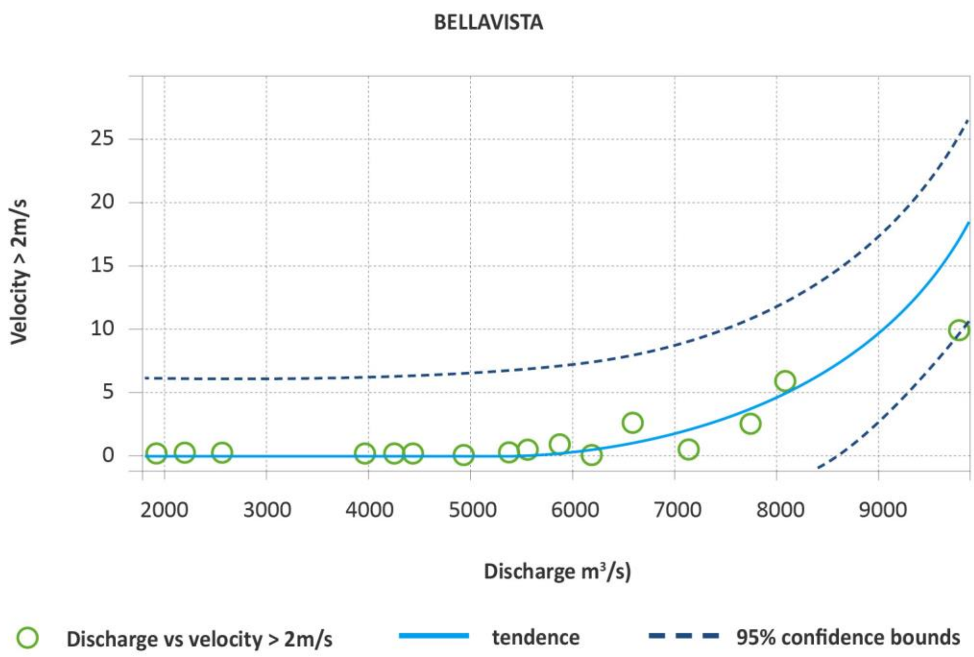
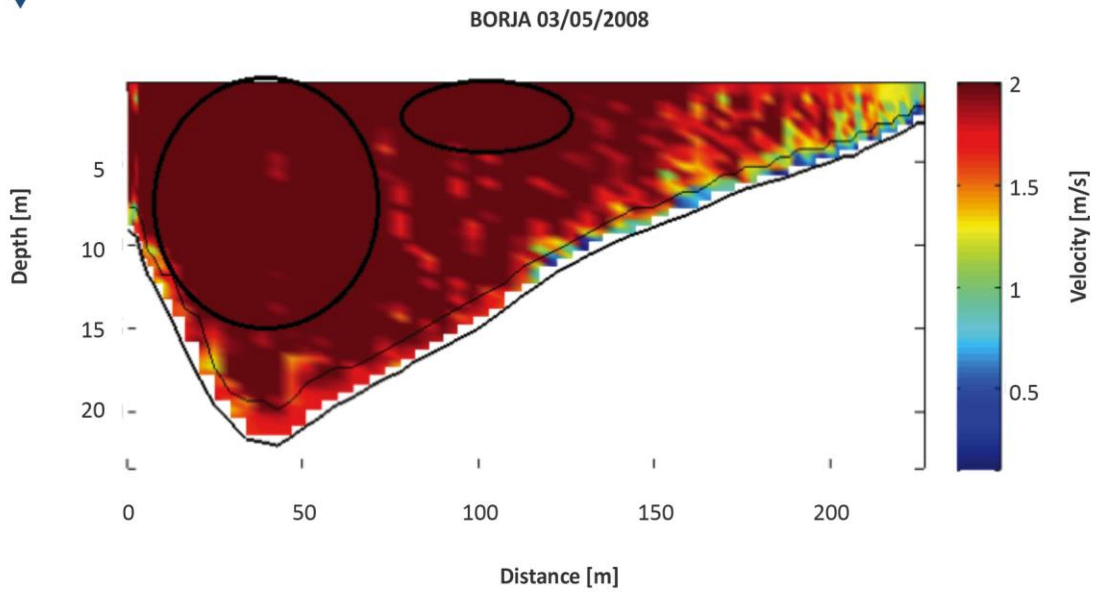

BELLAVISTA
Velocity > 2m/s
25
20
15
10
5
0
2000
3000
4000
5000
6000
7000
8000
9000
Discharge m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Figure 7G.


BORJA 03/05/2008
Depth [m]
5
10
15
20
0
50
100
150
200
Distance [m]
2
1.5
1
0.5
Velocity [m/s]

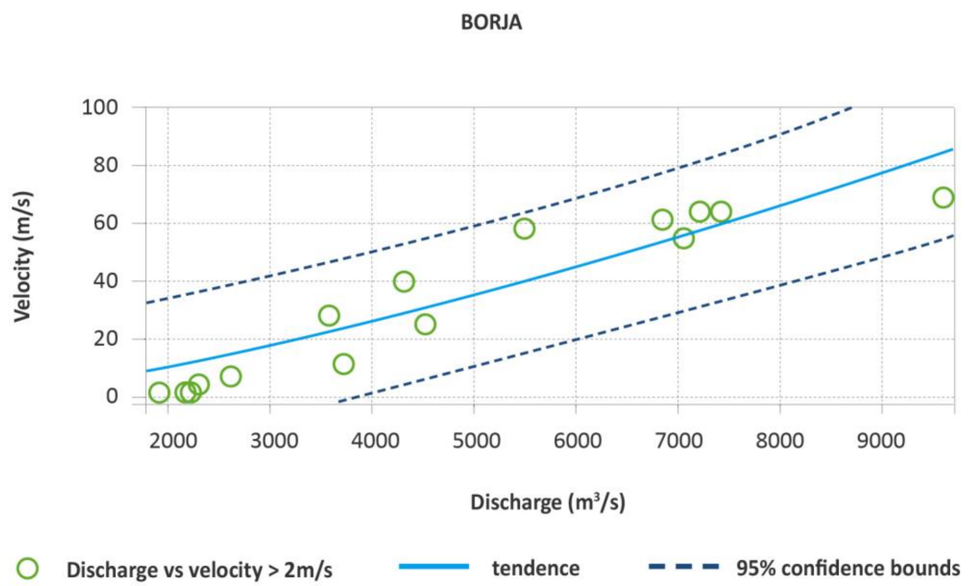
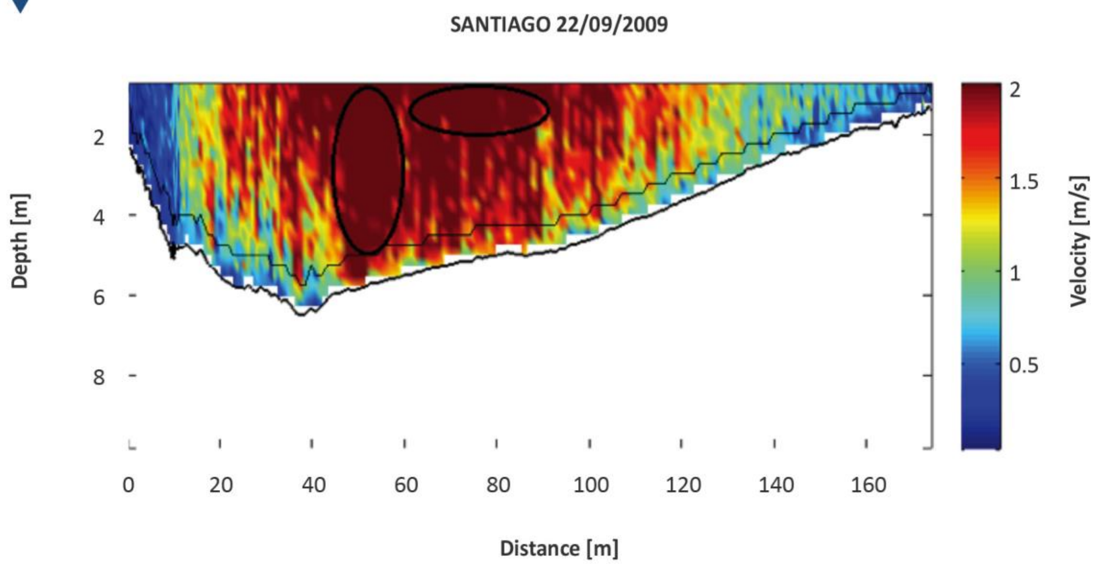
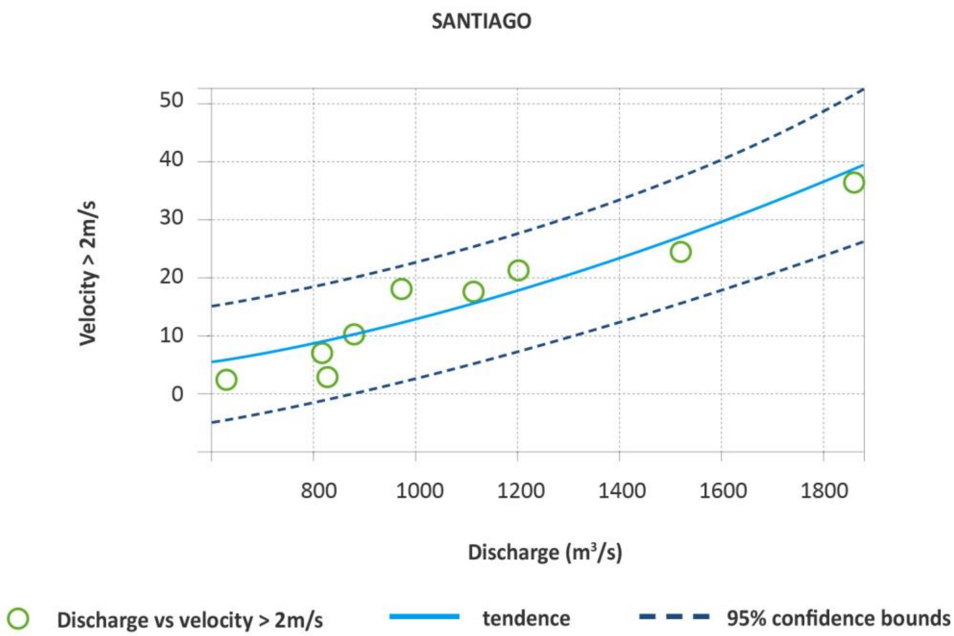

BORJA
100
80
60
40
20
0
Velocity (m/s)
2000
3000
4000
5000
6000
7000
8000
9000
Discharge (m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Figure 7H.


SANTIAGO 22/09/2009
Depth [m]
2
4
6
8
0
20
40
60
80
100
120
140
160
Distance [m]
2
1.5
1
0.5
Velocity [m/s]


SANTIAGO
Velocity > 2m/s
50
40
30
20
10
0
800
1000
1200
1400
1600
1800
Discharge (m³/s)
Discharge vs velocity > 2m/s
tendence
95% confidence bounds

Annex 2 – Discharge seasonal variation

Figure 8A.

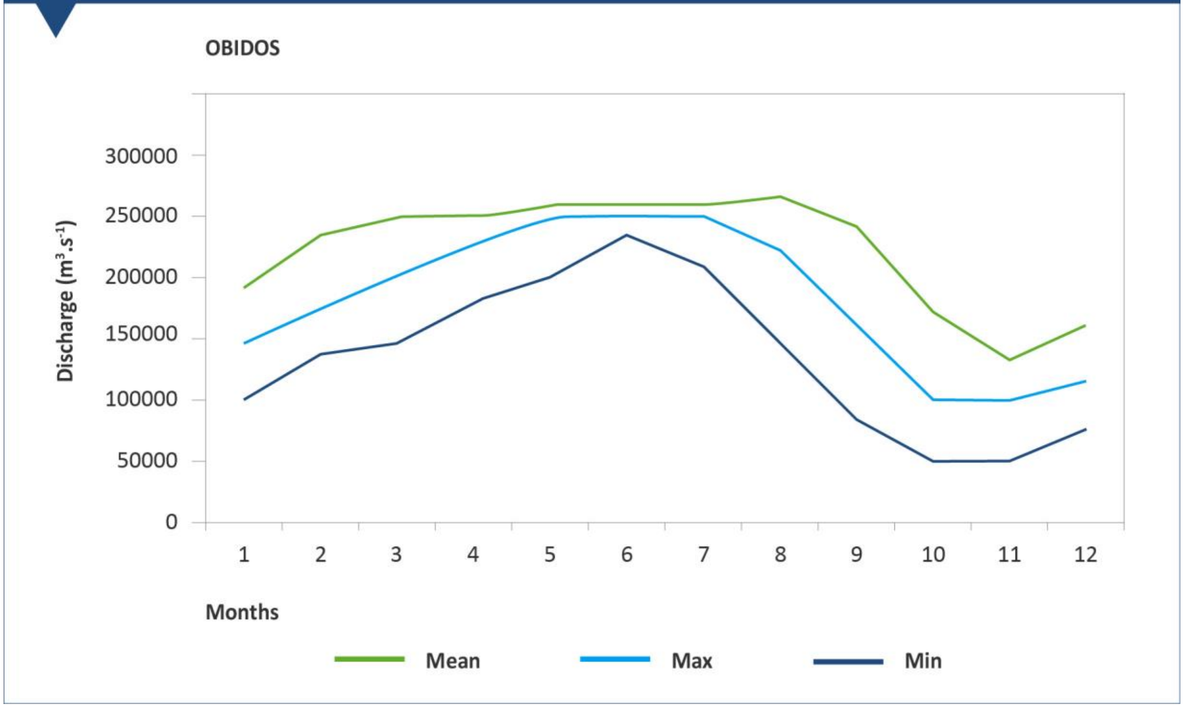


Figure 8B.

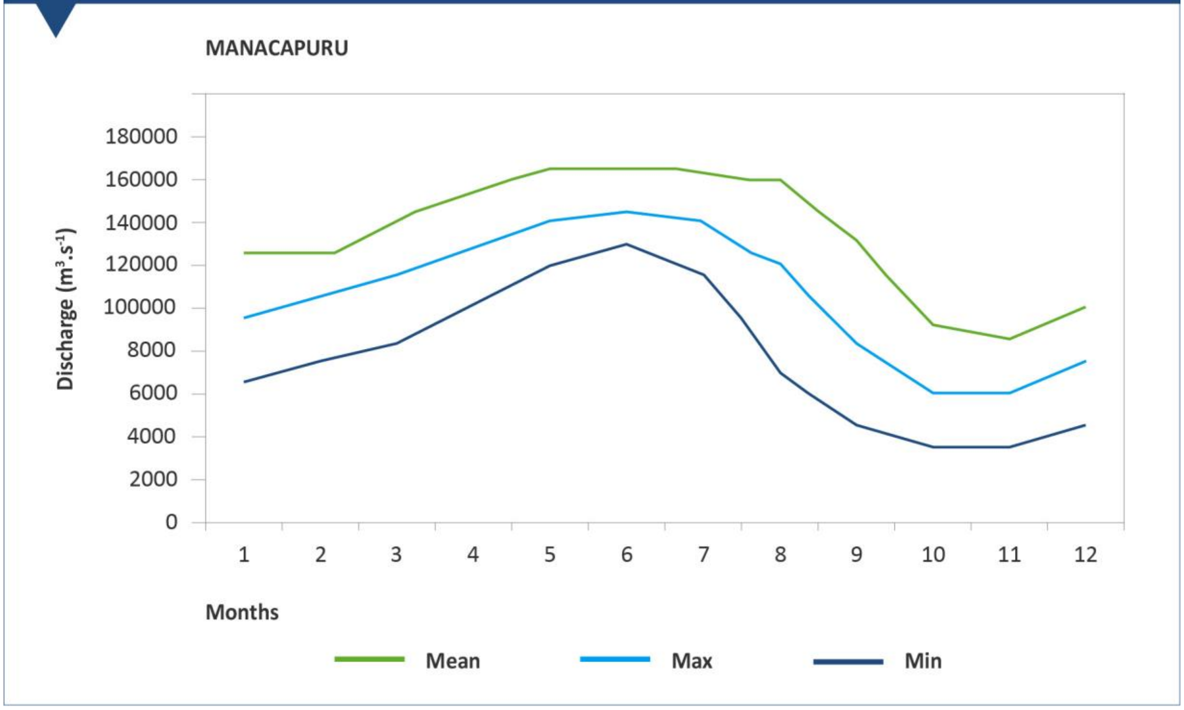


Figure 8C.

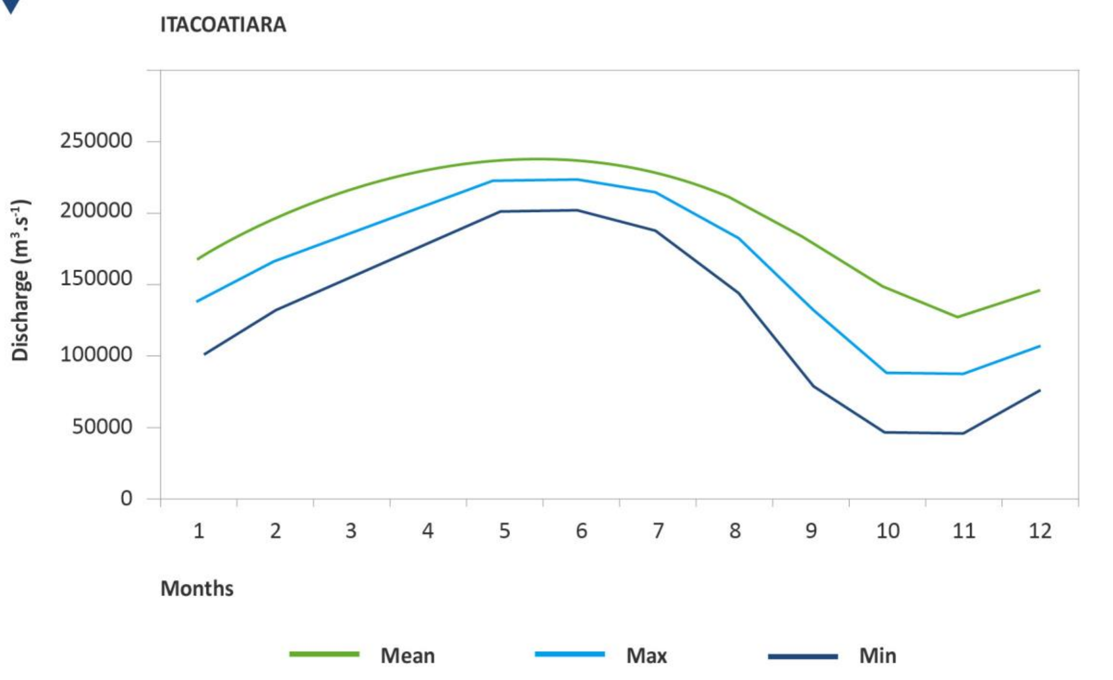


Figure 8D.

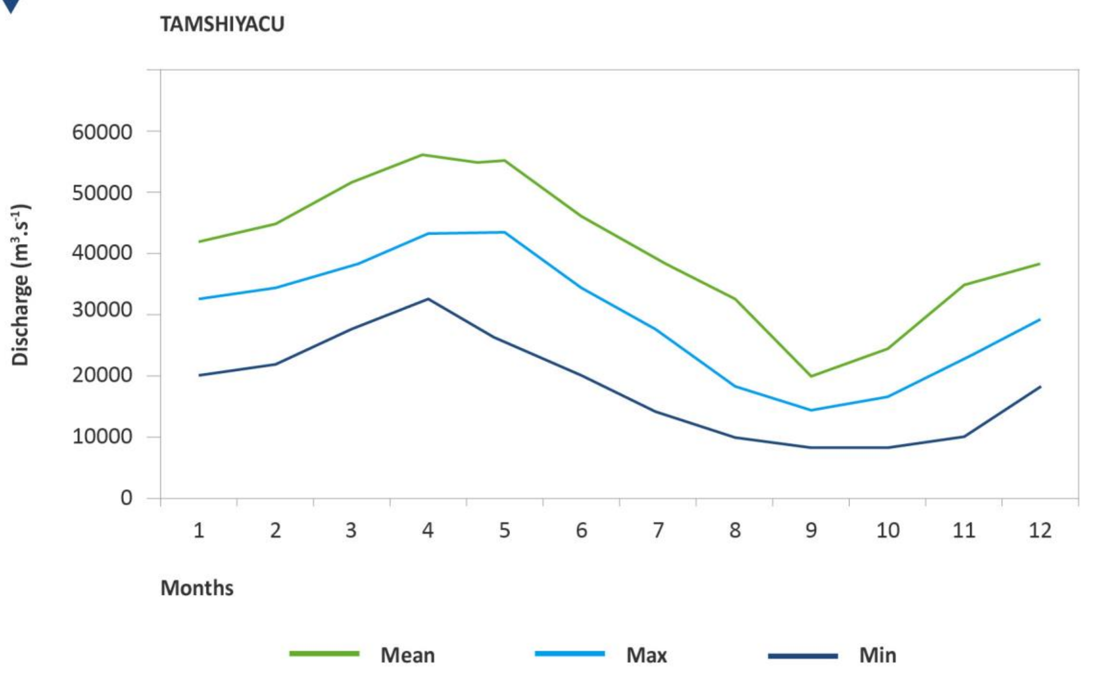


Figure 8E.

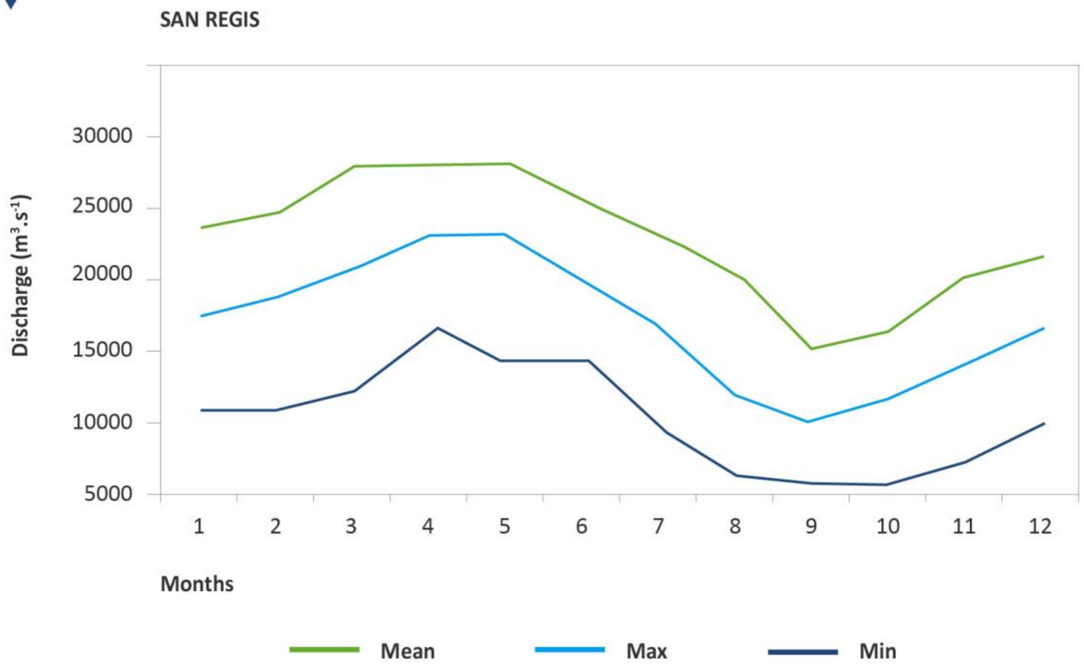


Figure 8F.

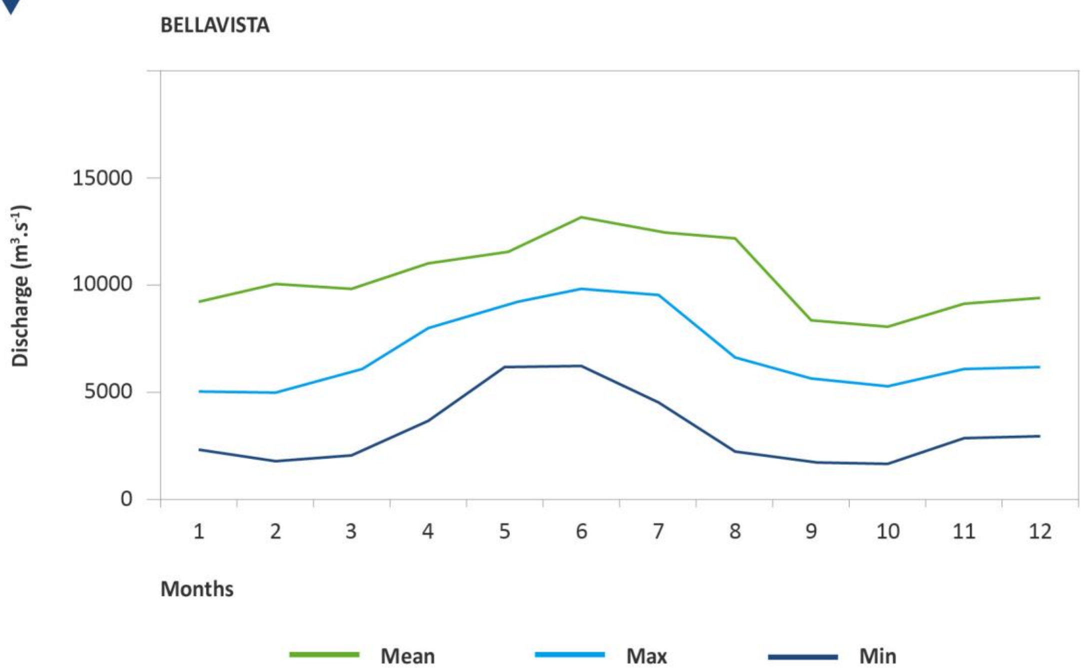


Figure 8G.

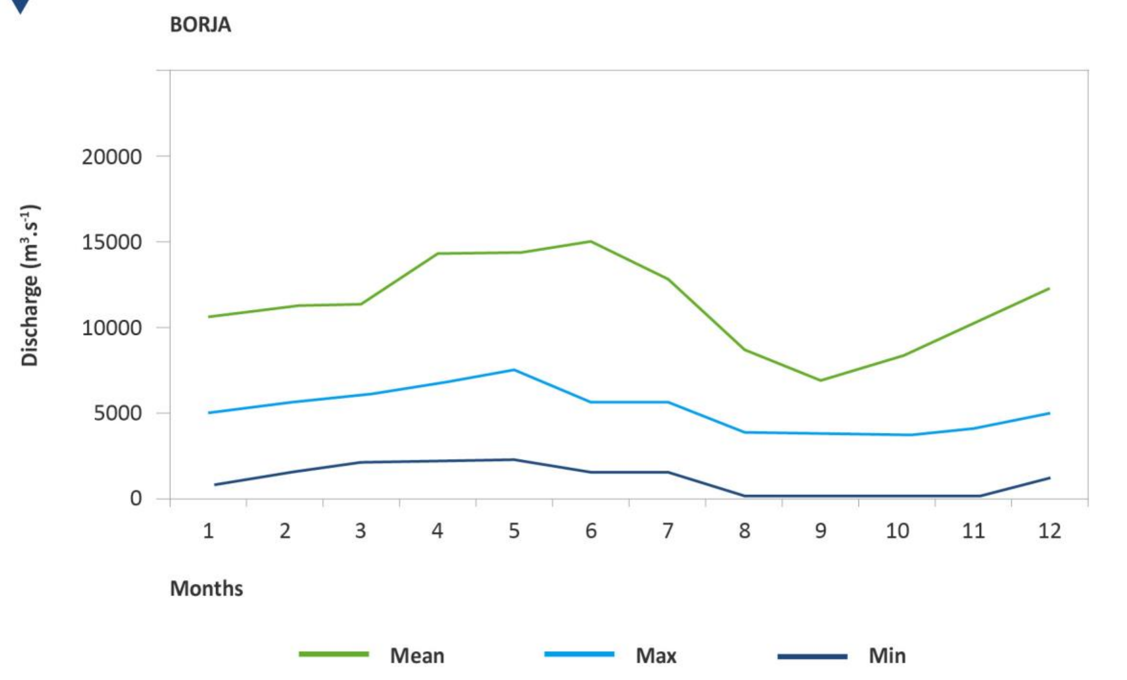
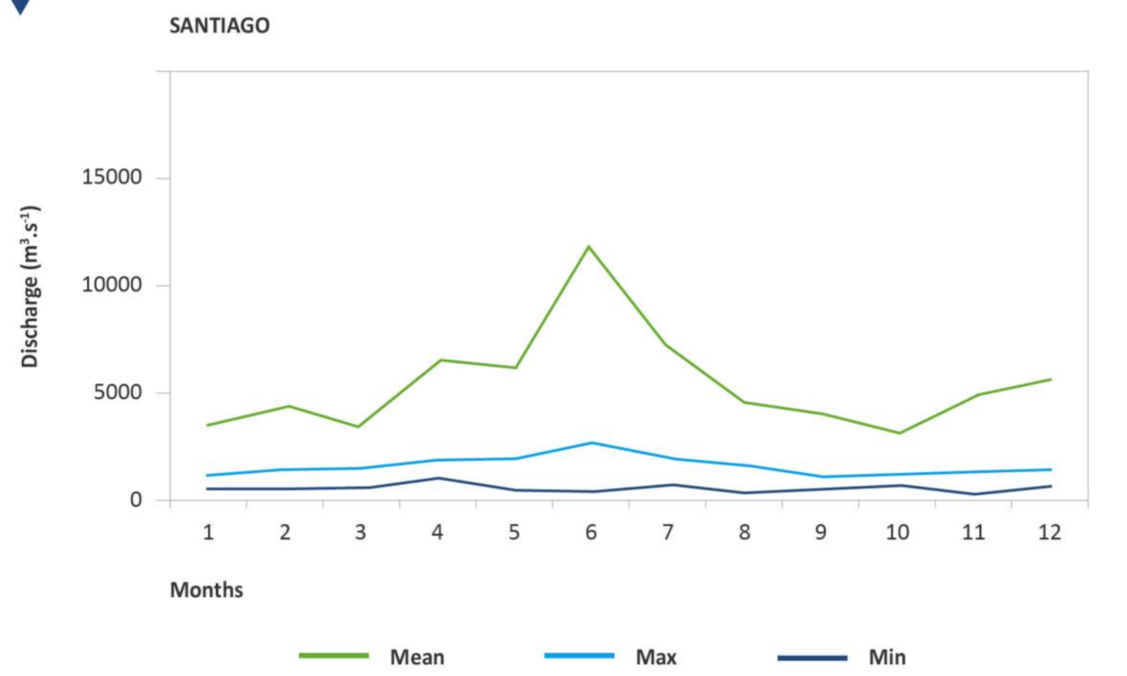


Figure 8H.



Annex 3 – Frequency of discharge occurrence (in percentage)

Figure 9A.

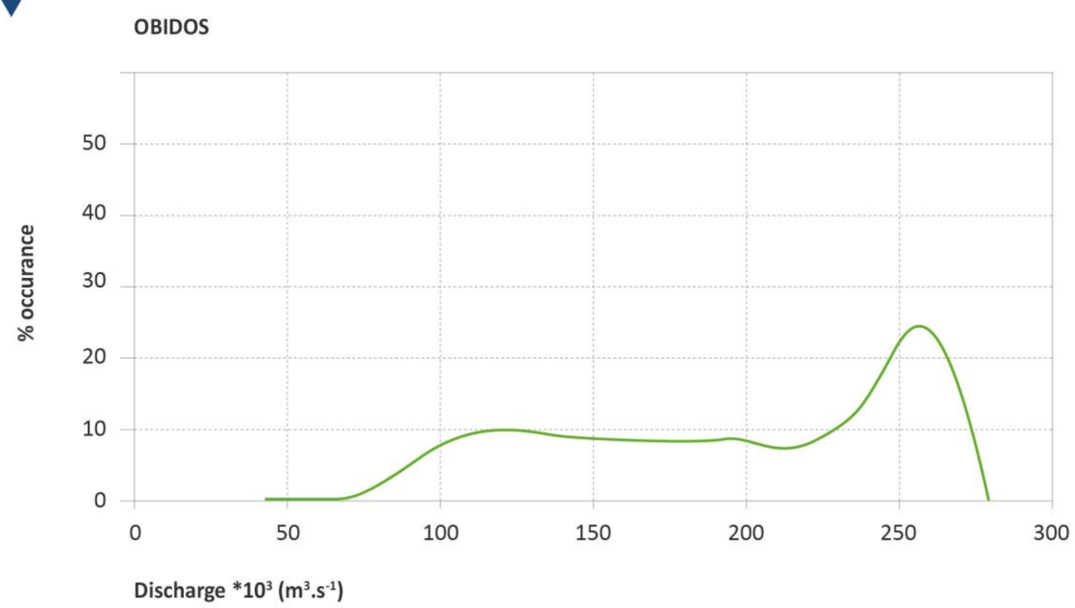


Figure 9B.

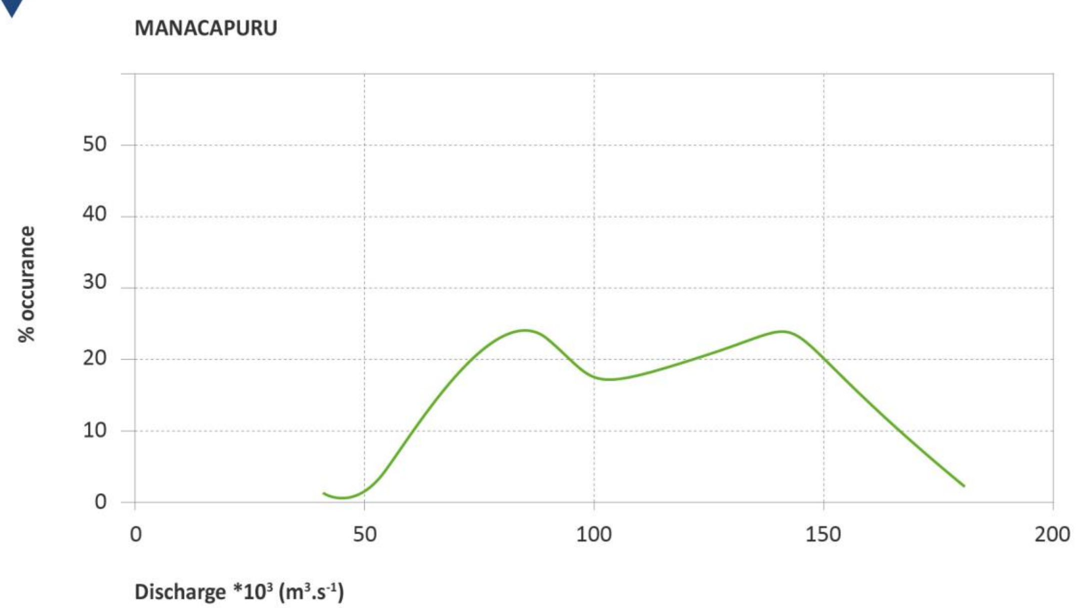


Figure 9C.

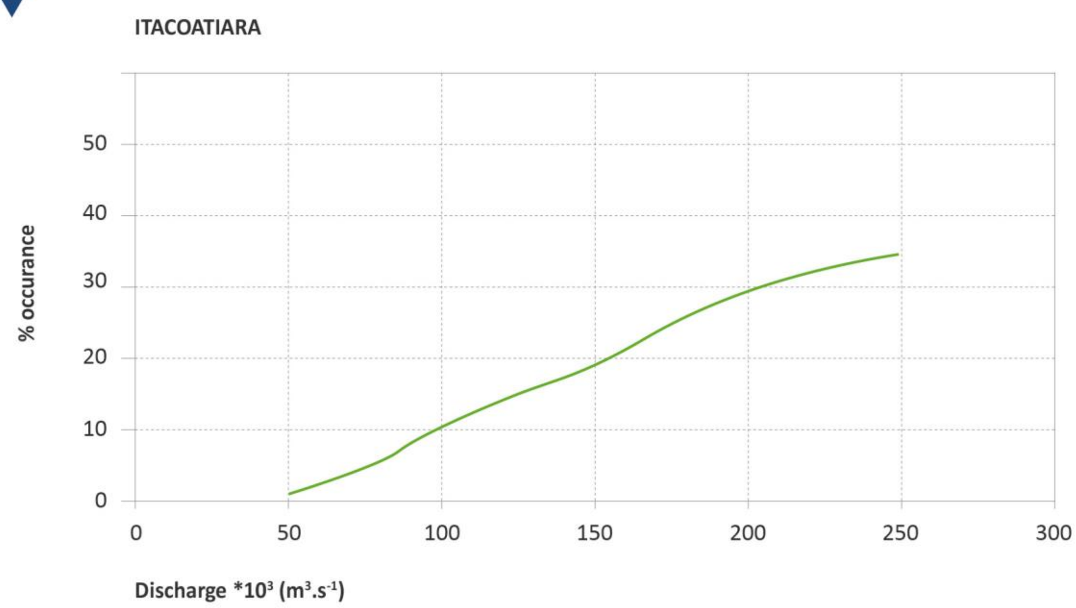


Figure 9D.

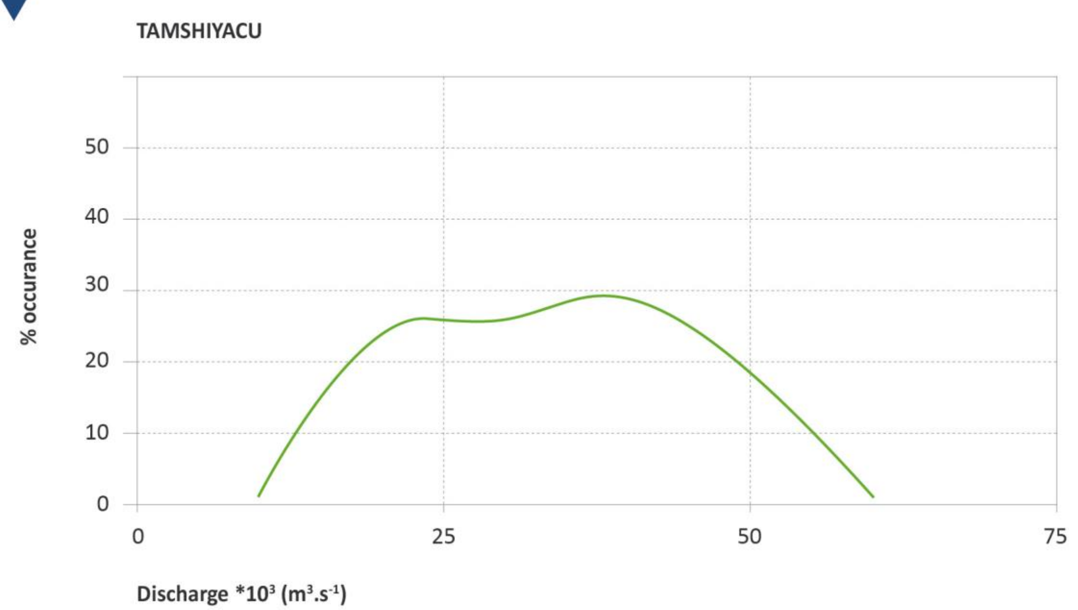


Figure 9E.

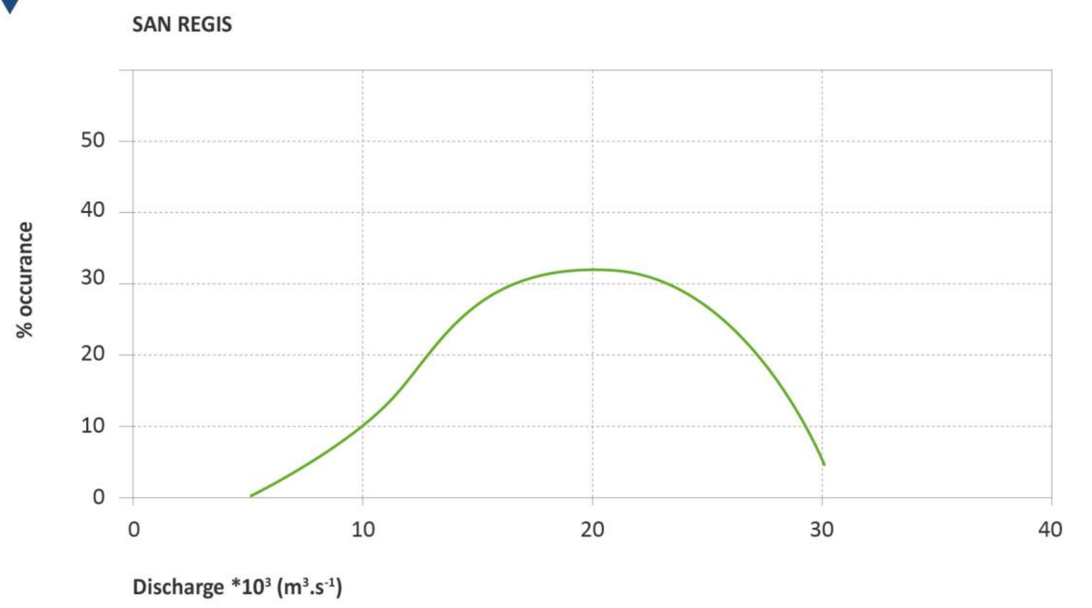


Figure 9F.

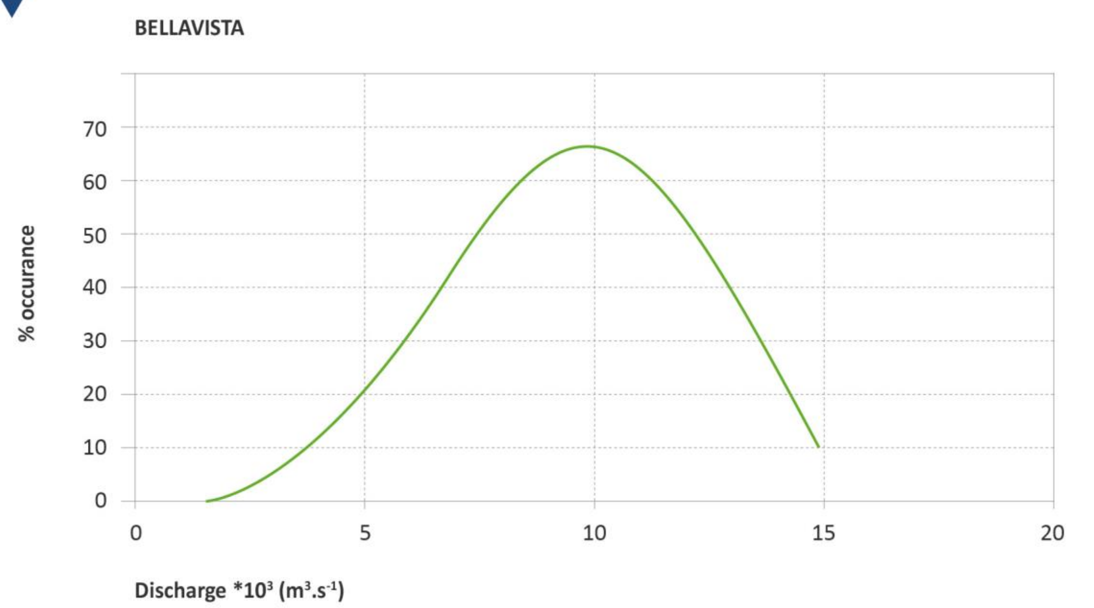


Figure 9G.

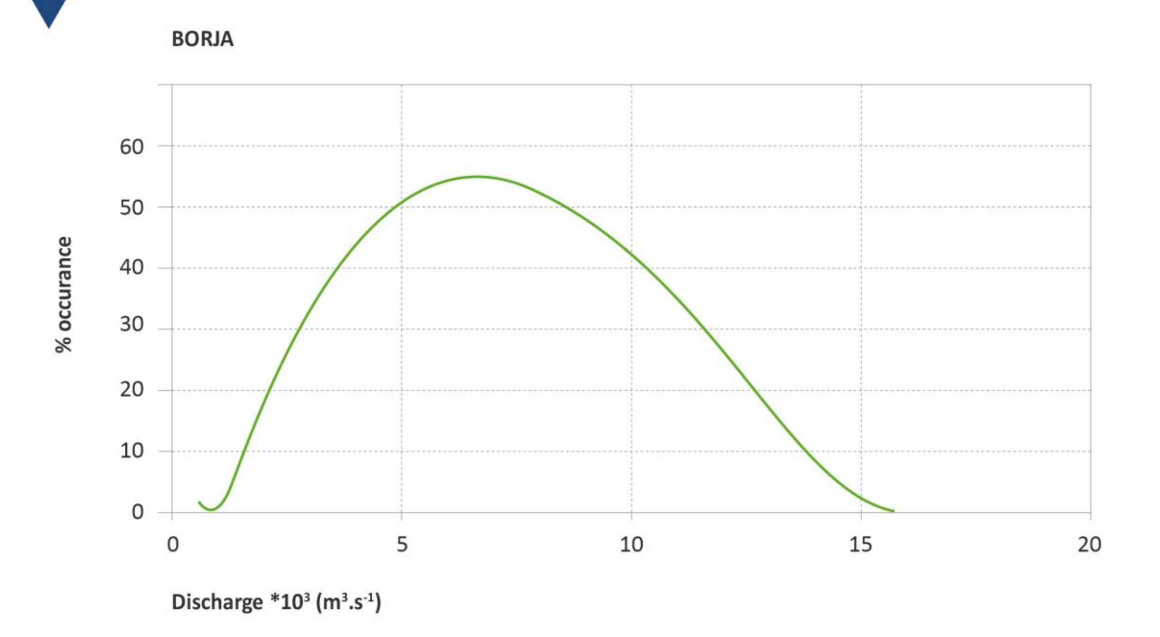
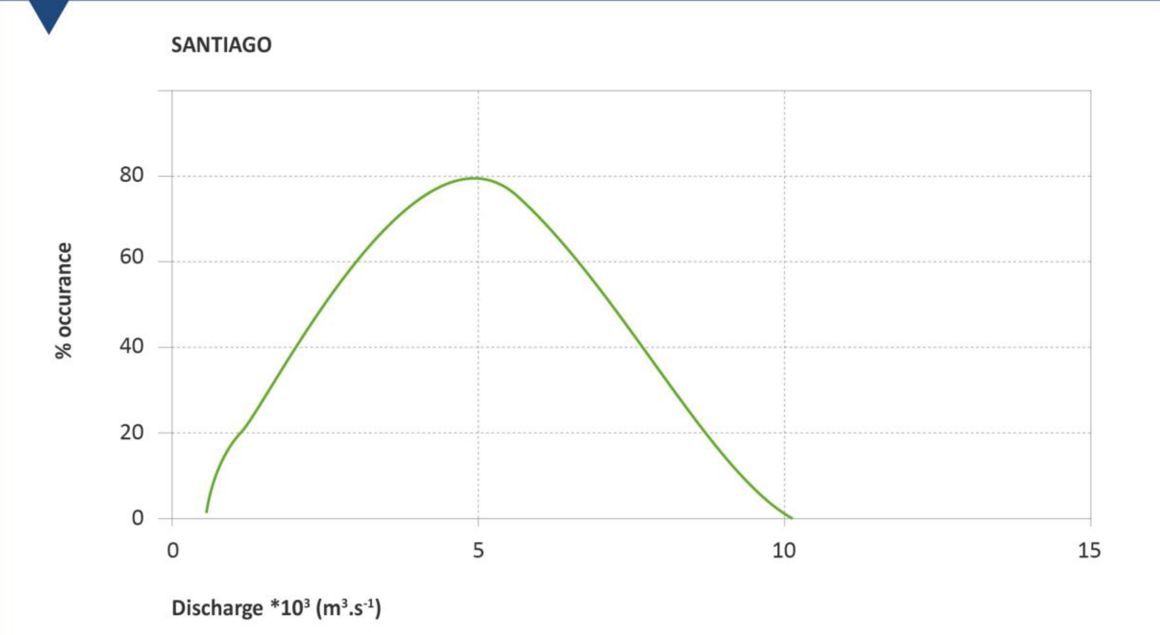
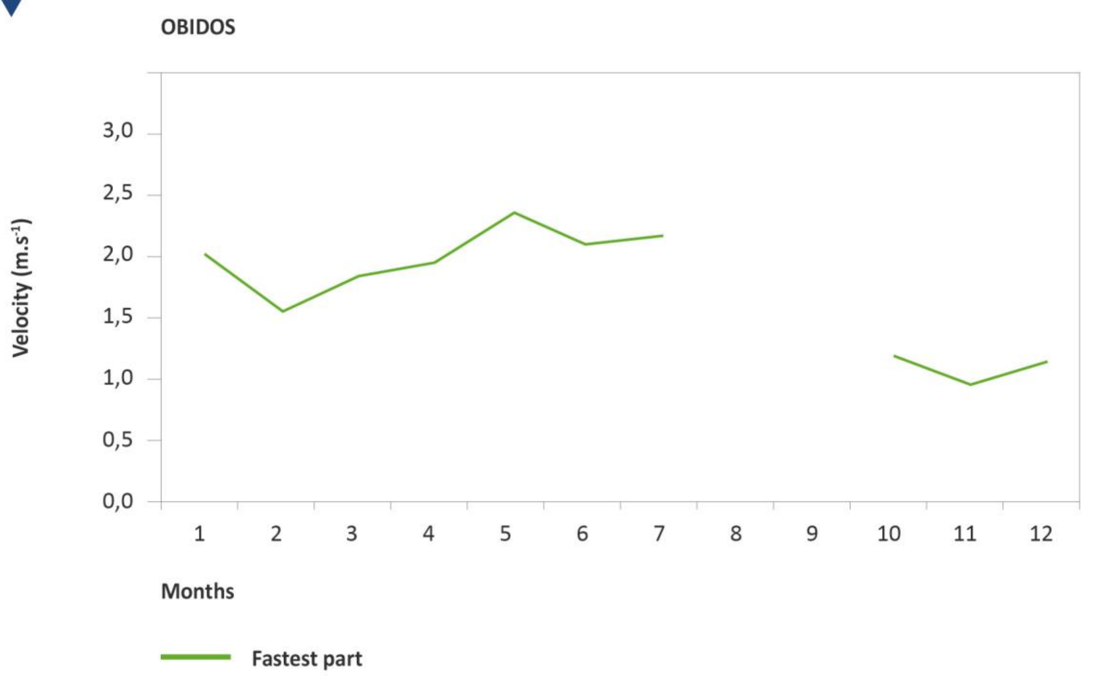


Figure 9H.



Annex 4 – Velocity intensity seasonal variability

Figure 10A.



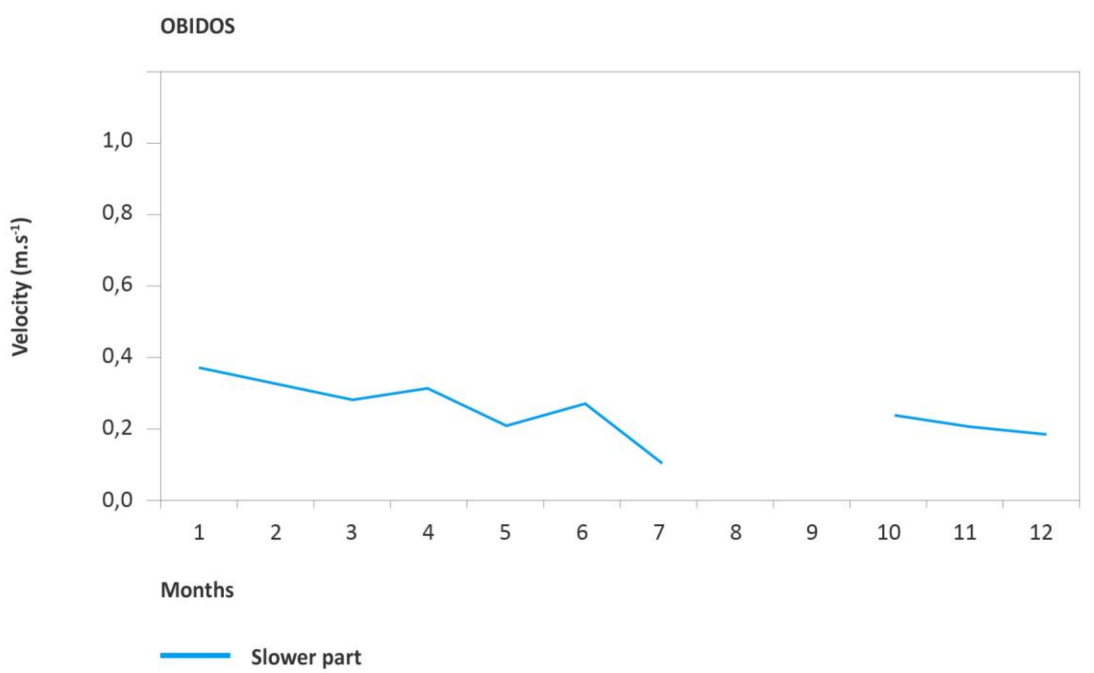
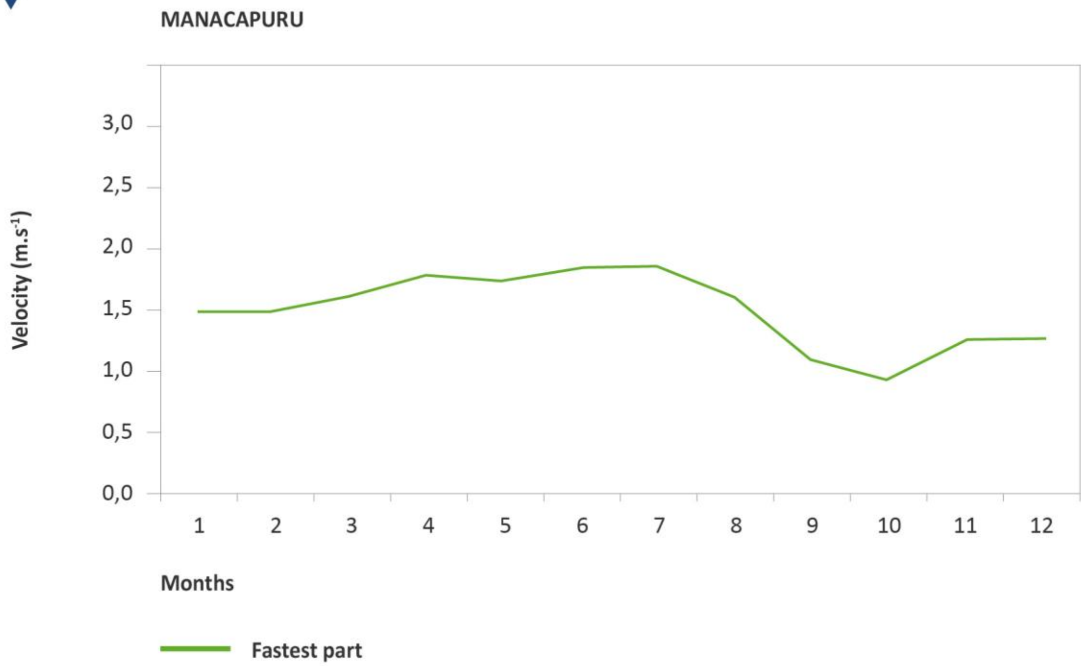


Figure 10B.


MANACAPURU
Velocity (m.s-1)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part

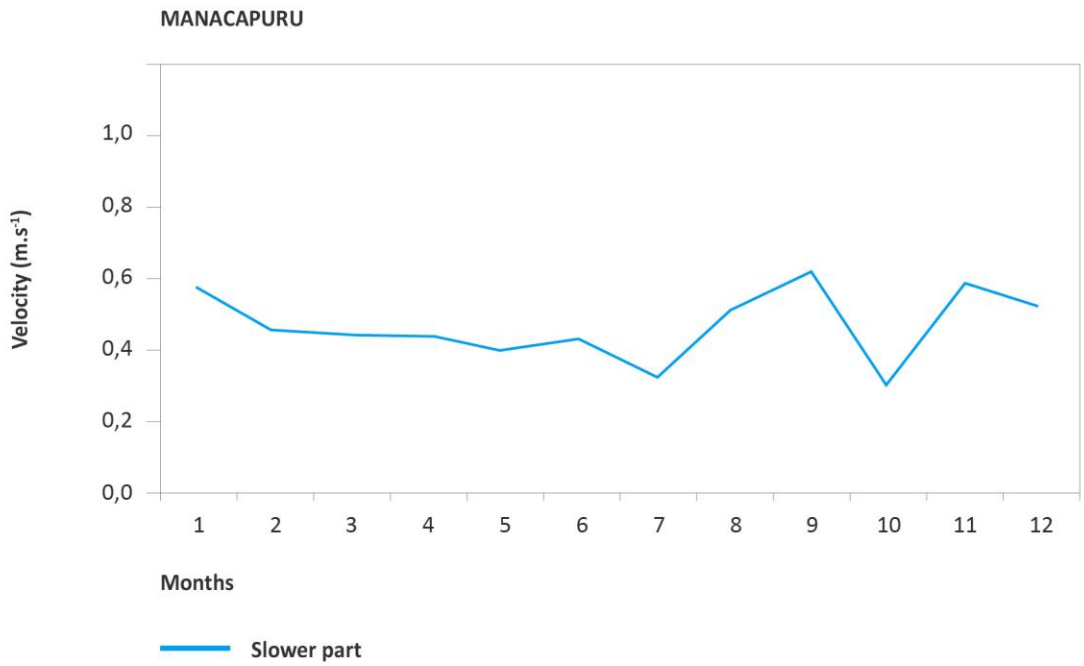
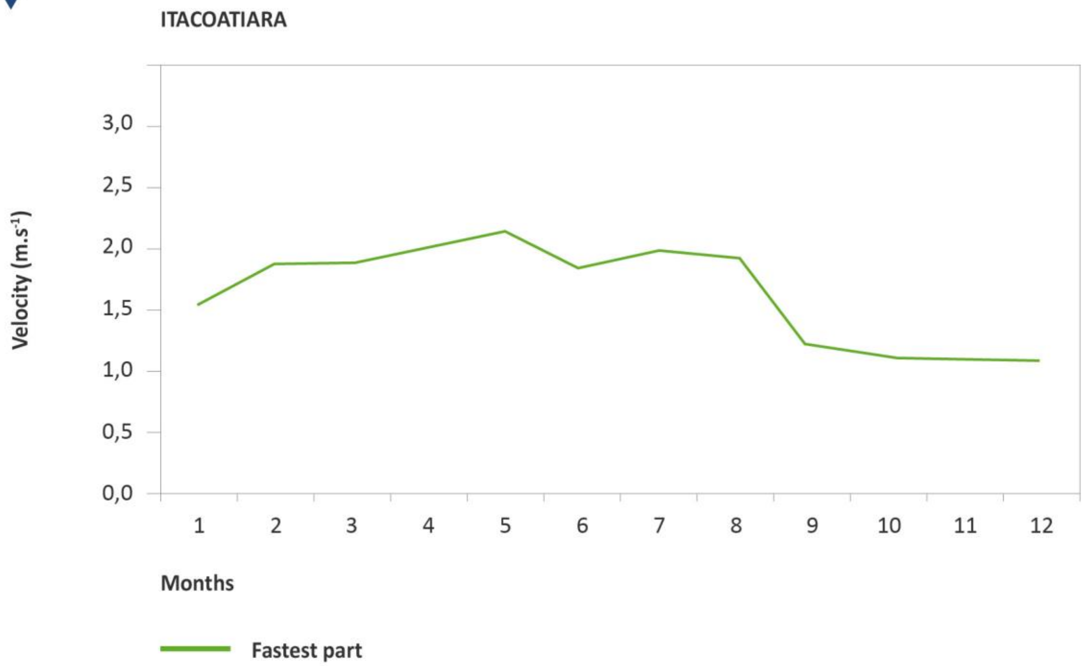

MANACAPURU
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

Figure 10C.


ITACOATIARA
Velocity (m.s-1)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part

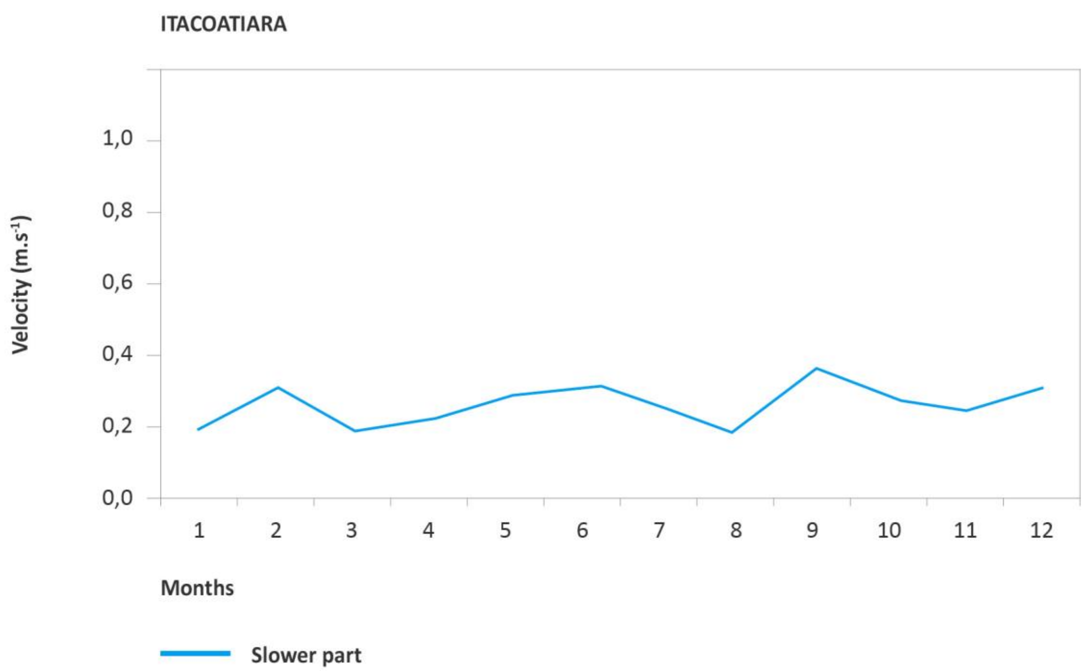
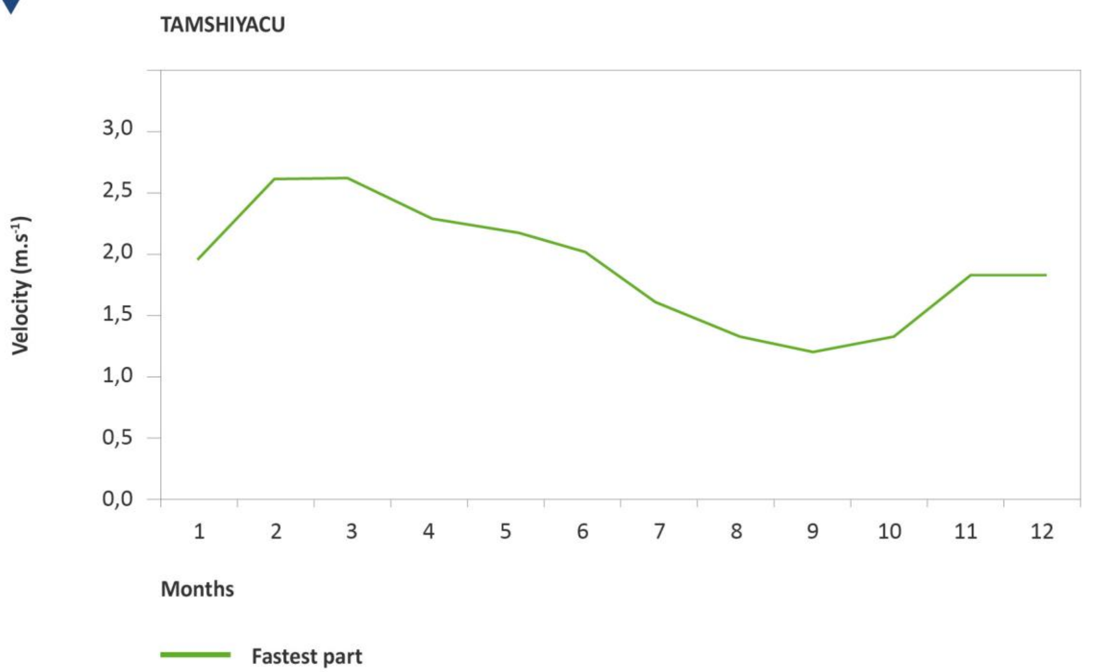

ITACOATIARA
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

Figure 10D.


TAMSHIYACU
Velocity (m.s-1)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part

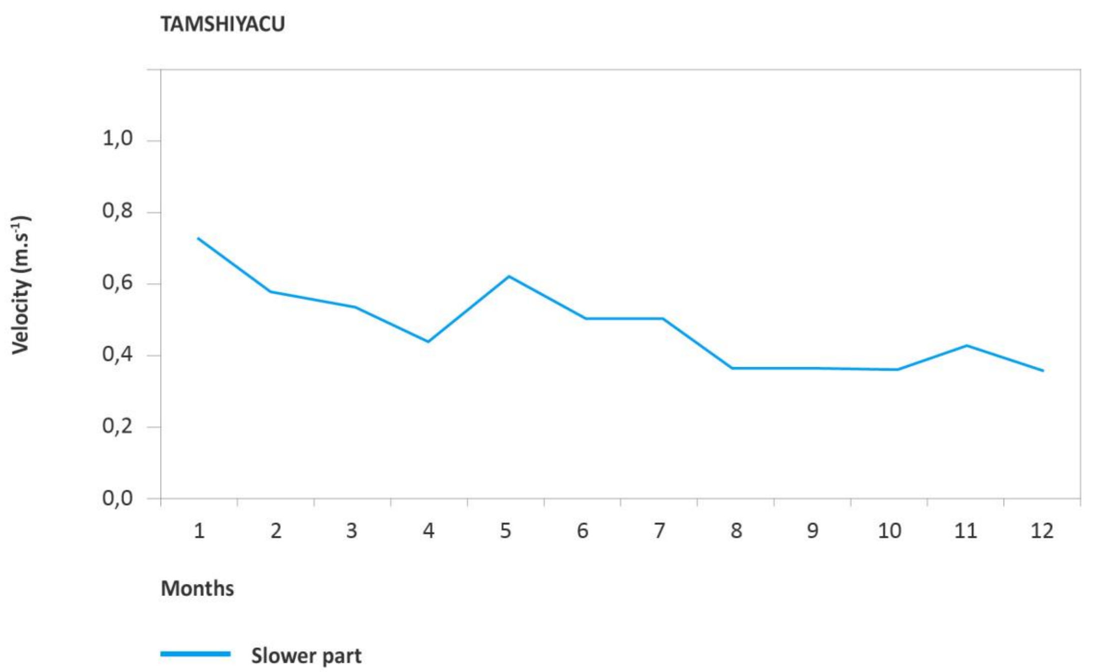
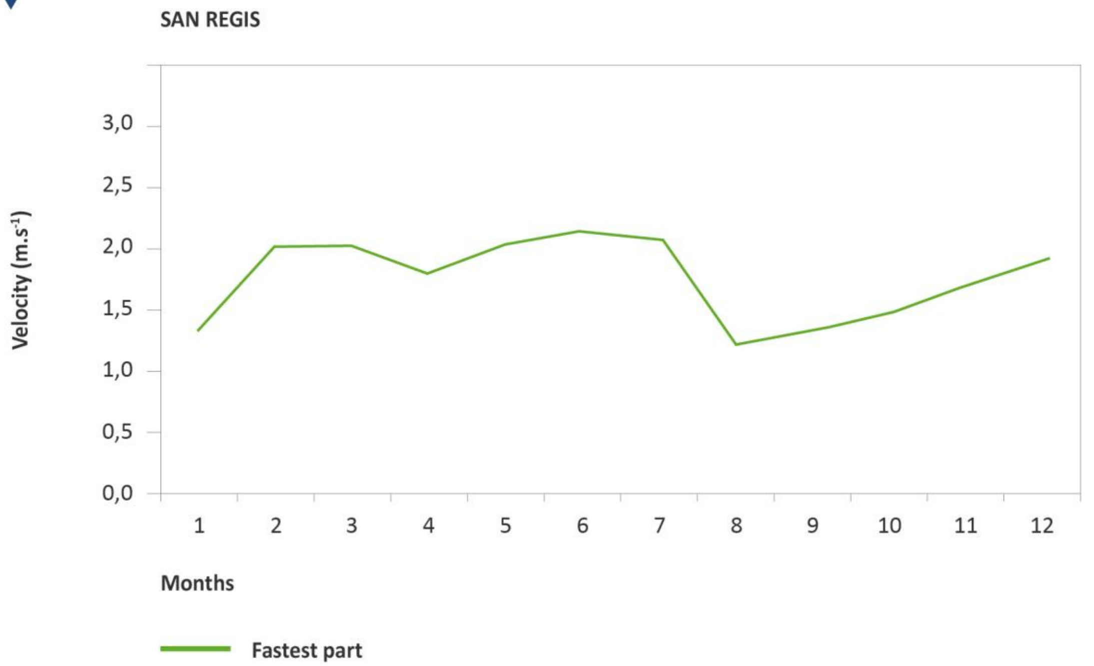

TAMSHIYACU
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

Figure 10E.


SAN REGIS
Velocity (m.s-1)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part

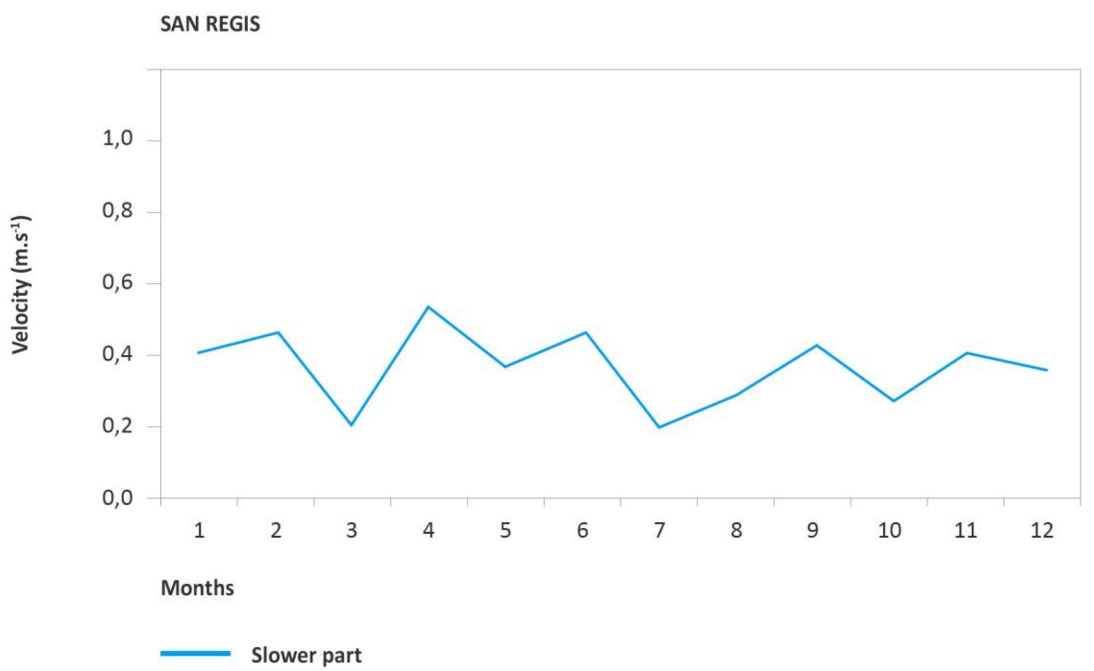
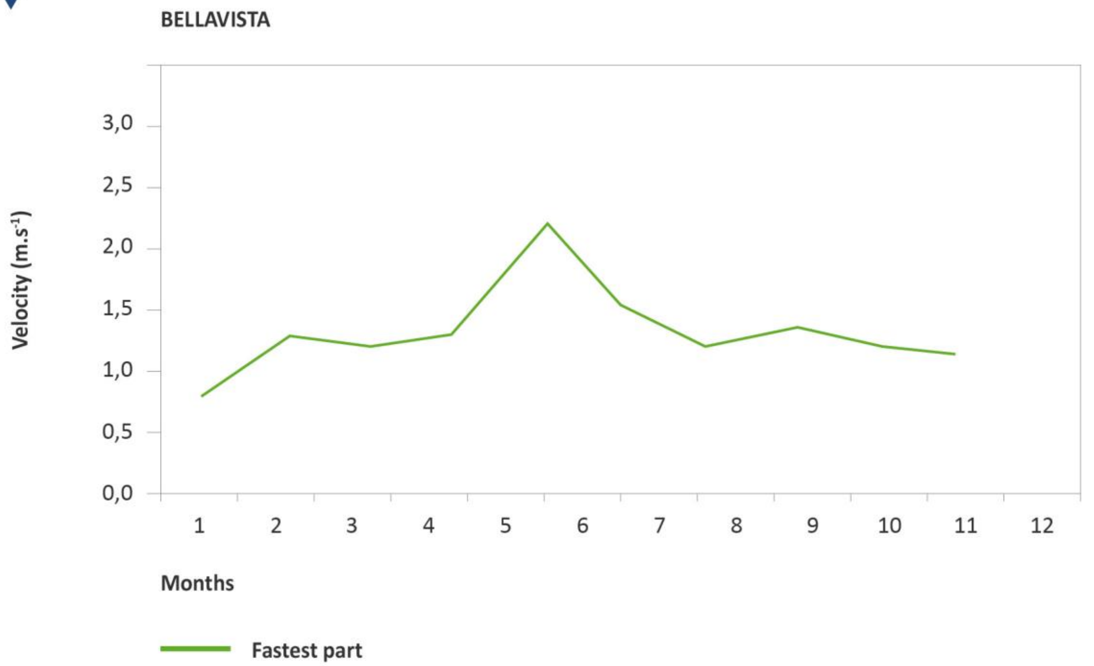

SAN REGIS
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

Figure 10F.


BELLAVISTA
Velocity (m.s-1)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part

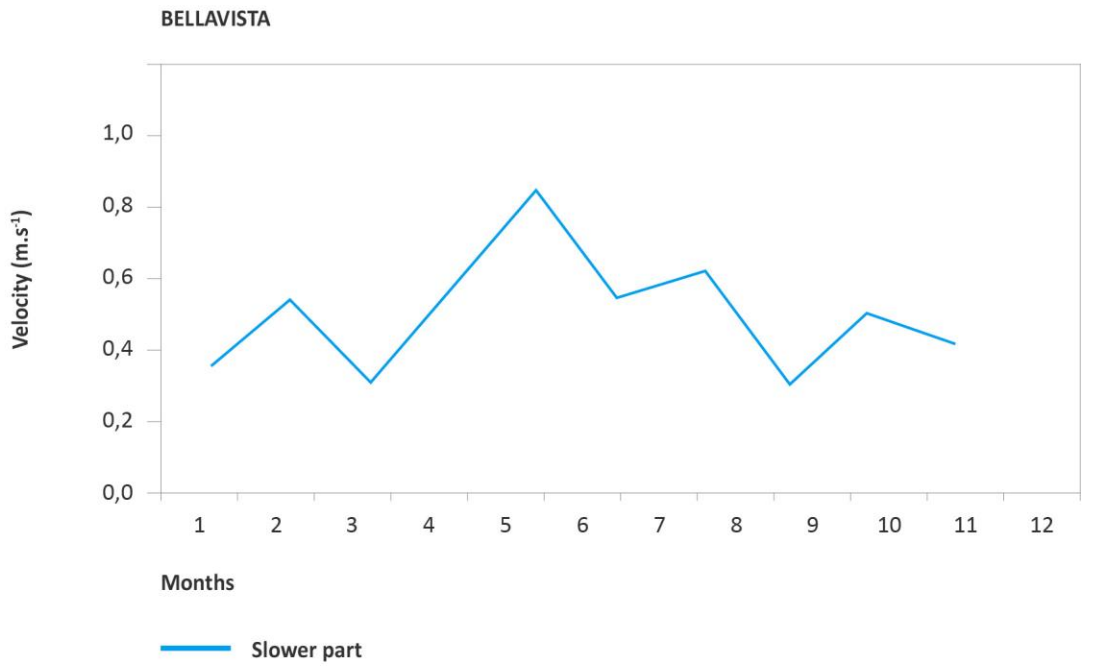

BELLAVISTA
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

Figure 10G.


BORJA
Velocity (m.s-1)
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part

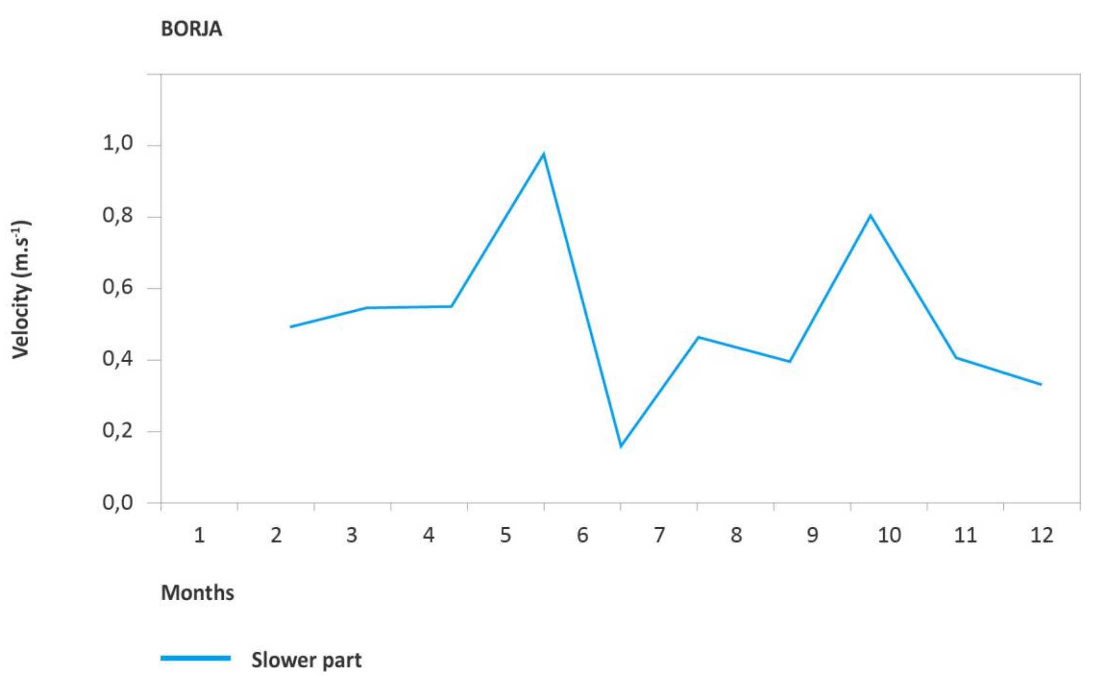
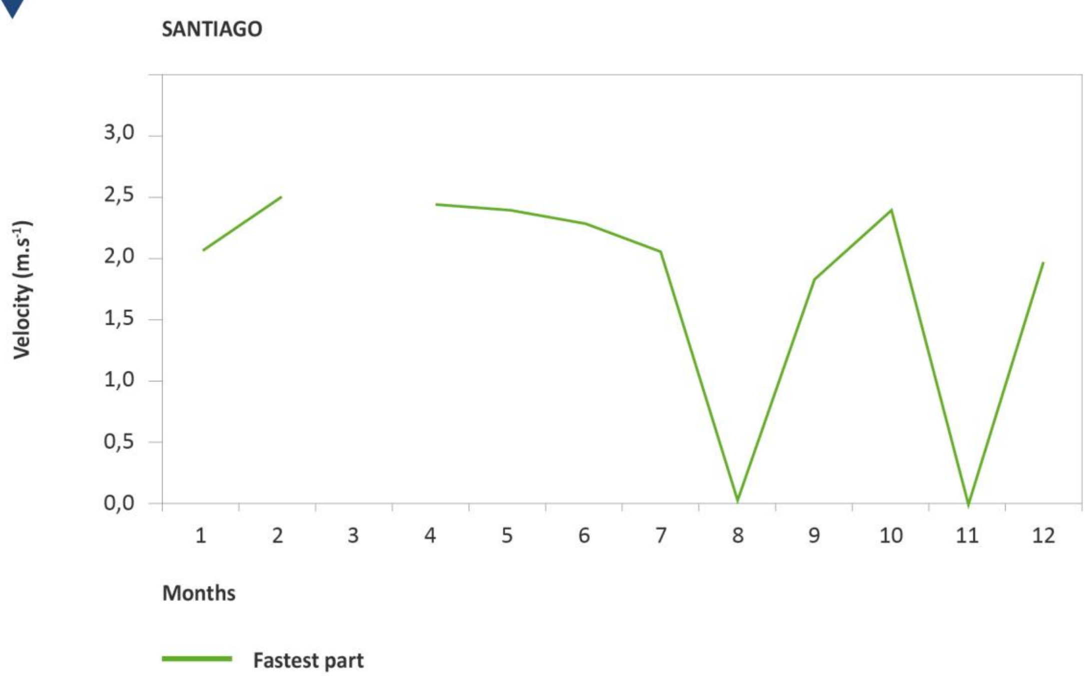
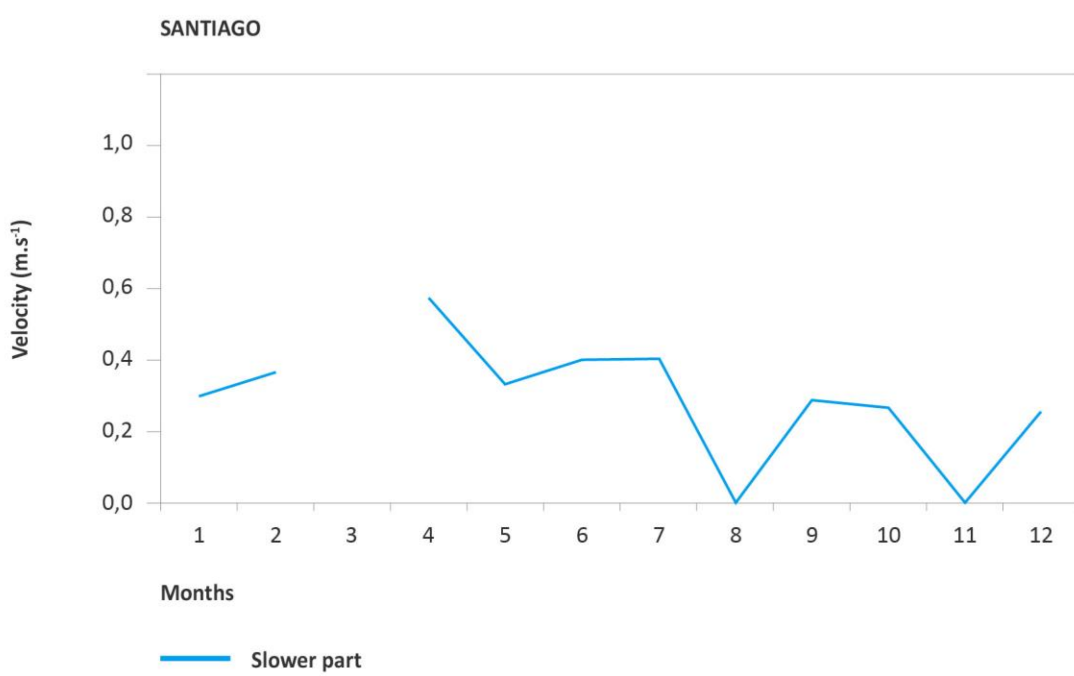

BORJA
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

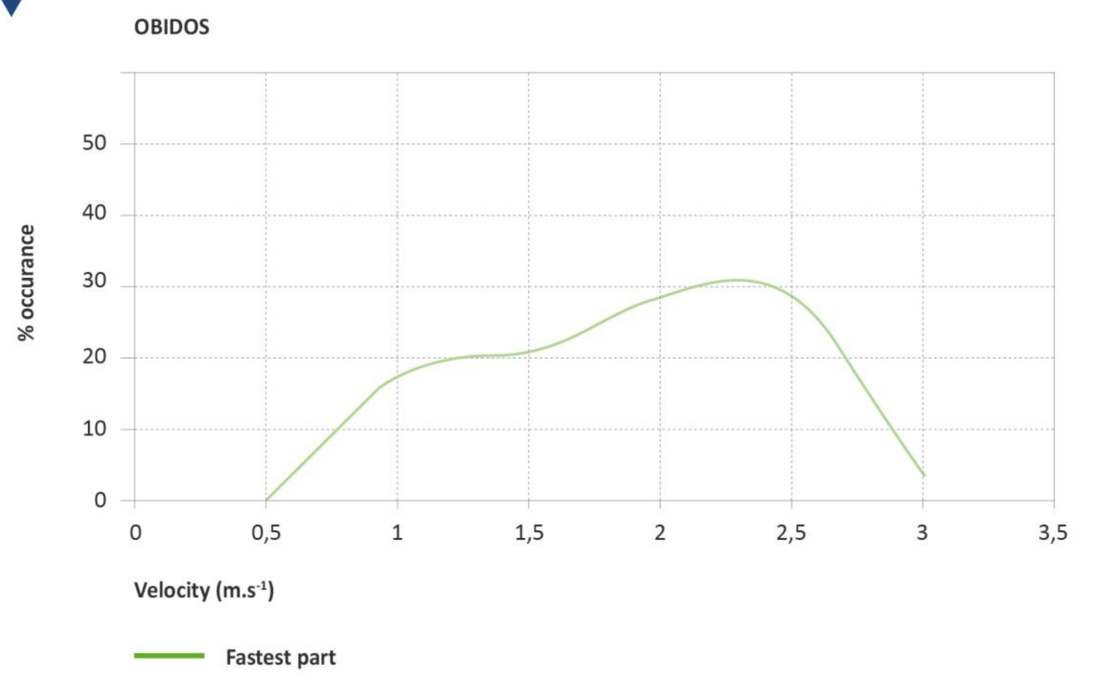
Figure 10H.


SANTIAGO
Velocity (m.s-1)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Fastest part


SANTIAGO
Velocity (m.s-1)
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Slower part

Annex 5 - Frequency of velocity occurrence (in percentage)

Figure 11A.



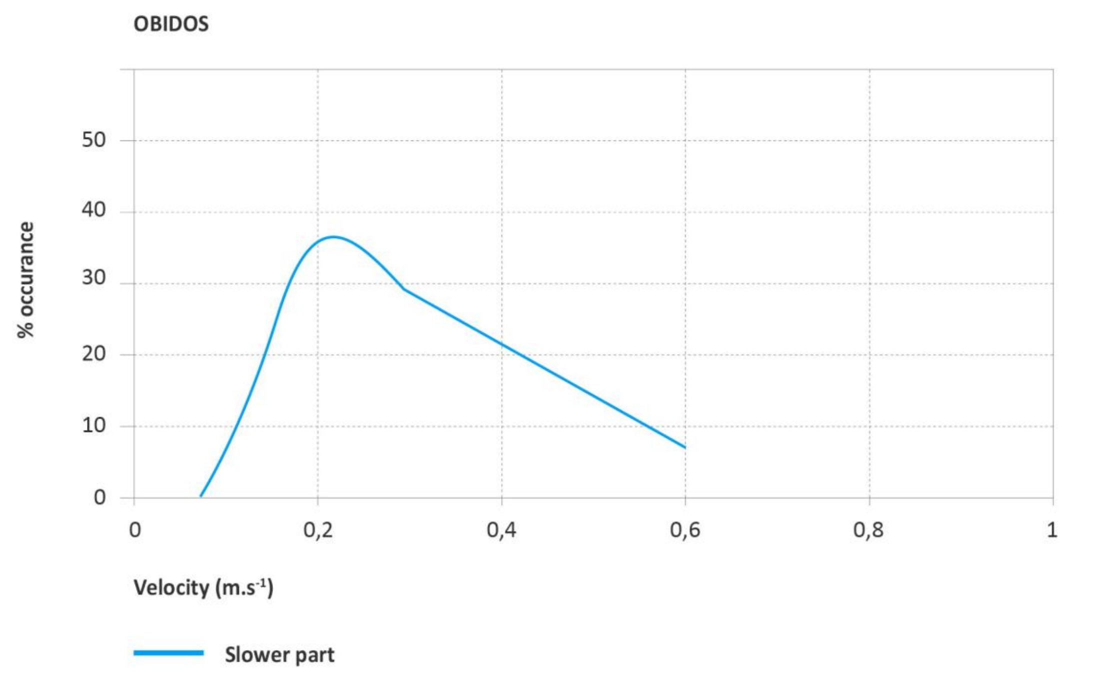
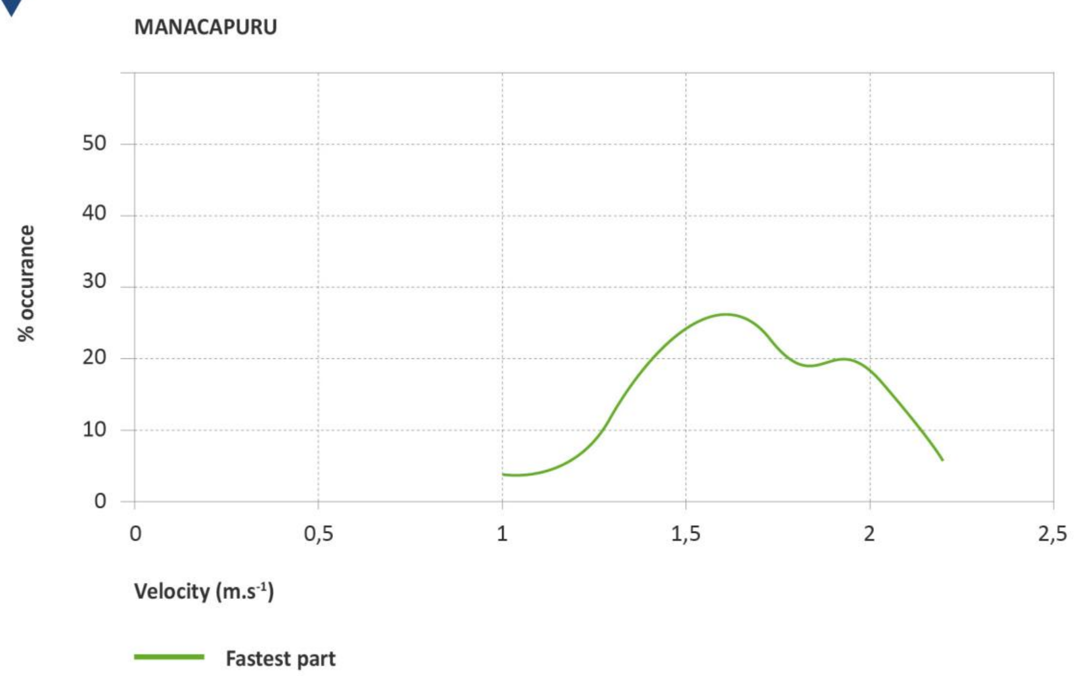


Figure 11B.


MANACAPURU
% occurance
50
40
30
20
10
0
0
0,5
1
1,5
2
2,5
Velocity (m.s-1)
Fastest part

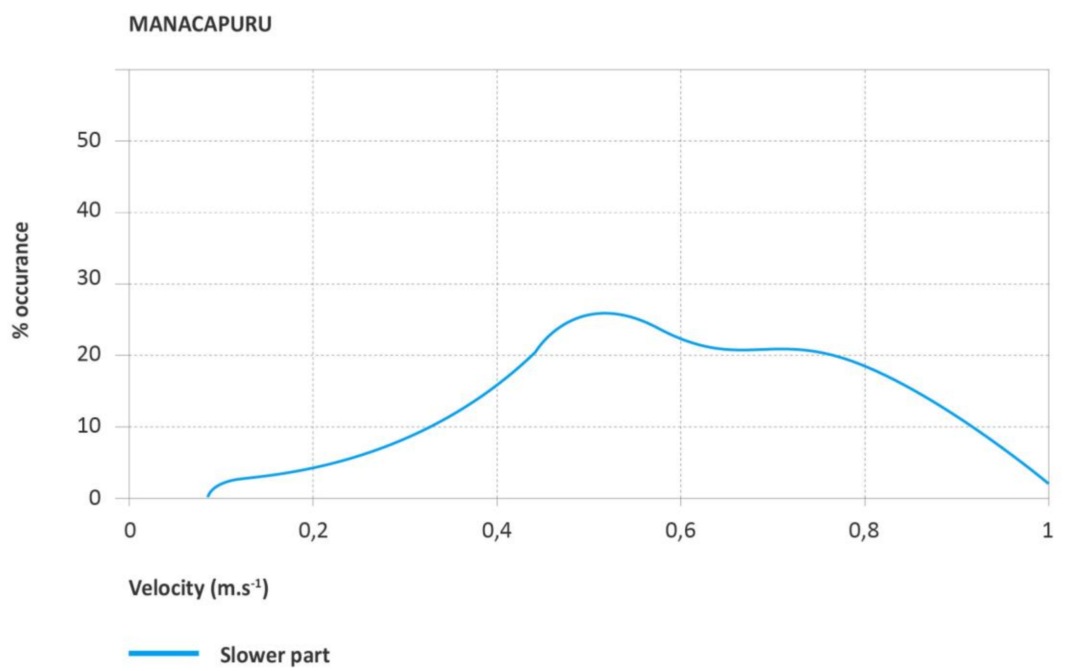
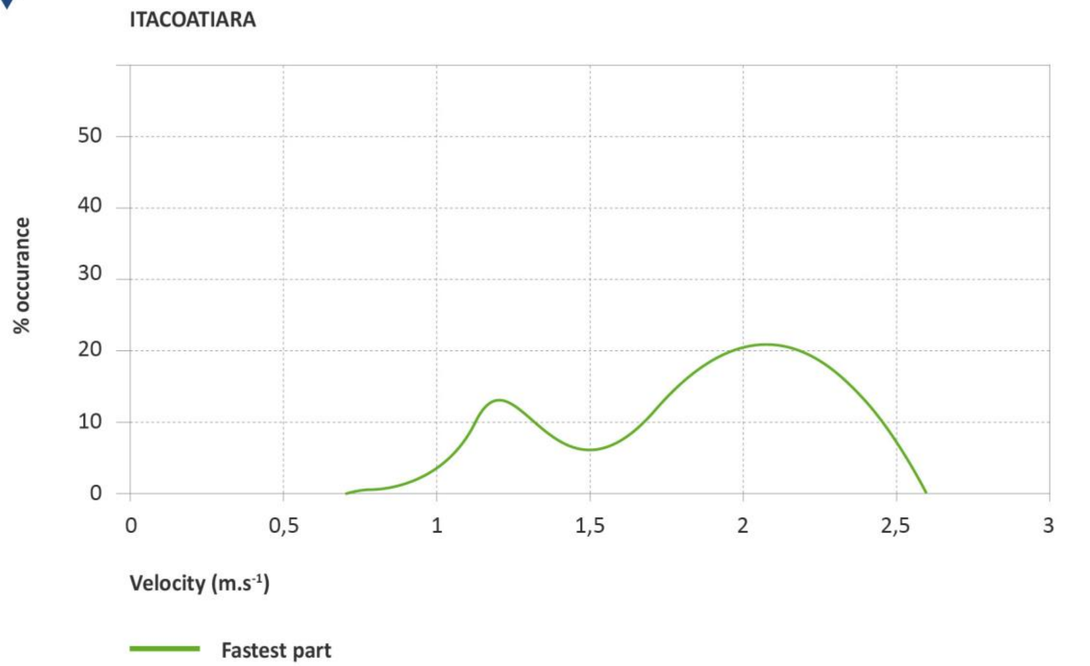

MANACAPURU
% occurance
50
40
30
20
10
0
0
0,2
0,4
0,6
0,8
1
Velocity (m.s-1)
Slower part

Figure 11C.


ITACOATIARA
% occurance
50
40
30
20
10
0
0
0,5
1
1,5
2
2,5
3
Velocity (m.s-1)
Fastest part

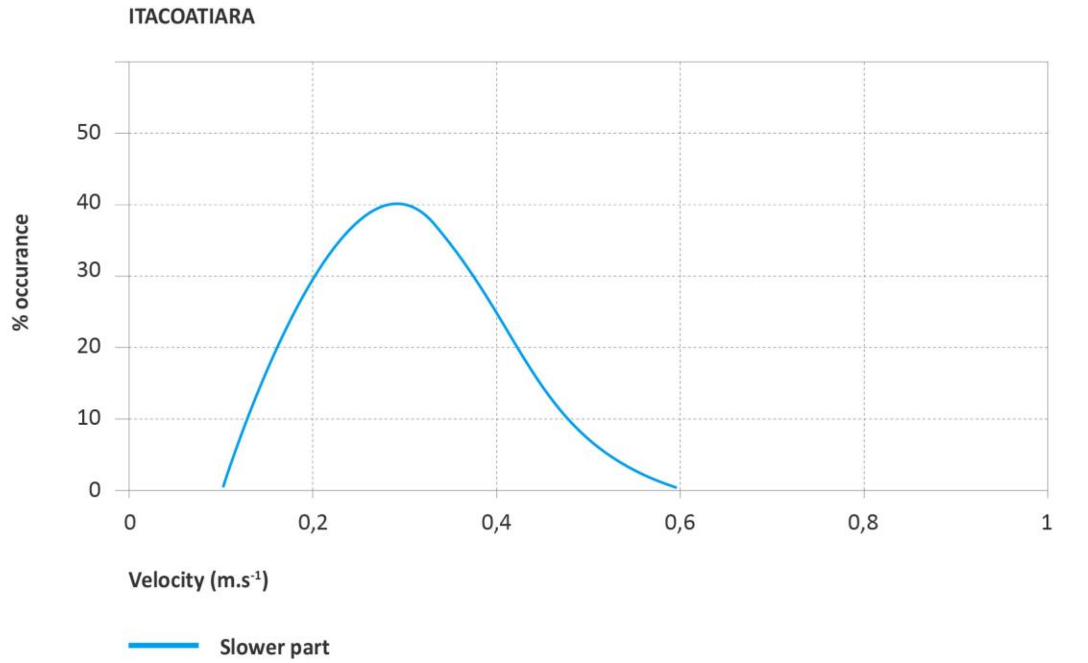
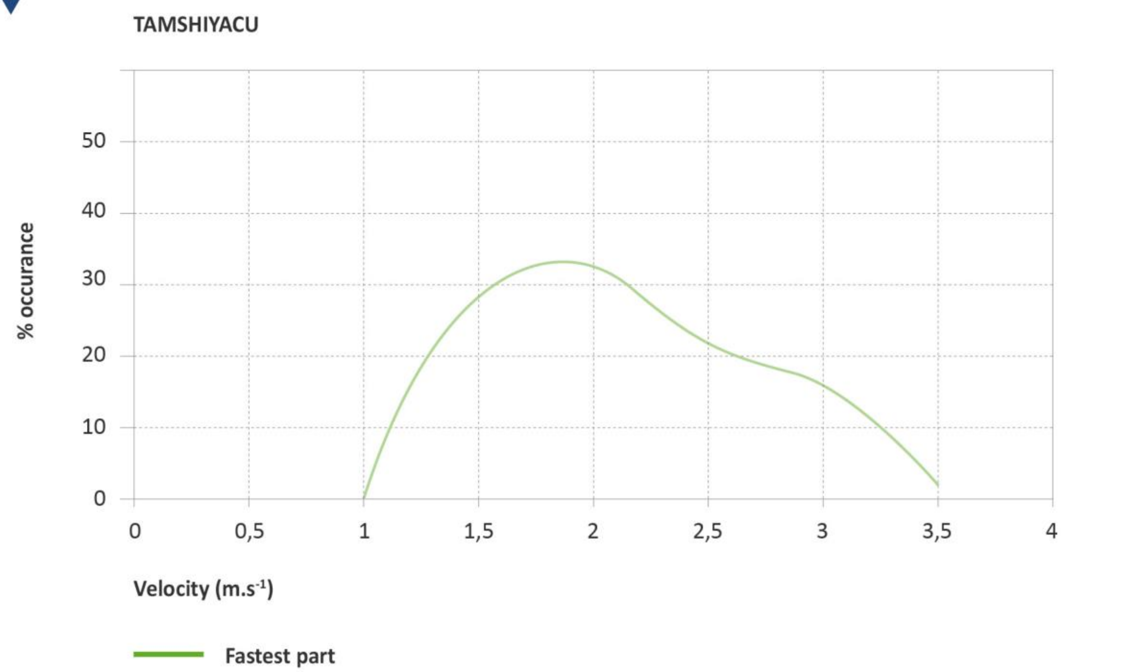

ITACOATIARA
% occurance
50
40
30
20
10
0
0
0,2
0,4
0,6
0,8
1
Velocity (m.s-1)
Slower part

Figure 11D.


TAMSHIYACU
% occurance
50
40
30
20
10
0
0
0,5
1
1,5
2
2,5
3
3,5
4
Velocity (m.s-1)
Fastest part

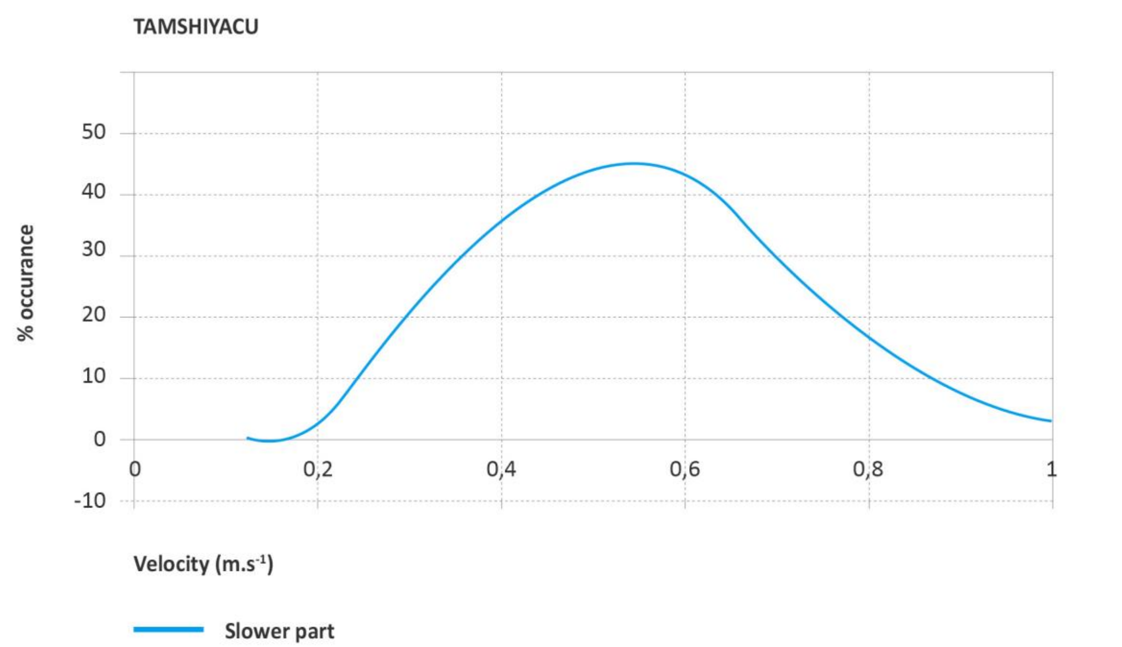
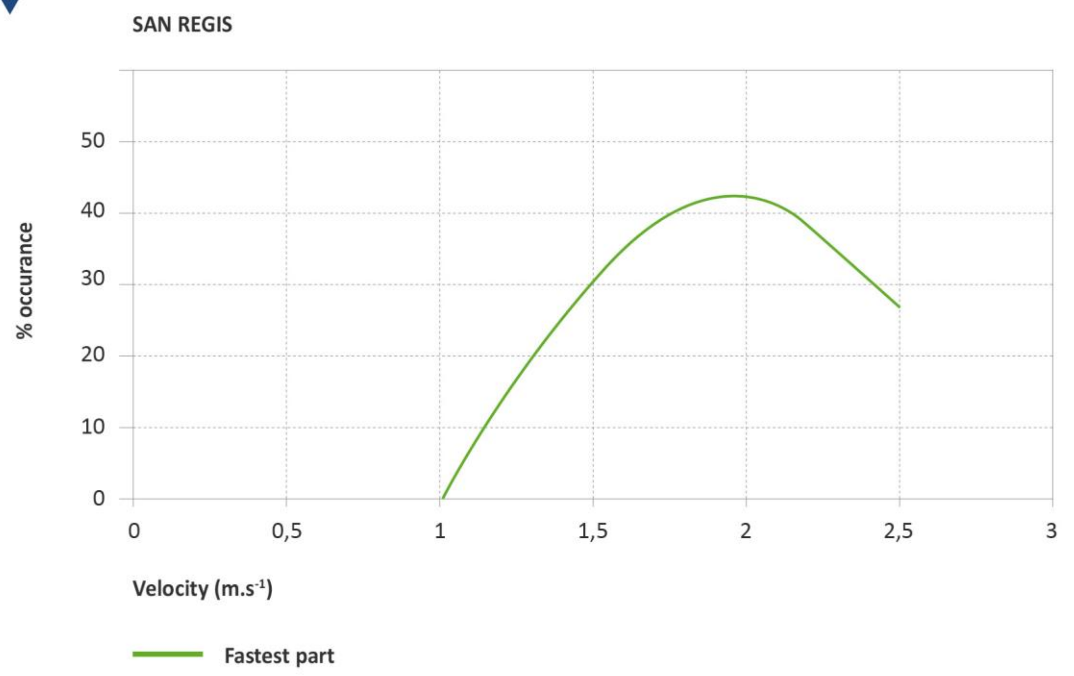

TAMSHIYACU
% occurance
50
40
30
20
10
0
-10
0
0,2
0,4
0,6
0,8
1
Velocity (m.s-1)
Slower part

Figure 11E.


SAN REGIS
% occurance
50
40
30
20
10
0
0
0,5
1
1,5
2
2,5
3
Velocity (m.s-1)
Fastest part

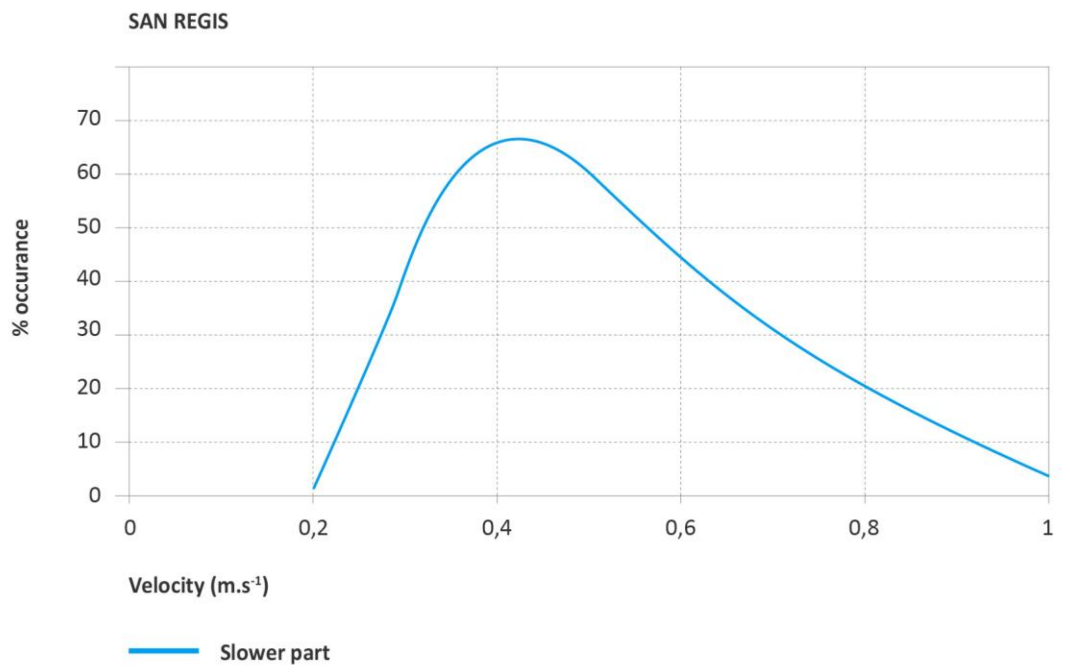
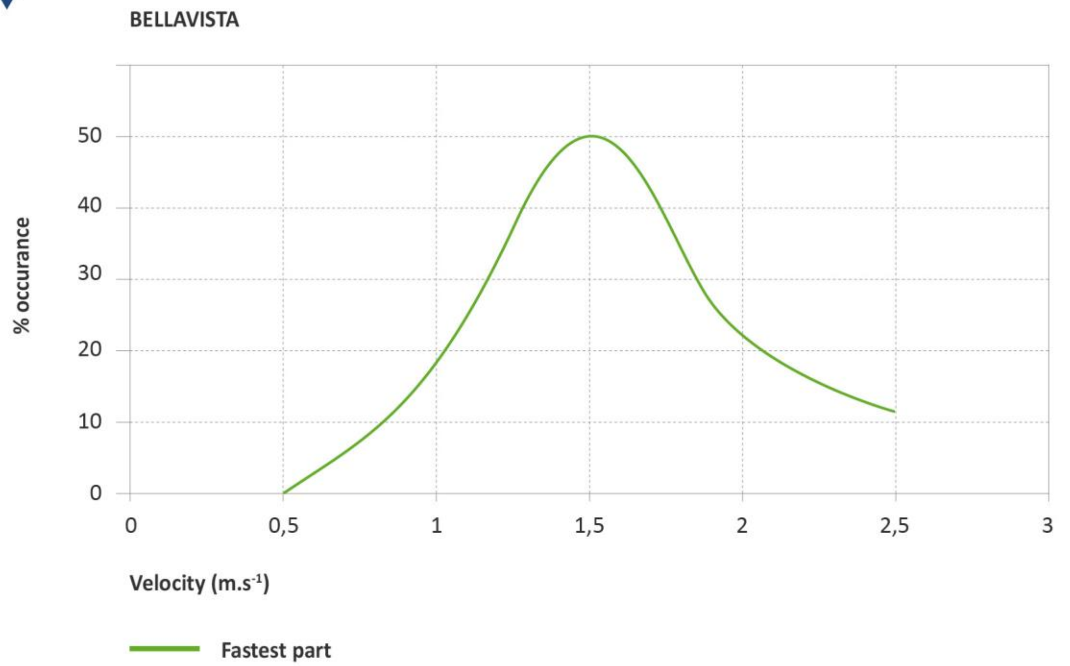

SAN REGIS
% occurance
70
60
50
40
30
20
10
0
0
0,2
0,4
0,6
0,8
1
Velocity (m.s-1)
Slower part

Figure 11F.


BELLAVISTA
% occurance
50
40
30
20
10
0
0
0,5
1
1,5
2
2,5
3
Velocity (m.s⁻¹)
Fastest part

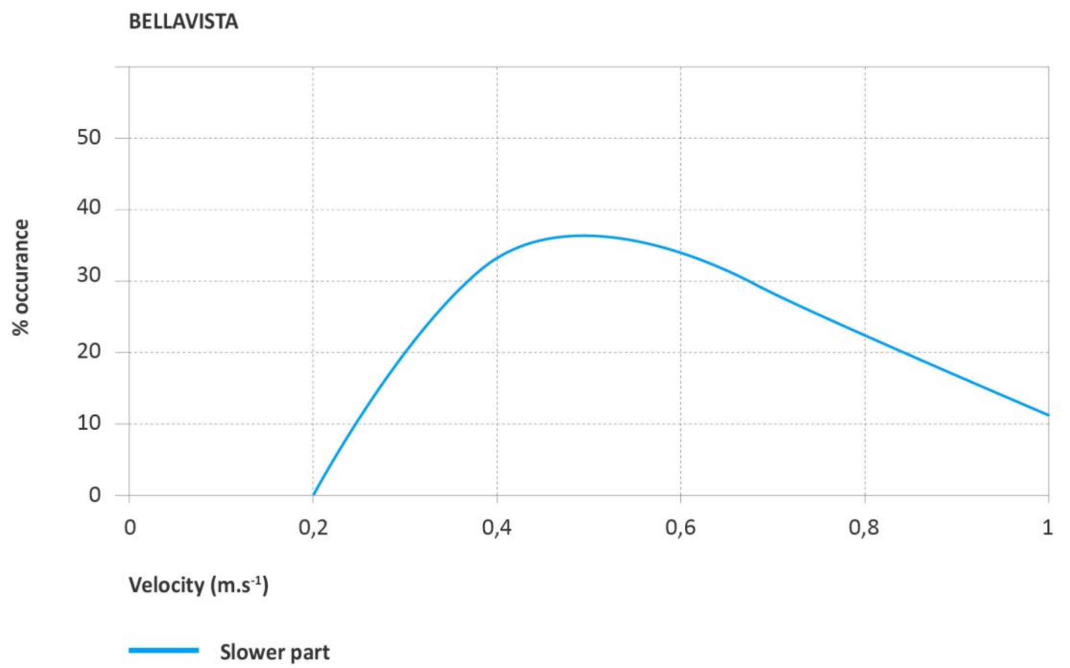
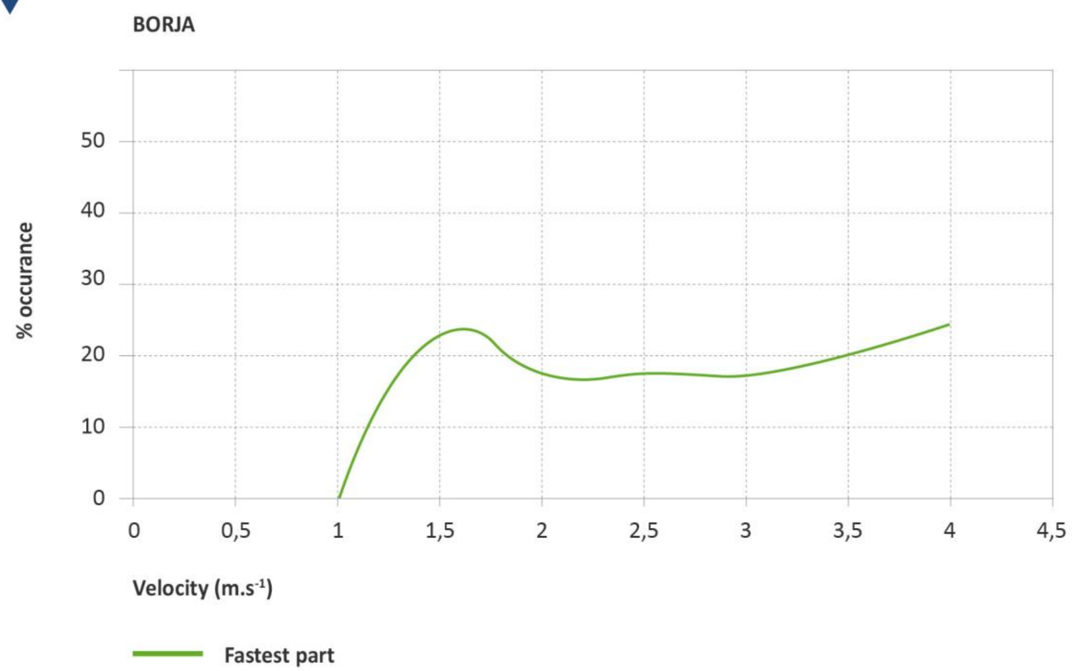

BELLAVISTA
% occurance
50
40
30
20
10
0
0
0,2
0,4
0,6
0,8
1
Velocity (m.s⁻¹)
Slower part

Figure 11G.


BORJA
50
40
30
20
10
0
% occurance
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Velocity (m.s-1)
Fastest part

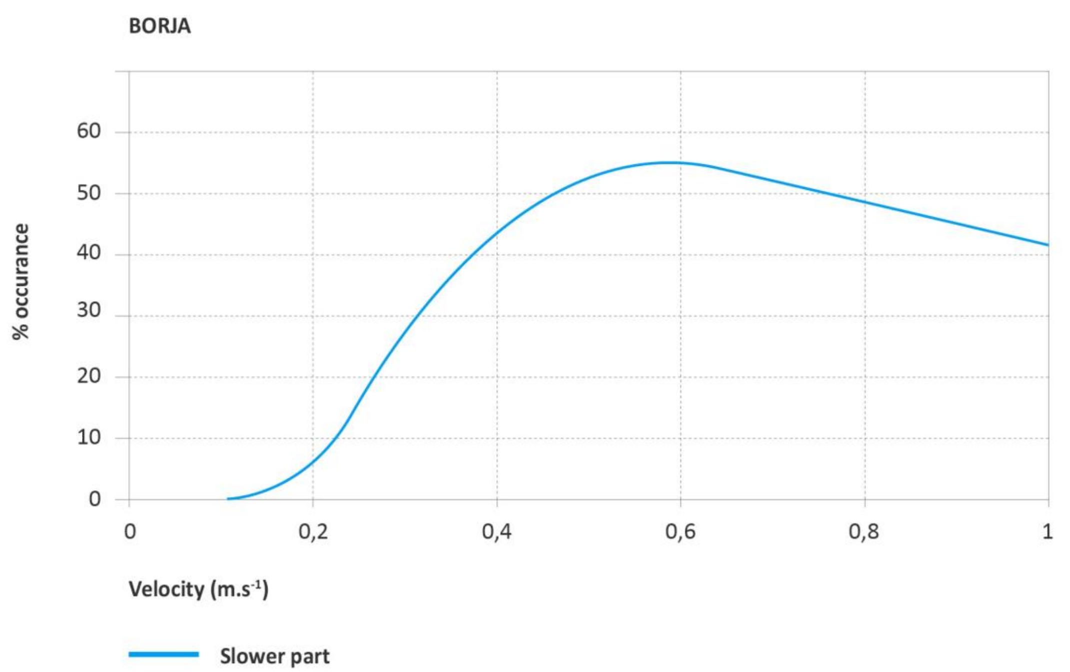
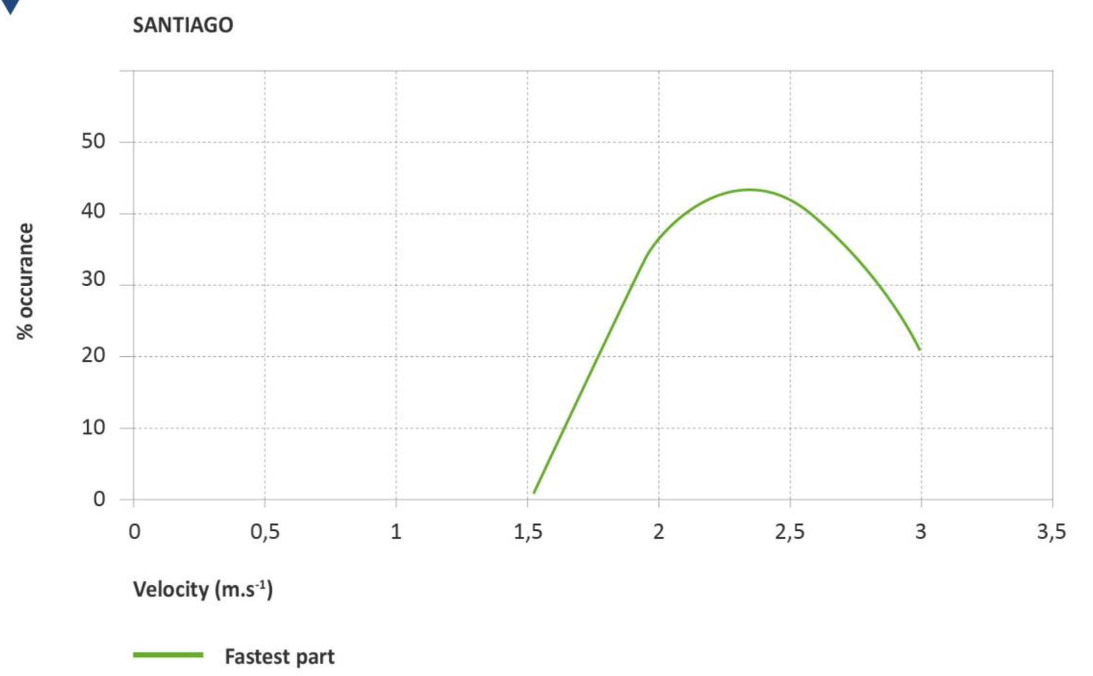
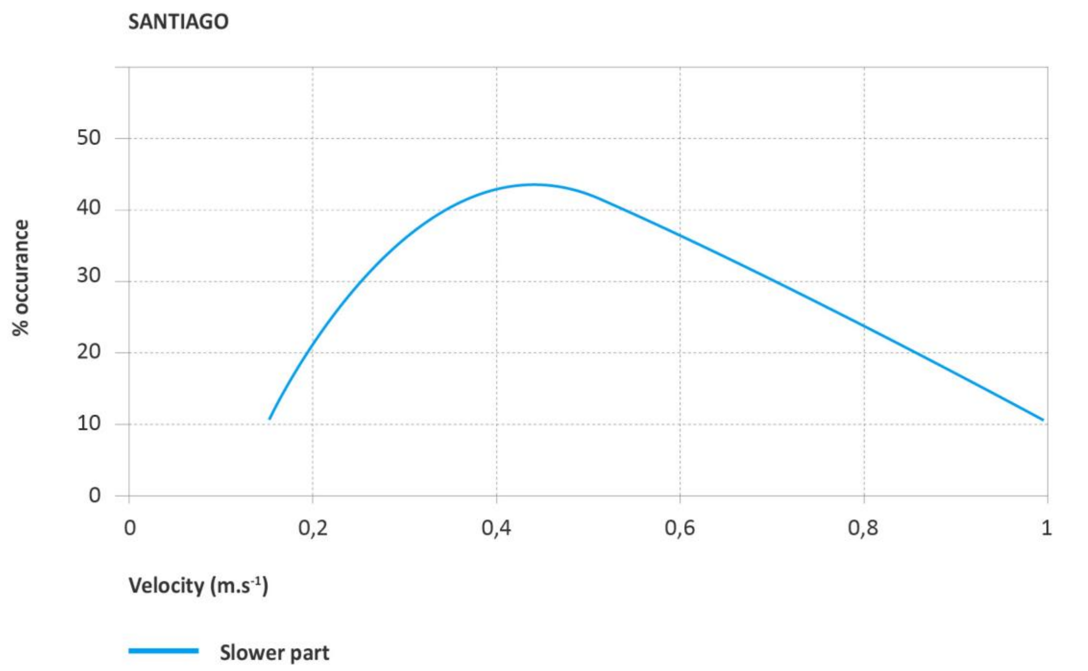

BORJA
60
50
40
30
20
10
0
% occurance
0
0,2
0,4
0,6
0,8
1
Velocity (m.s-1)
Slower part

Figure 11H.


SANTIAGO
% occurance
50
40
30
20
10
0
0
0,5
1
1,5
2
2,5
3
3,5
Velocity (m.s-1)
Fastest part


SANTIAGO
% occurance
50
40
30
20
10
0
0
0,2
0,4
0,6
0,8
1
Velocity (m.s-1)
Slower part

Annex 6 – Velocity intensity against discharge values separated by fastest and slower parts.

Figure 12A.

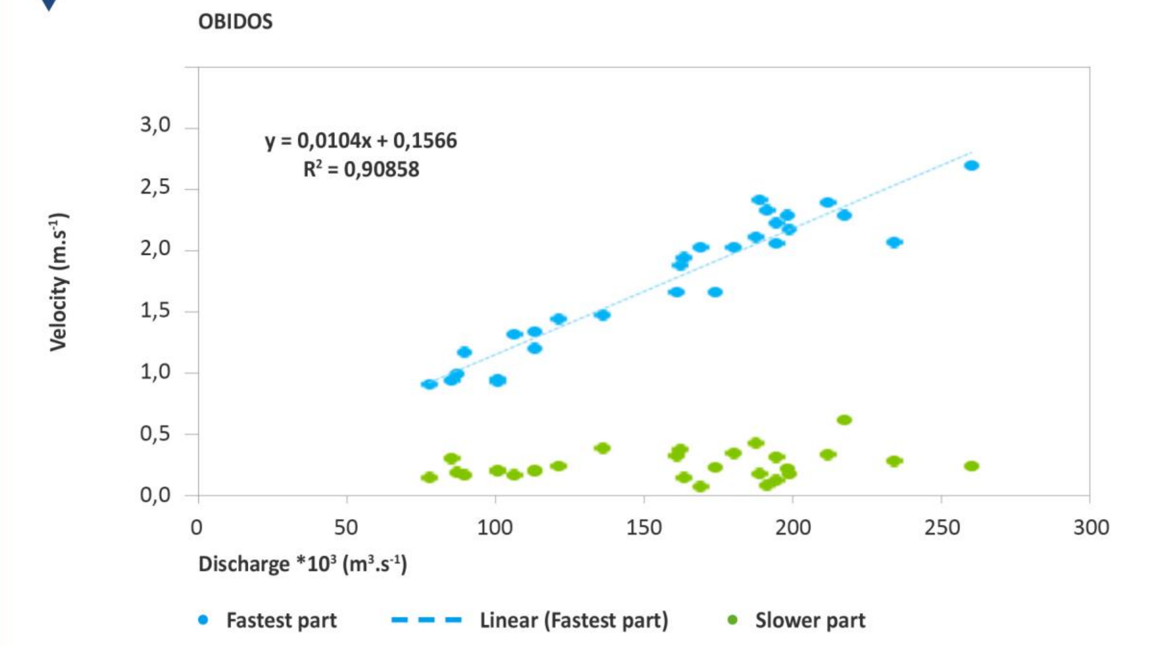


Figure 12B.

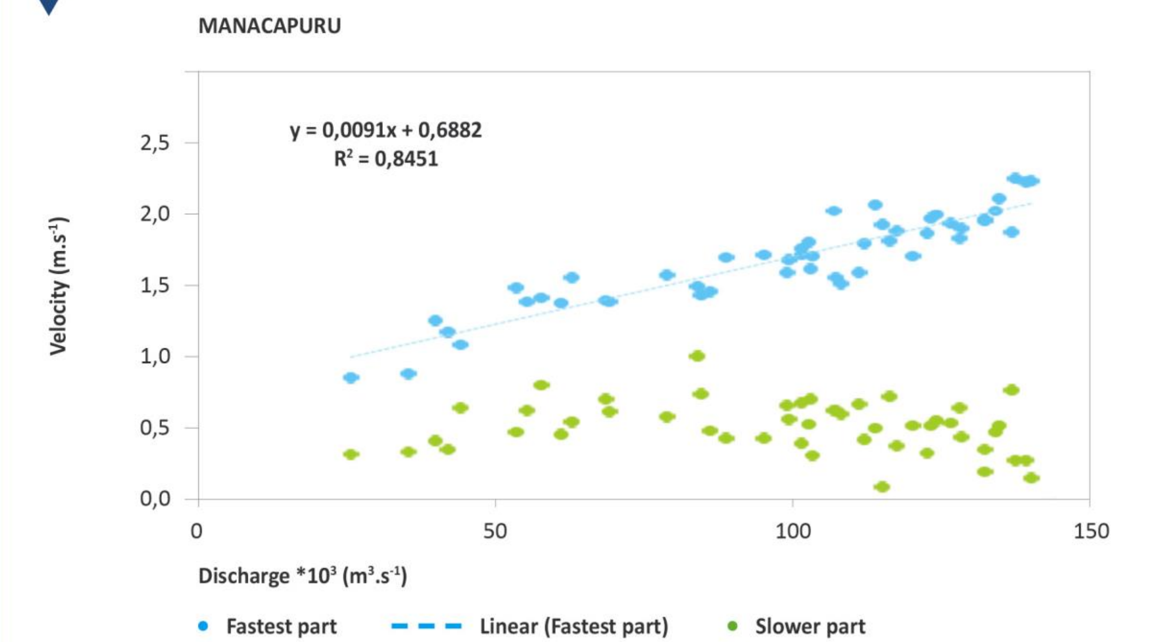


Figure 12C.

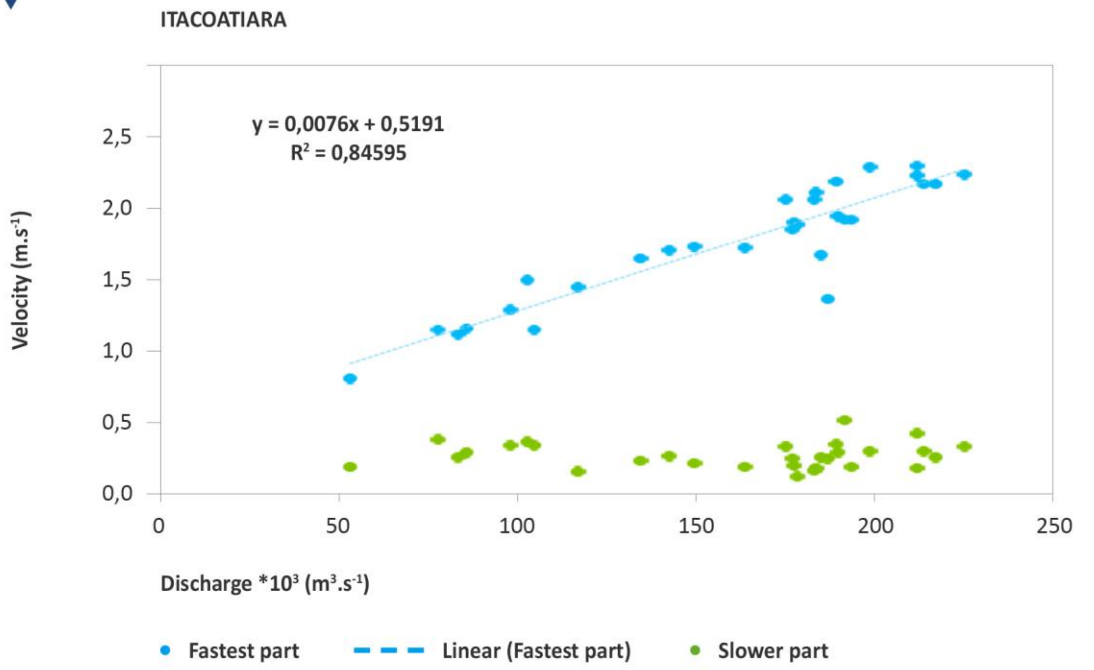


Figure 12D.

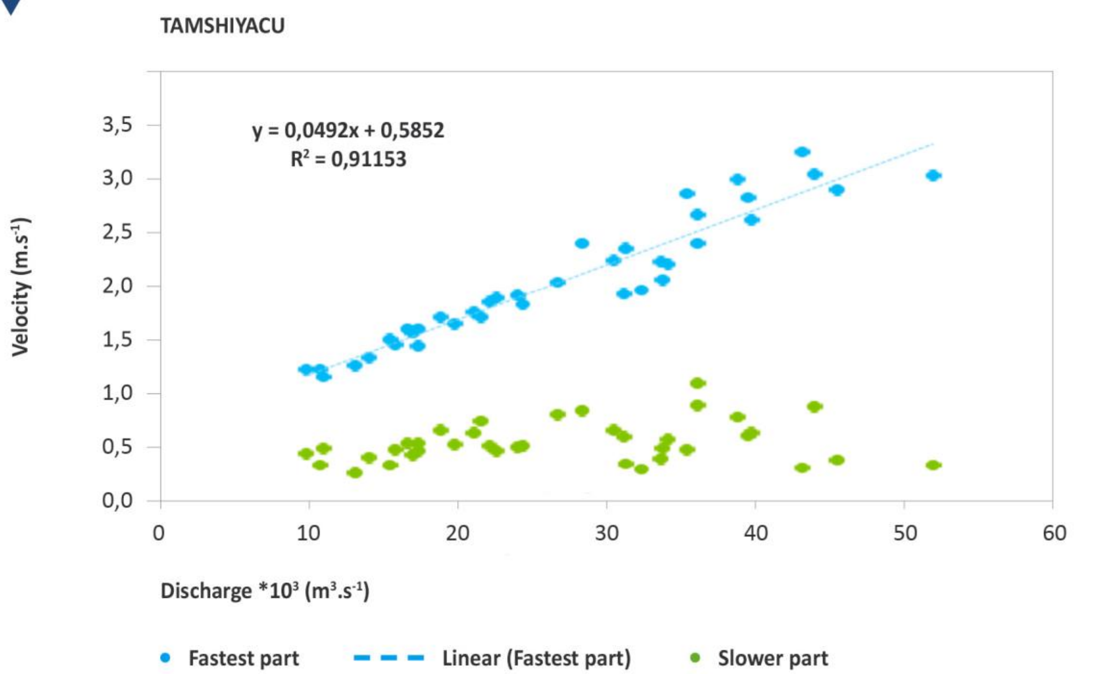


Figure 12E.

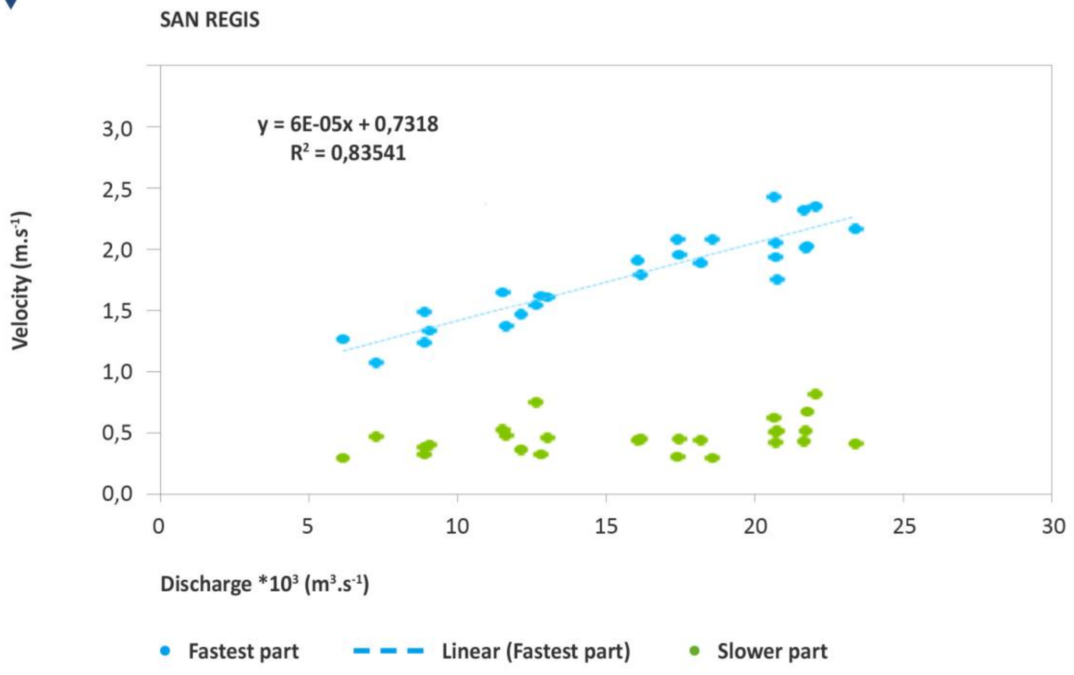


Figure 12F.

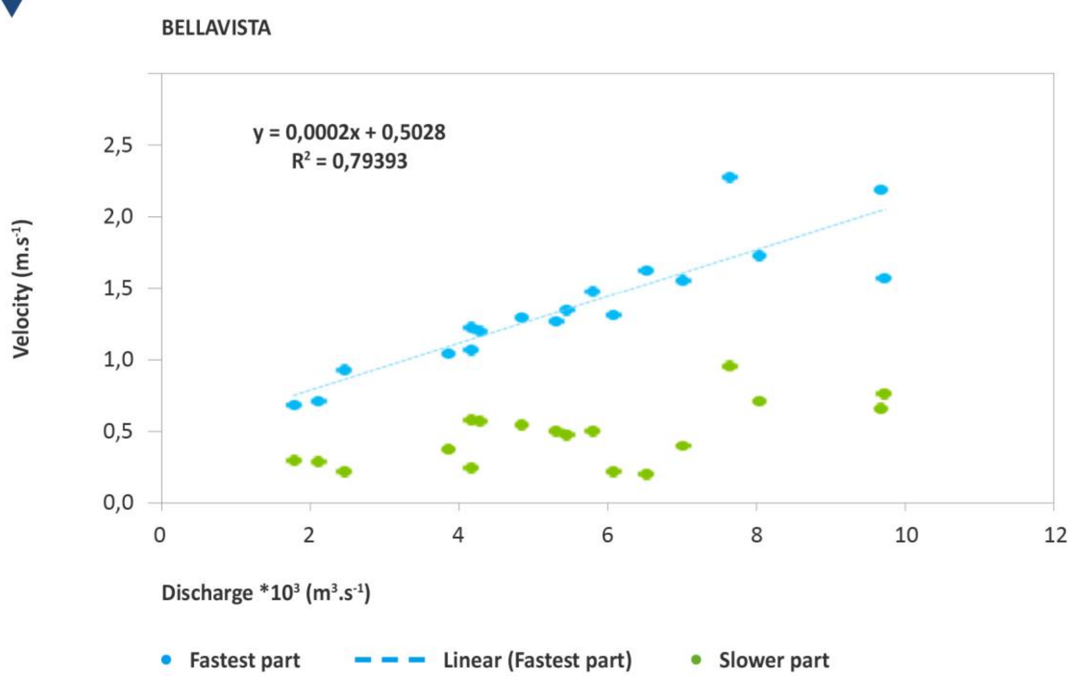


Figure 12G.

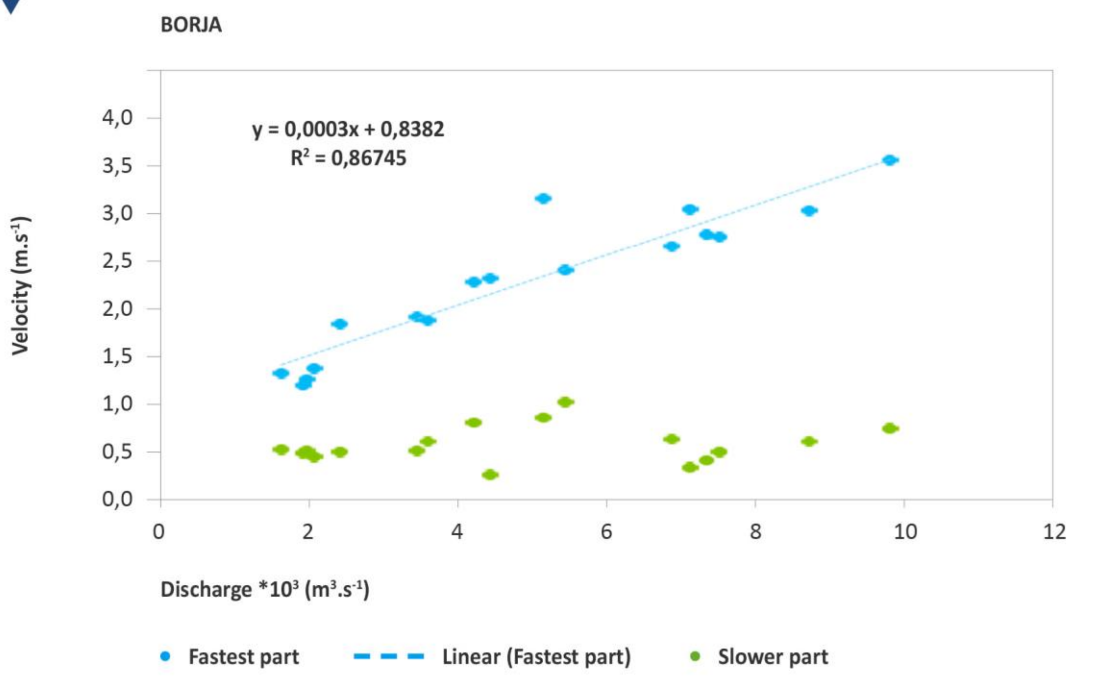
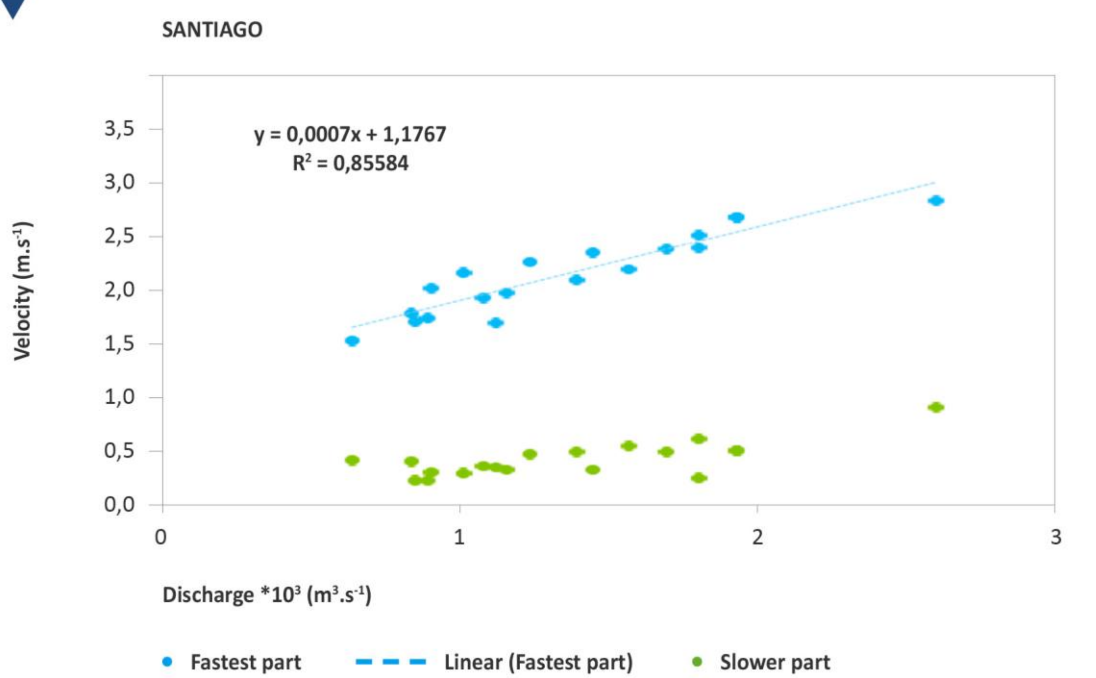


Figure 12H.



Annex 7 – Additional ADCP images for other periods of the hydrological year as complementary information.

Figure 13A.

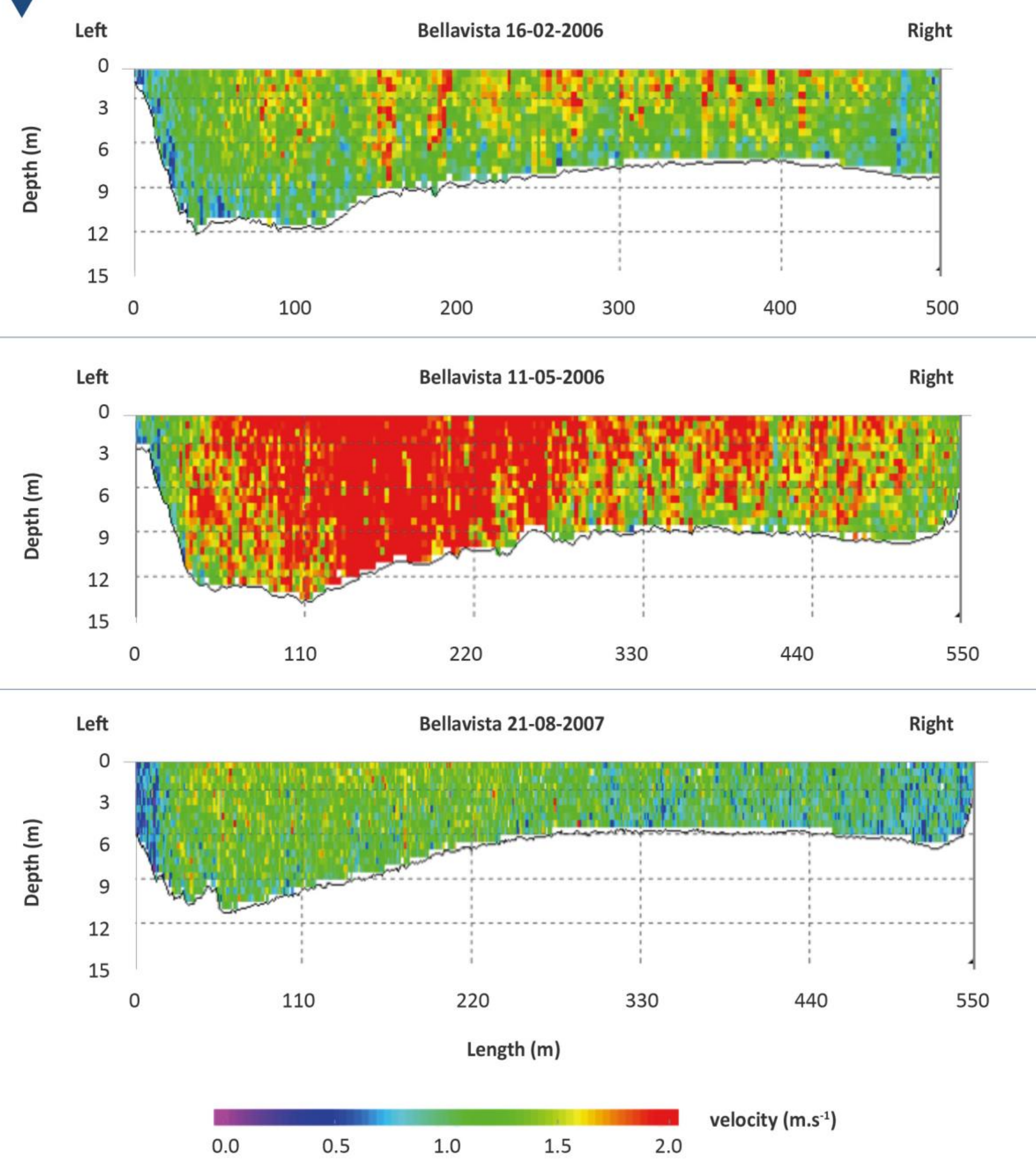


Figure 13B.

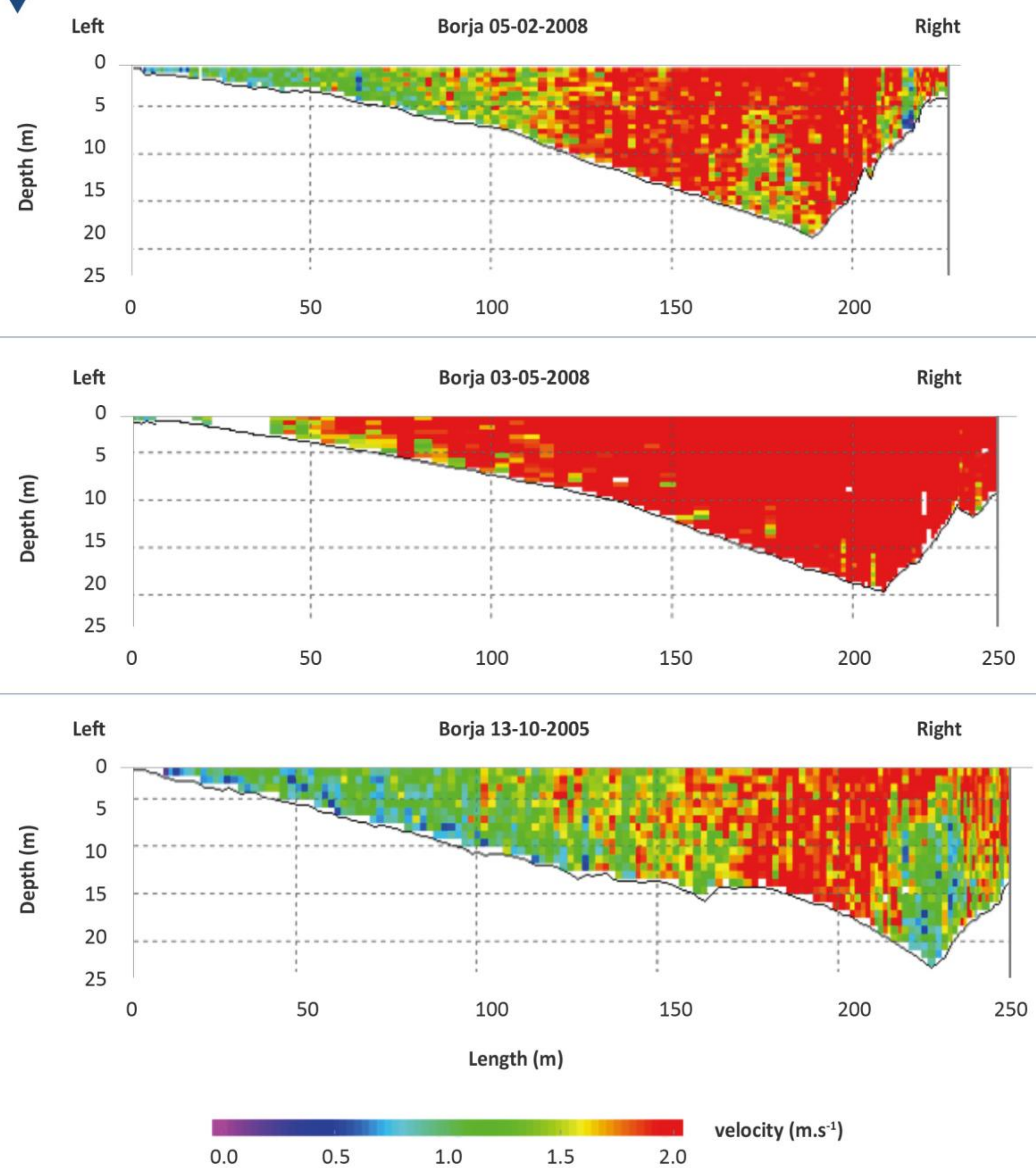

Left
Borja 05-02-2008
Right
Depth (m)
0
5
10
15
20
25
0
50
100
150
200
Left
Borja 03-05-2008
Right
Depth (m)
250
Left
Borja 13-10-2005
Right
Depth (m)
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0

Figure 13C.

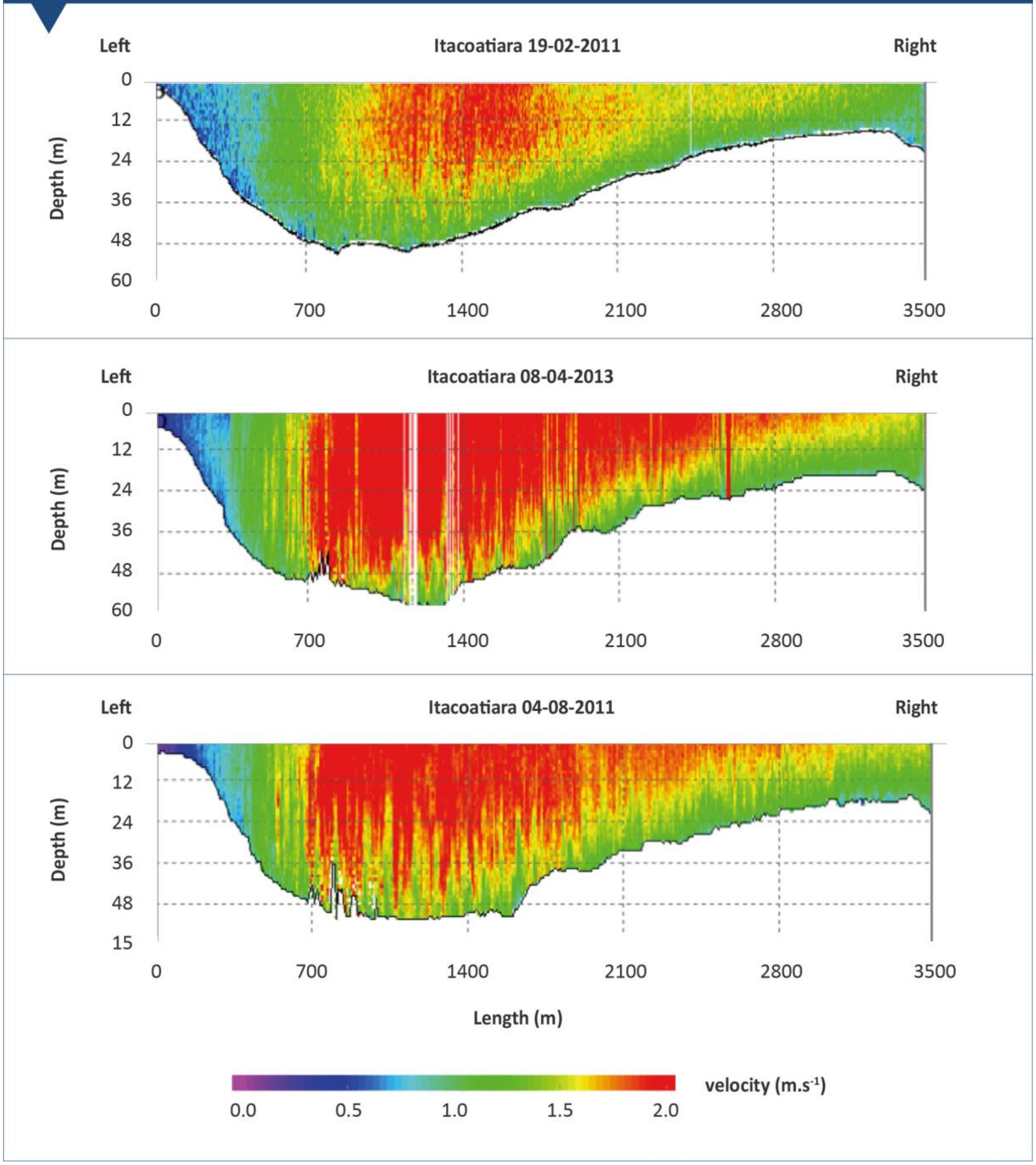

Left
Itacoatiara 19-02-2011
Right
Depth (m)
0
12
24
36
48
60
0
700
1400
2100
2800
3500
Left
Itacoatiara 08-04-2013
Right
Depth (m)
0
12
24
36
48
60
0
700
1400
2100
2800
3500
Left
Itacoatiara 04-08-2011
Right
Depth (m)
0
12
24
36
48
15
0
700
1400
2100
2800
3500
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0

Figure 13D.

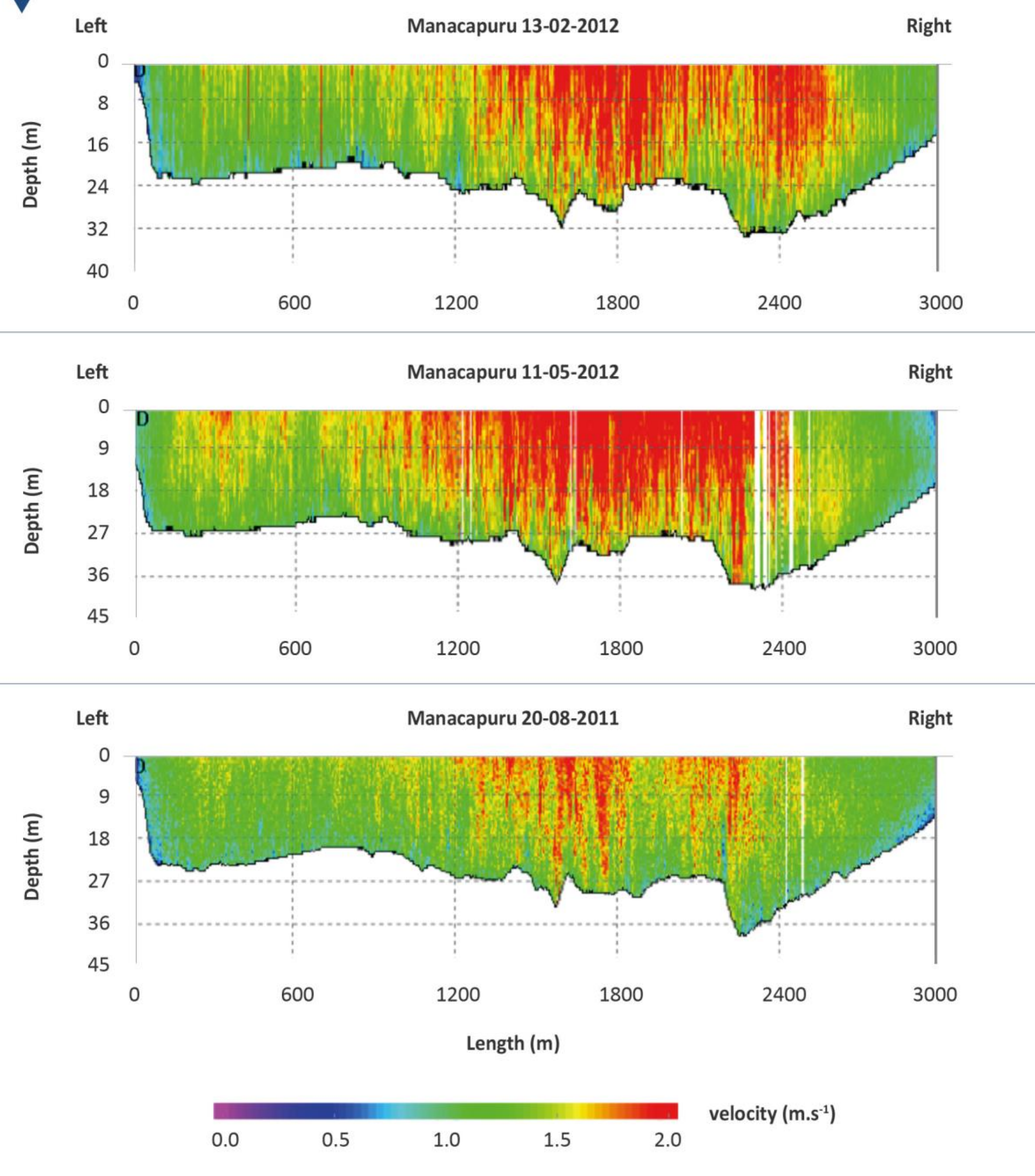

Left
Manacapuru 13-02-2012
Right
Depth (m)
0
8
16
24
32
40
0
600
1200
1800
2400
3000
Left
Manacapuru 11-05-2012
Right
Depth (m)
0
9
18
27
36
45
0
600
1200
1800
2400
3000
Left
Manacapuru 20-08-2011
Right
Depth (m)
0
9
18
27
36
45
0
600
1200
1800
2400
3000
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0

Figure 13E.

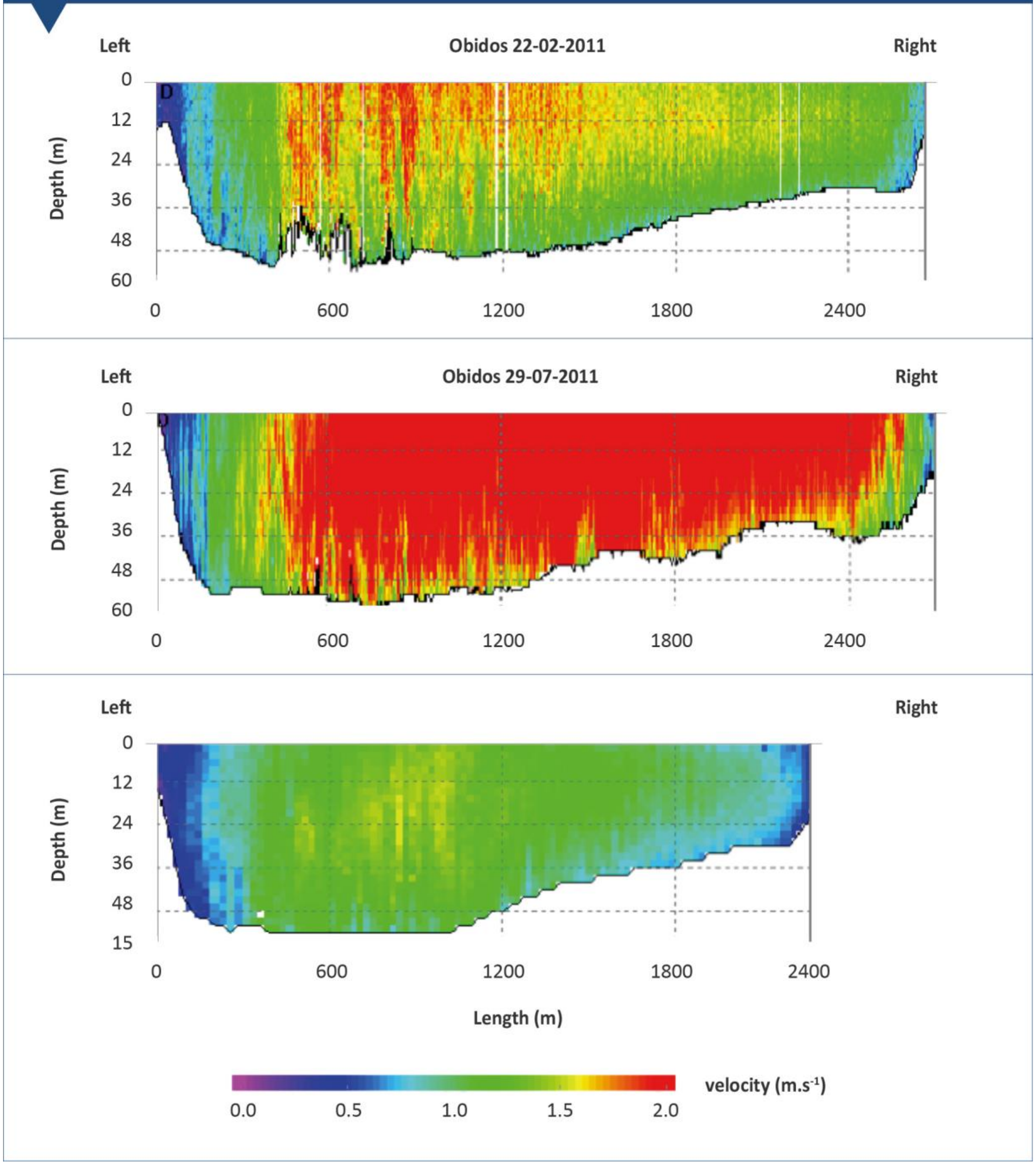

Left
Obidos 22-02-2011
Right
Depth (m)
0
12
24
36
48
60
0
600
1200
1800
2400
Left
Obidos 29-07-2011
Right
Depth (m)
0
12
24
36
48
60
0
600
1200
1800
2400
Left
Right
Depth (m)
0
12
24
36
48
15
0
600
1200
1800
2400
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0

Figure 13F.

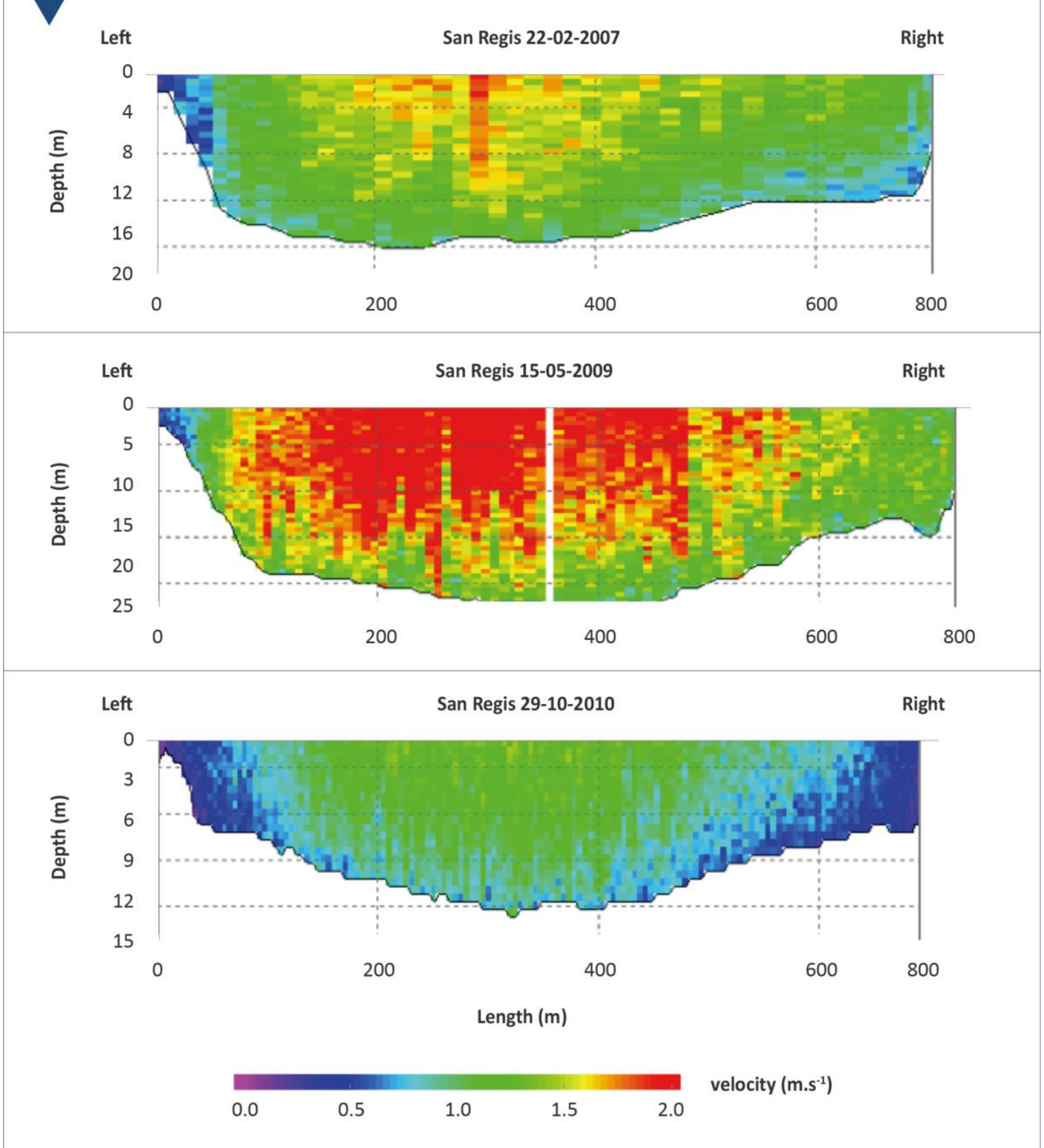

Left
San Regis 22-02-2007
Right
Depth (m)
0
4
8
12
16
20
0
200
400
600
800
Left
San Regis 15-05-2009
Right
Depth (m)
0
5
10
15
20
25
0
200
400
600
800
Left
San Regis 29-10-2010
Right
Depth (m)
0
3
6
9
12
15
0
200
400
600
800
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0

Figure 13G.

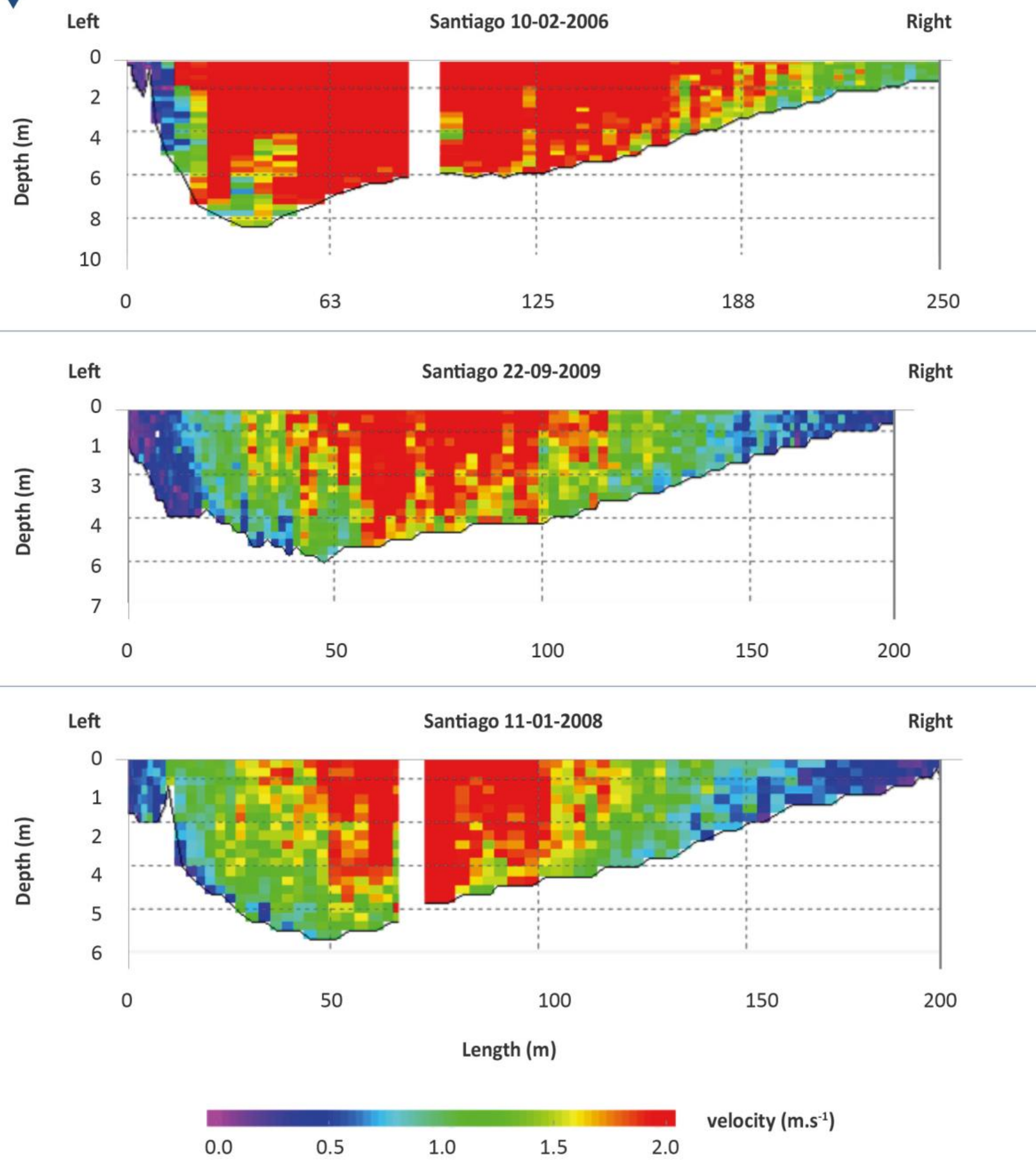
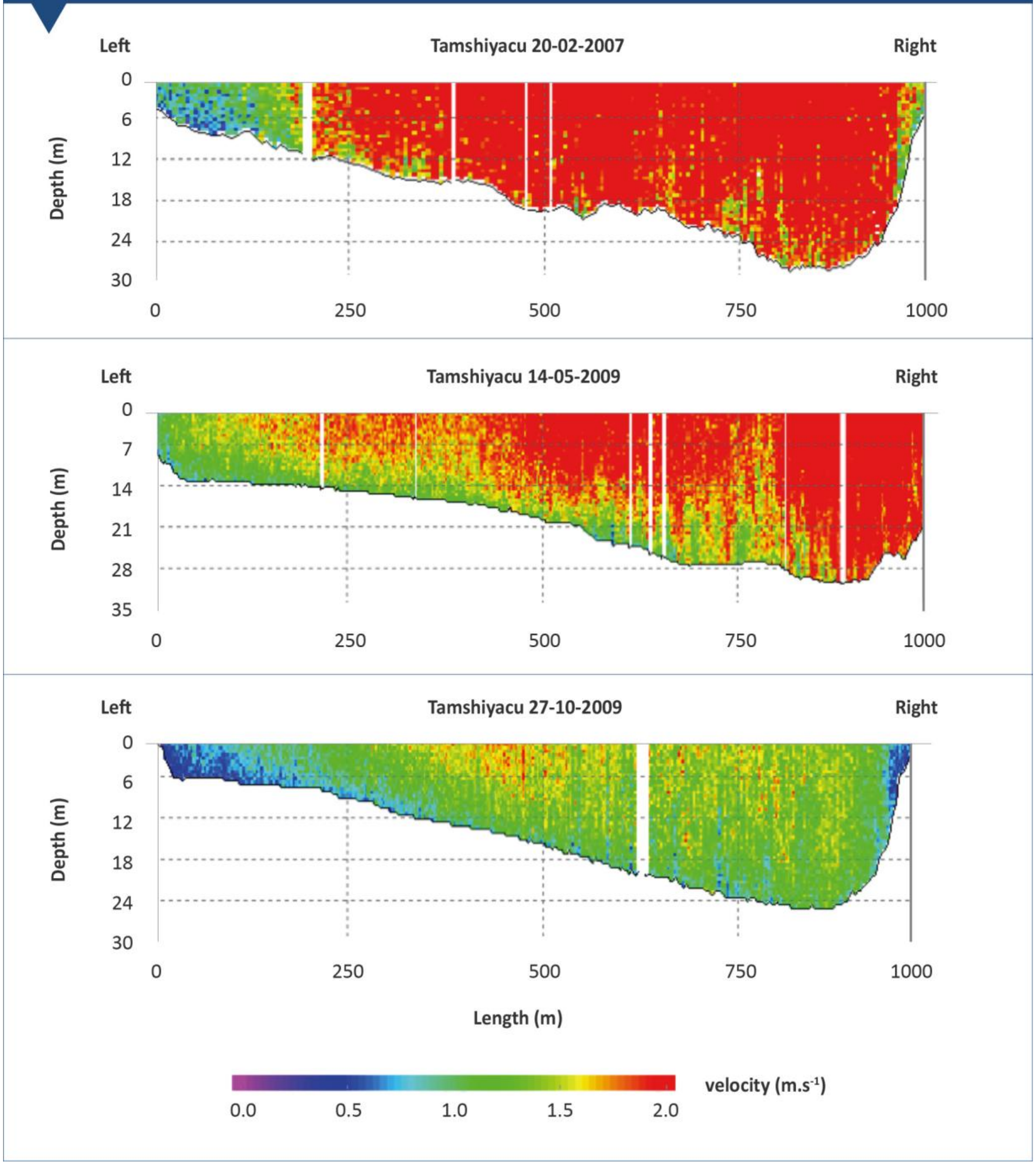

Left
Santiago 10-02-2006
Right
Depth (m)
0
2
4
6
8
10
0
63
125
188
250
Left
Santiago 22-09-2009
Right
Depth (m)
0
1
3
4
6
7
0
50
100
150
200
Left
Santiago 11-01-2008
Right
Depth (m)
0
1
2
4
5
6
0
50
100
150
200
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0

Figure 13H.


Left
Tamshiyacu 20-02-2007
Right
Depth (m)
0
6
12
18
24
30
0
250
500
750
1000
Left
Tamshiyacu 14-05-2009
Right
Depth (m)
0
7
14
21
28
35
0
250
500
750
1000
Left
Tamshiyacu 27-10-2009
Right
Depth (m)
0
6
12
18
24
30
0
250
500
750
1000
Length (m)
velocity (m.s-1)
0.0
0.5
1.0
1.5
2.0