ASSESSMENT OF MAXIMUM AND RESIDUAL HYDROPOWER POTENTIAL UNDER GLOBAL CHANGES: LA PLATA BASIN

Luigia Brandimarte [1], Maximo Peviani [2] & Ioana Popescu [1]

[1] UNESCO-IHE Institute for Water Education, The Netherlands, Westvest 7, 2601 DA Delft

2 RSE S.p.a. Research on Energy System, Italy, Via Pastrengo 9 - 24068 Seriate (BG)

E-mail: l.brandimarte@unesco-ihe.org

Abstract

Allocation and exploitation of water resources is more and more constrained by global changes: population growth, economical development, urbanization, changes in hydrological regimes and land. The energy demand and production in emerging countries is even more sensitive to the effect of the global drivers. Moreover, when these emerging countries share the fifth largest river basin in the world, then the need for assessing the maximum potential hydropower is of paramount importance. This is the case of La Plata basin, a transboundary river basin shared by Argentina, Bolivia, Brazil, Paraguay and Uruguay.

The aim of this research is to assess whether (and when) shortage and vulnerabilities in terms of hydropower generation are to be expected in La Plata basin in the next decades, taking into account the effects of economic development, population growth, land use changes and changes of cropping pattern, agricultural, industrial and infrastructure development.

The methodology proposed has focused on two aspects to reach the objectives: 1) assessment of hydropower production and electricity demand in the basin over the last twenty years (1987–2008), in order to establish growing trends for the short term, 2040; 2) computation of maximum and residual hydropower potential using the newly developed Arc-GIS based tool VAPIDRO–ASTE.

The first outcomes of this research show that La Plata Basin has high hydropower potential. About 40% of the hydropower potential is already used to produce and supply energy. Out of the remaining 60% potential, about 25% could hardly be exploited because of environmental issues or low cost/benefit ratio. Thus, the estimated residual potential hydropower is about 35% of the maximum potential hydropower calculated.

Introduction

Energy produced by hydropower has several advantages over fossil fuels (coal, petroleum, natural gas) and nuclear power (uranium): it is renewable; it has low impact on the environment; it reduces the green house emissions; it implies relatively low maintenance; it is reliable in terms of technology and it is proven over time.

Hydropower plays a vital role in more than 150 countries over the globe: according to the statistics of the International Journal on Hydropower and Dams, hydropower contributes to at least 90% of the electricity production in 23 countries and to at least 50% in 63 countries (IHA/IEA/CHA, 2000). The world's gross theoretical hydropower potential is about 40,000 TWh, of which 14,000 TWh could be used as the technical feasible hydropower potential. At present 7,000 TWh are used as economically feasible hydropower potential. Most of the unexploited economically feasible hydropower potential lays in emerging countries or countries in transition (Kurse et al., 2010).

The five countries sharing La Plata basin-LPB- are highly depended on hydroelectricity (Barros et al., 2008): 76% of the total installed capacity of power in the countries of LPB, in the year 2000, was provided by hydropower. LPB is endowed with 28% of world's water resources. This, along with its topographical distribution, contributes to the high hydropower potential that can be utilized for the increasing electricity demand due to growth of population and economic development of the five LPB countries.

However, the present hydropower production is exposed to stream flow variations due to climatic variability in the region. In addition to climatic variability, hydropower production has been limited by potential water withdrawals operated by different users such as agricultural, municipal and industrial sectors. The amount of water withdrawals are increasing with the growing population, urbanization, some factors associated with land use changes and changes of cropping pattern, agricultural, industrial and infrastructure development (OSA, 2005)

The Organization of American States (OSA, 2005) has identified that LPB has high hydropower potential due to basin characteristics and discharges. To exploit the remaining hydro potential of the basin, it is necessary to carry out a proper assessment of remaining potential. The advent of modern computation tools, such as geographical information system (GIS), remote sensing and hydrological models, can support us in the first accurate estimation of hydropower potential.

This work presents an analysis of the current hydropower production and electricity demand in La Plata Basin (LPB) and makes an analysis of the maximum and residual hydropower potential of the basin for a 30 year horizon (i.e. year 2040). Current hydropower production is estimated based on historic available data while future energy production is deduced from the maximum available water in the catchment, whereas electricity demand is assessed by correlating existing electricity demand with the estimated population growth and economic development (Popescu et al., 2012). The maximum and residual hydropower potential of the basin are assessed for the mean annual flows of the present hydrological regime (1970-2000) and topographical characteristics of the area.

Study area

La Plata Basin is the second largest river basin in South America and the fifth largest in the world with a drainage area over 3.1 million km2. Five countries -Argentina, Uruguay, Paraguay, Brazil and Bolivia- develop their daily activities within the basin borders (Figure 1).

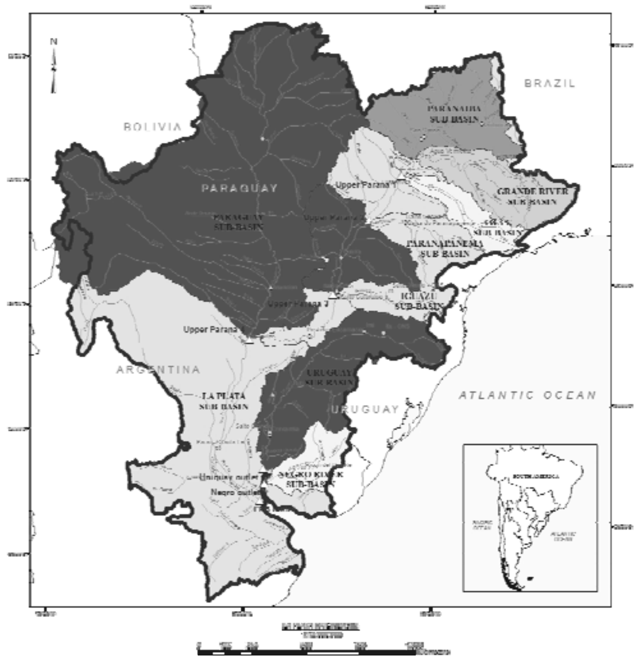

Figure 1: La Plata Basin

It has been estimated by (Barros et al., 2008) that almost 70% of the total Gross Domestic Product -GDP- of Argentina, Paraguay, Uruguay, Brazil and Bolivia is produced within the basin.

LPB has three main sub basins: Parana, Paraguay and Uruguay basins. The Parana basin is the largest of the three sub basins, in terms of drainage area, and constitutes 48.7% of the overall area of the basin followed by Paraguay and Uruguay with 35.3% and 11.8% respectively. The Parana River flows 4000 km from its source in Precambrian Brazilian Shield to its mouth in the Pampa Plain, the Paraguay River extends 2670 km southward from its sources in the western hills of the Brazilian shield to its confluence with the Parana River and the Uruguay River flows 1800 km from its source from the southern Brazil up to the Plata River. The third World Water Assessment Program of United Nation -WWAP- (WWAP-UNESCO, 2007) estimated that the population living in La Plata basin was over 100 million inhabitants in the early 2000. This represents more than 50% of the total population of the five countries sharing.

Data collection and analysis

In order to determine the maximum and residual potential of the LPB basin, different types of data were considered, such as hydrological data, population and population growth, land use practices, based on nowadays land use and predicted growth of population and economic industrial growth of the region (Popescu et al., 2012).

Natural stream water availability in the LPB basin was determined from stream flow time series data of 38 gauging stations, located throughout the LPB basin. Daily mean discharge, for a span of 80 years (1930-2010) was available for analysis. Standard deviation and Tukey's boxplot methods were used to check and filter the outliers in the data. Three homogeneity tests (i.e. Buishand Range, Pettitt and Standard Normal Homogeneity) were used as well to test further the homogeneity of data. After the elimination of the outliers in the data, all three homogeneity tests consistently showed that there is a split of stream flow time series, around the year 1970 in most of the stream flow series in LPB. It is clearly seen that the mean annual flow, of the years prior to 1970, is higher than the mean annual flow of the time series after 1970s. The explanation for this change in the hydrological regime of the catchment is due to the variation of land use pattern and deforestation after 1950s in LPB (Bartle, 2002; Collischonn et al., 2001; Garcia and Vargas, 1998).

This analysis pointed out that only the last 40 years of data should be used for the study and for prediction of the potential hydropower availability in the basin.

Population data in the LPB was gathered from the published census of the LPB countries (ISA, 2010; INDEC, 2011), as well as data for the GDP (FAOSTAT, 2011).
Data on land use, in year 2010, was downloaded from the (FAOSTAT, 2011).

Assessment of LPB maximum and residual potential hydropower

VAPIDRO-ASTE

In order to assess the potential hydropower an analysis of the past hydrological regime in the catchment for the last 70 years was made. Based on the hydrological regime in the catchment and on the physical characteristics of it, the potential hydropower of the basin was assessed by means of the GIS based tools Vapidro-Aste.

Finally, future energy demand in the basin was estimated by regression analysis on the historical data.

VAPIDRO-ASTE is a GIS integrated numerical tool (the software is developed in Visual Basin language and integrated with ARCGIS 9) that allows the evaluation of the residual potential hydropower energy and all possible alternatives concerning the sites for hydroelectric plants along the drainage network, taking into account the relationship between the full costs of the hydropower and the benefits from selling the generated power in the national market. The tool takes into account the current water resources exploitation with its geographical location and elevation (with respect to irrigation uses, drinkable water, existing hydropower plants, etc.) and the limitation that this creates regarding the potentiality for energy production. Based upon a user friendly graphical interface the tool is able to split the river into hundreds of cross sections and to calculate the available discharges and potential hydropower production, considering constrains like minimum flow, withdrawals and restitutions scheme.

A brief overview of the equations applied to compute maximum potential and residual hydropower is outlined here, for a comprehensive description of the methods applied by VAPIDRO-ASTE to compute maximum potential and residual hydropower the reader is invited to check Alterach et al. 2008 (a and b).

The maximum potential hydropower establishes the theoretical top of energy that the study basin can produce assuming that all water resources are used to produce energy, which in real life application does not occur, because of environmental flows, other water uses and economic cost/benefit analysis.

The potential hydropower in a given point of the river basin, with respect to the basin outlet section, has been computed with the following equation:

$$E_{own\_\max_i} = Conv \times g \times \eta \times (A_i \times p_i \times cd_i)(H_i - H_{closure}) = = Conv \times g \times \eta \times Q_i \times (H_i - H_{closure}) \quad (1)$$

where: *Conv* is an adimensional conversion factor, to calculate energy in GWh (*Conv* = 0.00876); g the gravity constant ; η the overall electrical efficiency, which depends on kind of turbine, generator, transformers and/or electrical transmission, water conductors, etc; Q_i the basin discharge; H_i the elevation of the given elementary area *i*; $H_{closure}$ the elevation at closure point.

Thus, the potential of the entire watershed is given as the sum of the contributions of the N elementary areas that create the river basin itself:

$$E_{own\_\max} = Conv \times g \times \eta \times \sum_i^N [(A_i \times p_i \times cd_i)(H_i - H_{closure})] \quad (2)$$

If the river basin is seen as a physical entity, as a first approximation, it can be assumed that each basin has a unique constant precipitation (*p*) and runoff coefficient (*cd*), uniformly distributed in the elementary areas. This means then that $p_i = p$ = constant and $cd_i = cd$= constant.

The above equation (2) can then be expressed, in terms of mean watershed elevation, as:

$$E_{own\_\max} = Conv \times g \times \eta \times Q \times (H_{mean} - H_{closure}) \quad (3)$$

The residual annual potential hydropower related to a given watershed (E_{own_res}), without considering upstream flow contributions, can be calculated, accounting for the Minimum Instream Flow (E_{own_mif}) and the actual withdrawals (E_{prel}), as follows:

$$E_{own\_res} = E_{own\_mif} - E_{prel} \quad (4)$$

where:

$$E_{own\_mif} = Conv \times g \times \eta \times (Q - MIF_{aff}) \times (H_{mean} - H_{closure}) \quad (5)$$

being MIF_{aff} the Minimum Instream Flow computed as 10% of the *Q*

and

$$E_{prel} = Conv \times g \times \eta \times \sum_j^n [q_{j\times}(h_j - H_{closure})] \quad (6)$$

where q_j represents the mean annual withdrawals from the given watershed (+ positive)

or the restored flows to the given watershed (- negative) in a particular point "j" and hj is the elevation over sea level of the "j" sections where the flows are taken or restored

LPB Population growth analysis

From the census of the years 1980 up to 2010, the population growth of LPB, and its estimation for the year

2040 was analyzed using Exponential and Logistic growth models. After determining the population growth model of each of the LPB country, the estimation of the expected population in 2040 could be determined. For each country the percentage of population which leaves in the LPB basin was determined and the population of the entire basin was determined. Table 1 shows the prediction for the population in the LPB, per country, every 10 years, from 2010 (collected data from census) till 2040.

Table 1: Estimated population

Country	Estimated population			
	2010	2020	2030	2040
Argentina	26,197,439	27,436,096	28,289,833	28,863,087
Bolivia	1,782,806	2,008,099	2,261,862	2,547,693
Brazil	84,265,841	94,754,936	105,244,030	115,733,124
Paraguay	7,085,714	9,149,932	11,733,657	14,917,630
Uruguay	2,969,506	2,977,566	2,982,178	2,984,813
Total	122,301,305	136,326,627	150,511,560	165,046,347

Agricultural water withdrawal

Agricultural water withdrawal (AWW) depends on the water requirements for irrigation, which varies depending on the land use. Moreover, the change in land use over the years is very important in order to determine future agricultural water requirements. While analyzing the land use pattern of the last three decades, 1980-2010, it can be noticed that there is a significant change of cultivation of crops and deforestation (Barros et al., 2008) which result in variations in the annual water demand for agriculture. For each country of the LPB future water requirements were determined, by analyzing the main crops of the countries, such as rice, sunflower, maze, soybean, sorghum, wheat, cassava and sugarcane (Statistical Yearbook for Latin America and the Carribbean CEPALSTAT 2010). Most of the cultivations in LPB are done using rain water; therefore irrigation water requirements will be significantly small when compared with the actual water requirement. The necessary irrigation water requirements (IWR) for each crop was computed and correlated with the nowadays measured agricultural water withdrawal (AWW). Based on this correlation, the future AWW, for each country in LPB was estimated as:

$$AWW = a + \sum_{i=1}^{n}(bIWRC_{i1} + cIWRC_{i2}) \qquad (7)$$

where *a, b, c* are coefficients, *IWR* Ci_1- Irrigation water requirement for a certain crop I and *IWR* Ci_2 - Crop i water requirement times percentage of the irrigated area and n the number of considered crops. Table 2 indicates the total estimated AWW in LPB, by country.

Table 2: Estimated agricultural water withdrawal

Year	Agricultural water withdrawal (10^9 m^3/yr)				
	Argentina	Bolivia	Brazil	Paraguay	Uruguay
2010	16.99	0.87	31.24	0.36	3.73
2020	20.86	0.93	36.84	0.37	4.43
2030	24.72	0.98	42.44	0.38	5.13
2040	28.58	1.04	48.04	0.39	5.84

Municipal water withdrawal

Municipal water withdrawal (MWW) increases with the population growth. Population growth correlated with the historic MWW is used in order to estimate the future MWW in LPB:

$$MWW = (a + bPG) \qquad (8)$$

where *a, b* are coefficients and *PG* is the population correlated to the municipal water withdrawal.

Table 3 shows the estimated MWW in LPB for each country of the basin.

Table 3: Estimated municipal water withdrawal

Year	Municipal water withdrawal (10^9 m^3/yr)				
	Argentina	Bolivia	Brazil	Paraguay	Uruguay
2010	3.93	0.05	5.37	0.13	0.08
2020	4.42	0.06	5.98	0.17	0.09
2030	4.91	0.07	6.65	0.22	0.09
2040	5.40	0.09	7.37	0.26	0.10

Industrial water withdrawal

Industrial water withdrawal (IWW) depends on factors such as product type, demand for product, rate of production, however when these type of data are not available, population growth and economic development can be used for assessing future IWW. The IWW is expressed by:

$$IWW = a + bPG + cGDP \qquad (9)$$

where a, b, c are coefficients, PG is population growth and GDP is the Gross Domestic Product.T he estimated IWW, for the year 2040 is given in Table 4.

Table 4: Estimated Industrial water withdrawal

Year	Industrial water withdrawal (10^9 m^3/yr)				
	Argentina	Bolivia	Brazil	Paraguay	Uruguay
2010	2.30	0.10	8.62	0.05	0.04
2020	2.67	0.14	9.70	0.07	0.05
2030	3.04	0.18	10.67	0.08	0.06
2040	3.41	0.24	11.54	0.09	0.07

Electricity demand of LPB on 2040

The electricity demand (ED) of the LPB countries, in the year 2040, is dependent on the population growth and economic development of the region. The consumption of electricity increases with the population growth and also there is a need for more energy (electricity) for the industrial development which contributes to the economic development.

Per Capita Gross Domestic Product (GDP) was used as an indicator to measure the economic development in each LPB country. The existing GDP product variation in each LPB country was analyzed and future GDP was estimated based on the present trend.

The relation that gives the ED for year 2040 is:

$$ED = (a + bPG + cGDP) \tag{10}$$

where a, b, c are coefficients, determined from the hystorical data, PG is the population and GDP is the gross domestic product. The computed ED is plotted in Figure 2, for all five countries of LPB, up to year 2040.

Determination of hydropower potential of the LPB basin using Vapidro-Aste tool

The maximum available hydropower potential of the LPB basin is determined using the Vapidro Aste 2.0 GIS integrated tool. The basin scale analysis is a theoretical concept which determines the available maximum hydropower potential of a river basin based on the natural available hydrological regime and the topography of the catchment, whereas, the reach scale does the same analysis at a smaller scale.

The residual hydropower potential expresses the hydropower potential of a basin after taking into account all water withdrawals (AWW, MWW, IWW) and the Minimum Instream Flow (MIF) determined from the natural available hydrological data.

Two types of Vapidro-Aste models have been developed: 1) first models for estimating the maximum hydropower potential, where no withdrawals were considered, were built, and 2) secondly models for estimating the residual hydropower potential, where all future potential water withdrawals from the basin were considered.

The maximum and residual hydropower potential was computed for 0% and 10% of the idrological flow as MIF respectively. The overall efficiency factor for the generation of energy was selected to be 70% and loss coefficient for the transformation of gross head in net head as 0.05. In case of power generation, hydraulic machine efficiency was selected as 80% and transmission coefficient between average seasonal maximum discharge and instant discharge was selected as 1.5.

The LPB was divided into 66 sub-basins, based on measured stream flow data availability. These 66 sub-basins cover the entire LPB basin taking into account all the main rivers (Parana, Paraguay, Uruguay, Grande, Tiete, Paranapenama, Ivai, Iguacu, Paraniba, Picomayo, Bermejo,Negro) and main tributaries. The flow data which determined this division are located at the gauging stations and forms the outlets of the sub-basins.

The models main assumption is that there are no diversion structures along the river reaches. The model splits the stream into a number of cross sections based on the selected distance between two adjacent cross sections and computes the power and energy available at each cross section. A distance of 50m was selected for all the models except for the Parana, Paraguay and Uruguay main rivers, where distance was selected to be 250 m.

Results and discussion

The maximum and residual hydropower potential of the LPB at river reach scale are 354,134 MWh and 307,034 MWh respectively, whereas at the basin scale, these are 829,202 MWh and 715,602 MWh respectively (Popescu et al., 2012).

An analysis of the 2040 hydropower production, electricity demand, and maximum and residual hydropower potential together shows to what extend hydropower can contribute for the energy supply in LPB. Figure 2 shows the results obtained in the present research in comparison with other existing researches in LPB basin, carried out within the EU-FP6 project CLARIS -LAB, where upper and lower limits for electricity demand in LPB were determined.

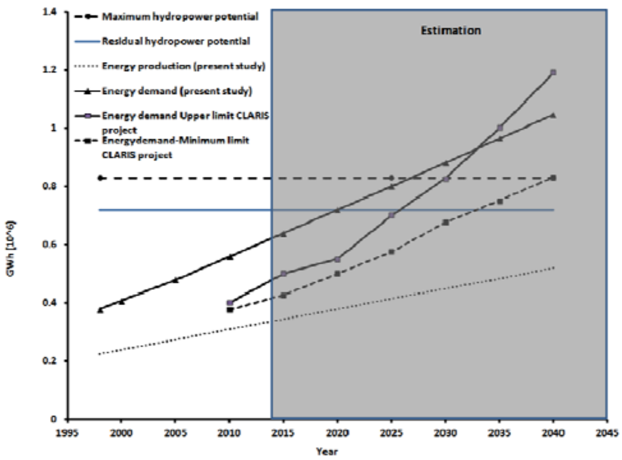

Figure 2: Potential energy in LPB

The analysis shows that the present hydropower production is below the electricity demand of LPB. The gap between residual hydropower potential at basin scale and the hydropower production is the remaining hydropower potential that can be utilized to supply the future electricity demand in LPB. As the electricity demand in LPB in short term is higher than the maximum hydropower potential at basin scale, hydropower cannot supply the total electricity demand in LPB in short term, clearly there is a need for other sources of energy in order to meet the energy demand of the LPB basin.

In case of hydropower production and electricity demand, nowadays (year 2010) hydropower production is 309,503 GWh and the electricity demand is 557,597 GWh, therefore, hydropower contributes 55.5% of the total electricity demand of LPB. By 2040, the estimated hydropower production and estimated electricity demand will be 523,078 and 1,045,054 GWh respectively, and hydropower will be able to contribute to this demand only with 50.4% of the total electricity demand. There is a clear need to increase the hydropower production or look into other sources of energy to supply the demand.

Conclusions

There is a worldwide concern to get the maximum use of renewable sources, especially hydropower to supply the increasing energy demand. In this regard, in order to predict the energy demand and availability for the expected future socio-economic developments of the five fast growing countries sharing La Plata basin, we used a GIS-based tool to assess maximum and residual hydropower potential in the basin, taking into account energy losses, due to different water withdrawals.

The main outcomes of this study can be summarized in the following points: 1) there is unexploited hydropower potential in LPB; 2) for the assessment of maximum and residual hydropower potential at river reach scale, the present study considered only 66 streams of LPB, however there are many unaccounted streams which could be used for the hydropower generation on a small scale; 3) the basin has more hydropower potential than the estimated maximum and residual hydropower potential at river reach scale.

References

Alterach J., Peviani M., Davitti A. & Vergata M. (2008a). *Evaluation of the residual potential hydropower production in Italy*. Cesi Ricerca SpA, Milano, Italy.

Alterach J., Peviani M., Davitti A., Vergata M. & Elli A (2008b). *A GIS integrated tool to evaluate the residual potential hydropower production at watercourse scale*. Cesi Ricerca SpA, Milano, Italy.

Barros, V., Clarke, R., Silva Dias, P. (2008). Climate change in the La Plata Basin. SGA II 057; Inter American Institute on Global Change (IAI). Buenous Aires.

Bartle, A. (2002) Hydropower potential and development activities. *Energy Policy* 30: 1231-1239 DOI Doi: 10.1016/s0301-4215(02)00084-8

Collischonn, W., Tucci, C. & Clark, R. (2001). Further evidence of changes in the Hydrology regime of the Paraguay River. *Journal of Hydrology*, 245:218-238.

Food and Agricultural Organization of the United Nations (FAO), (2011). http://www.fao.org/nr/water/aquastat/dbase/index.stm last accessed online December 2011

Garcia, N.O. & Vargas, W. (1998). The temporal climatic variability in the Rio de la Plata Basin displayed by the river discharges. *Climatic Change Journal*, M., l8 (3), pp. 359-379.

International Statistical Agencies (ISA) (2010). Censuses Bureau. www.census.gov/aboutus/stat_int.html. Last accessed online on December 2011

IHA/IEA/CHA (2000). Hydropower and the World's Energy Future. White Paper published by the International Hydropower Association, the International Energy Agency—Implementing Agreementon Hydropower, and the Canadian Hydropower Association.

Kusre, B.C., Baruah, D.C., Bordoloi, P.K., & Patra, S.C. (2010). Assessment of hydropower potential using GIS and hydrological medeling techniques in Kopili basin in Assam (India). *Applied Energy*, 87, pp. 298-309.

National Institute of Statistics and Censuses (INDEC) (2001). www.indec.mecon.ar/indec/ingles.asp. Last accessed online on December 2011

Organisation of American States (OSA) (2005) La Plata basin: A framework for the sustainable management of its water resources with respect to the hydrological effects of climate variability and change. Organization of American States, Water project series, November 6 - October 2005. 1-2

Popescu, I., Brandimarte, L., Perera, M.S.U. & Peviani, M. (2012, under review). Assessing residual hydropower potential of the La Plata Basin accounting for future user demands. *Applied Energy*.

Statistical Yearbook for Latin America and the Carribbean CEPALSTAT http://website. eclas.cl/anuario_estadictico/anuario_2010/eng/index.asp Cited January 2011