The Water Footprint of Hydroelectricity in Santa Catarina State - Southern Brazil

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1. INTRODUCTION

Population growth and the substantial expansion of industrial activities and irrigation over recent decades have triggered substantial increases in the demand for water across the world. As a result water scarcity has rapidly spread across several areas, and satisfying human demands for this resource while maintaining its ecological support functions has been deemed to be one of the most difficult and important challenges of the 21st century (Postel, 2000). Some regions of Brazil, a country generally acknowledged for its abundant water resources, have faced severe droughts in recent years, leading to losses in the industry and agriculture and rationing in public water supplies.

Such a context has led to a heightened level of awareness and public demand for optimal management of water resources. The thorough consideration of all water uses is a key aspect for this aim to be achieved. Energy generation, and more specifically in-stream dams for hydroelectricity production, have traditionally been considered a non-consumptive water use in Brazil (ANA, 2013), despite a contrasting point being made at the international level (IEA, 2012, IPCC, 2012). Although the design and operation of dams generally accounts for evaporation losses in reservoirs (ONS, 2004), these are seldom – if ever – considered in the context of water resources planning and management on a river basin level.

In Brazil, annual grid electricity consumption is expected to rise from 473,395 GWh in 2014 to 693,469 GWh in 2024, an average annual increase of 3.9% (EPE, 2015). Large hydropower plants (with an installed capacity above 30 MW) are the country's main source of electricity, comprising approximately 64.87% of the generation in 2015 and 67.76% of the future installed capacity of facilities under construction as of February 2016 (ANEEL, 2016a). The southern State of Santa Catarina presents a similar pattern, where hydropower corresponds to 70.39% of the total installed capacity of 4,572.105 MW – these figures are even higher when considering some large facilities located in the border with the neighboring state of Rio Grande do Sul.

Internationally, the burden of electricity generation on water resources has been widely recognized, often in the context of what is called the water-energy nexus, which has been discussed in several publications (Cooley *et al*, 2011, IEA, 2012, Rodriguez *et al*, 2013). However, it was only after the publication of the "Special Report on Renewable Energy Sources and Climate Change Mitigation" by the Intergovernmental Panel on Climate Change (IPCC, 2012) that the impact of hydroelectricity on the downstream availability of water resources began to receive considerable attention by the academia. The main reason for that is deemed to be the wide range of estimates on water consumption per unit of energy generated by hydropower plants, and the fact that some of such figures placed it substantially above all other power sources – including thermal, nuclear and biomass.

Due to the significant disparities in size and layout between hydroelectric facilities, there has been considerable debate over the method to be adopted in order to normalize their associated water consumption. Mekonnen and Hoekstra (2012) employed the Water Footprint concept, which has been proposed as a general approach to standardize the allocation of water resources to human activities in order to allow for comparison between alternatives (Hoekstra *et al*, 2011). The authors adopted a formula that consisted on the division of the annual estimated volume of water losses through evaporation in reservoirs by their respective energy outputs in that period, yielding a wide range of figures that spun from 0.3 m^3GJ^{-1} to 846 m^3GJ^{-1} (Mekonnen & Hoekstra, 2012).

Considering the scenario previously exposed, the current study aimed to provide estimates of the water footprint of hydroelectricity generation in the state of Santa Catarina, Brazil. The methodology proposed by Mekonnen and Hoekstra (2012) was adopted, as explained in the following section.

2. METHODS

2.1. Study Area and Site Selection for Meteorological Stations and Hydropower Facilities

The state of Santa Catarina is located within the geographic coordinates 25°57'41" S to 29°23'55" S and 48°19'37" W to 53°50'00" W, and comprehends an area of approximately 95.346,181 km^2 (Santa Catarina, 2007). According to the Köppen classification, there are two predominant climate types in the state: Cfa and Cfb. The average annual rainfall is 1,300 mm, ranging from approximately 855 mm in the South to 2,174 mm in the Northern region of the state (Santa Catarina, 2007).

In the methodology proposed by Mekonnen and Hoekstra (2012), electricity generation is the basis by which the water footprint of hydroelectricity is normalized. – see Eq. (1) in section 2.2. Monthly power generation for most large-scale electricity-generation facilities in Brazil is publicly disclosed through the country's Electricity Regulatory Agency (ANEEL, 2016b). The spatial scope of the current study comprised all the facilities located within or at the borders of the state of Santa Catarina for which such data is available. Monthly energy output data series were available for nine hydropower stations according to the period each one was commissioned, but limited to the earliest date of January 1994. Each power plant was allocated a weather time series from the nearest station, as illustrated in Figure 1.

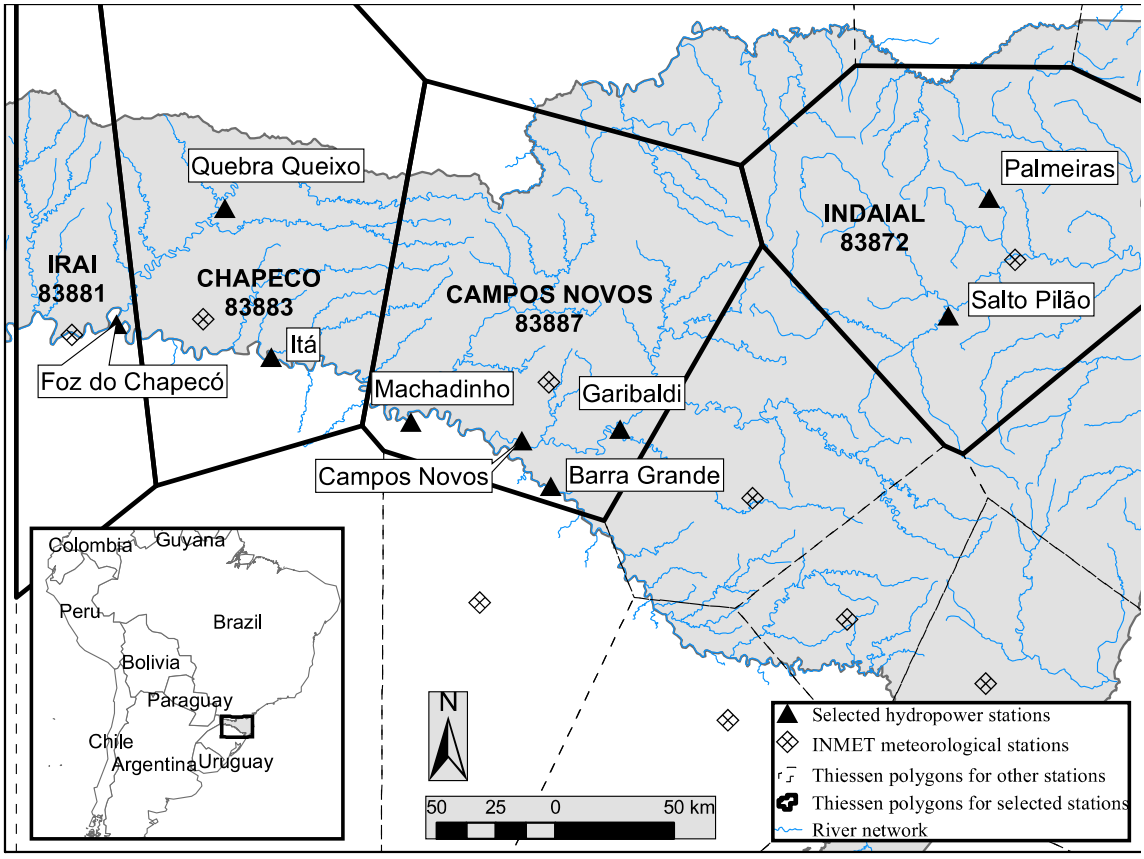

Figure 1 State of Santa Catarina and the locations of selected hydropower plants and weather stations with respective WMO codes.

2.2. Water Footprint Estimation for Hydroelectricity

The current study adopted the water footprint formula for hydroelectricity proposed by Mekonnen and Hoekstra (2012), according to which:

$$WF = \frac{WE}{EG} \quad (1)$$

where WF is the water footprint (m^3 GJ^{-1}), WE is the volume of evaporated water (m^3 $month^{-1}$) and EG is the electricity generated (GJ $month^{-1}$). It is important to clarify that the aforementioned work adopted a yearly time step in its calculations. However, studies have demonstrated that there is considerable fluctuation in the evaporation and power output – and, hence, of the water footprint – values along different months for a given facility (Yesuf, 2012 as cited in Bakken *et al*, 2013). Therefore, a monthly time step was adopted for the current study in order to verify such fluctuations within the state of Santa Catarina.

2.3. The Complementary Relationship and the WREVAP Algorithm

The estimation of gross evaporation rates in reservoirs is a crucial parameter for the determination of the water footprint of hydroelectricity, regardless of the chosen calculation approach. Since the mid-twentieth century several methods for the estimation of evaporation on water surfaces have been proposed. Bouchet (1963) pondered that in relatively extensive and homogeneous areas where there is reduced heat and humidity transportation through advection, there is a feedback loop between soil and air moisture. This phenomenon translates into a reciprocal regulation pattern between real and potential evapotranspiration, and was coined the "oasis effect".

Morton (1983) proposed the concept of the complementary relationship. According to the theory, a decreasing water content in the soil will incur in declining humidity in the air and therefore in a rise in potential evaporation (PEV). However, the lower water availability for evaporation means that the actual evaporation (AEV) figure will likely be significantly inferior to that of the PET. In this sense, the drier the soil, the drier the air above it, the higher the PET and the lower the AET, and one equals the other when the soil is saturated.

The Complementary Relationship Lake Evaporation (CRLE) algorithm was devised by the same author in order to account for water body heat storage and temperature and salinity gradients though linear routing (Morton, 1986). Such a process was employed by McMahon *et al* (2013a), who made it available as a Fortran code and as an executable file (McMahon *et al*, 2013b) – the WREVAP algorithm. The required input data for the program involves site characteristics (latitude, elevation and average annual rainfall) and monthly time series (average air temperature, average air humidity and average daily sunshine hours). Specifically for deep lake evaporation, average depth and salinity are also required.

The Brazilian Electric System National Operator (ONS, 2004) has published a study which aimed to estimate average monthly evaporation values for all major Brazilian hydropower plants, based on average climate data for several locations estimated between the years 1961 and 1990. The SisEvapo system, which incorporated the algorithms proposed by Morton, was developed for that purpose. Some of the advantages of the CRLE involve the relatively small amount of required input data and the possibility to apply it to varying contexts without the need for locally optimized coefficients (Morton, 1983). These facts, together with the possibility of validating generated estimates against those of the ONS (2004), have led to the adoption of the CRLE model – through the WREVAP executable file developed by McMahon et al (2013b) – for the estimation of monthly evaporation figures.

Time series data of weather parameters were retrieved from the website of the Brazilian National Institute of Meteorology (INMET, 2016). All stations located in Santa Catarina and in the adjoining states of Rio Grande do Sul (to the south) and Paraná (to the North) were considered. Each power plant was matched to the closest weather station for which data was available. Gaps in the time series were replaced by the respective average values for the given months over the time period spanning from January 1994 to January 2016. Figure 1 illustrates the distribution of the hydropower stations considered in the current study and the weather stations for which time series data was available. Thiessen polygons were drawn in order to illustrate the area of influence of each station and the power plants located within the respective perimeters. Four weather stations were adopted, as indicated in

Elevation and average lake depth data were retrieved from Environmental Impact Assessment Reports, contracts involving leases for the generation of electricity, the websites of companies or personal communication. Due to the lack of monitoring of salinity data and to the fact that freshwater in Brazil generally contains 0 to 0.5 ppm of salts, the value for this parameter was set to 0.25 ppm for all reservoirs.

3. RESULTS AND DISCUSSION

AET values estimated through WREVAP were compared to those generated though SisEvapo by the ONS (2004), which was also based on the complementary relationship. Although average annual values were significantly close, there is an apparent lag between monthly values. While the evaporation figures generated by SisEvapo followed closely the predictable seasonal behavior, the monthly values estimated though WREVAP indicate higher evaporation rates in late fall and winter, when air temperatures and insolation are lower than in

summer months. This difference may be explained by the linear routing heat storage model embedded in the CRLE algorithm (Morton, 1986). Figure 2 illustrates such pattern for the specific case of the Itá power plant reservoir, where the average depth is 36 m.

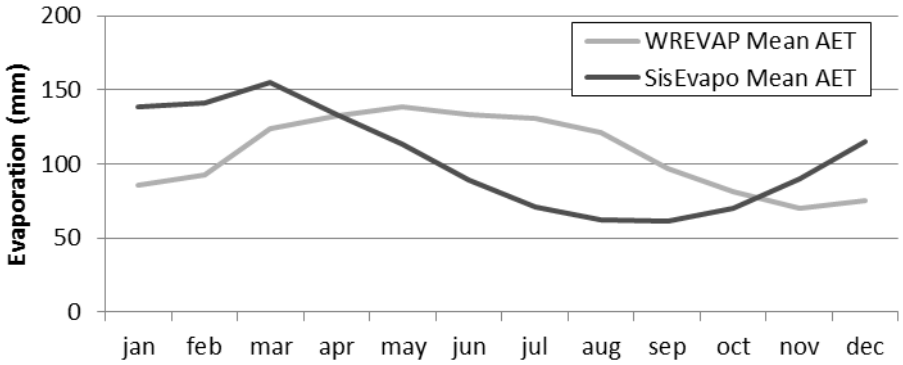

Figure 2 Mean monthly actual evaporation (AET) values estimated by WREVAP and SisEvapo (ONS, 2004) for the Itá dam.

Despite the considerable monthly variation in evaporation values, the power outputs from power plants tend to involve much greater disparities and do not follow a seasonal pattern, as represented in Figure 3.

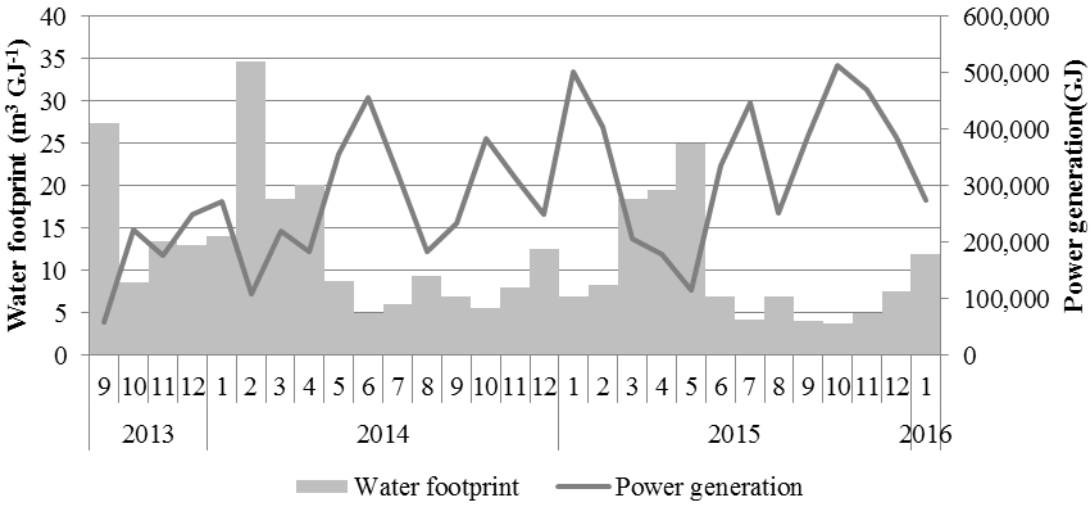

Figure 3 Monthly power generation and estimated water footprint values for the Garibaldi plant.

The distribution of monthly water footprints for the selected power plants is summarized in Figure 4. It can be noticed that there are major discrepancies between monthly values for any given plant, justifying the need for the adoption of a monthly time step instead of a yearly one. Furthermore, there are significant differences between the estimated average water footprints between facilities, which did not appear to bear any relationship to their installed capacity.

The figures presented in Figure 4 indicate relatively low water footprint values in comparison to those estimated by other authors – especially for other dams located in Brazil, for which Mekonnen and Hoekstra (2012) found values between 14.4 and 399 m^3GJ^{-1}. Authors studying individual hydropower plants in Southeastern Brazil estimated values of 126 m^3GJ^{-1} (Bueno, 2014) and 56.9 m^3GJ^{-1} (Ferreira, 2014).

In this context, attention should be drawn to the Salto Pilão plant. Despite having approximately the same installed capacity of the Garibaldi plant, the Salto Pilão Station requires a flooded area of 0.15 km^2 (Consórcio Empresarial Salto Pilão, 2016), which corresponds to 0.56% of the area for the Garibaldi station. As a result, its water footprint is nearly two scales of magnitude lower than that of other stations with higher and lower installed capacity. Such a finding goes in line with the findings of Gleick (1992), who asserted that the type of facility is normally more relevant to its relative environmental impact than its installed capacity.

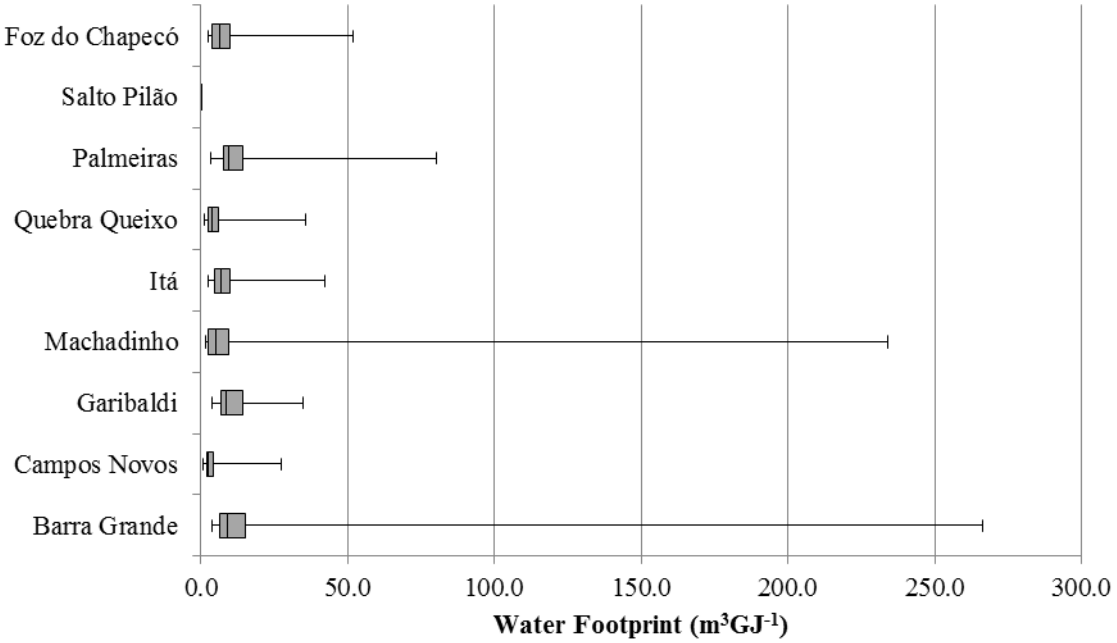

Figure 4 Distribution of water footprint values for selected hydropower plants.

4. CONCLUSIONS

The current study aimed to provide estimates of the water footprints associated with most large-scale hydropower facilities within the Brazilian state of Santa Catarina. The WREVAP algorithm, based on Morton's complementary relationship was used to generate deep lake evaporation figures. Despite the relative proximity to the mean annual estimates from the ONS (2004) significant variation in monthly evaporation and power output values – and, hence, of the water footprint – provides support for adopting a monthly time step for such estimates.

Despite the considerably large range of mean water footprint estimates between facilities, such values were generally low in comparison to those reported for power plants in other locations, and particularly in other regions of Brazil. This finding may be linked to the comparatively higher latitude of the state of Santa Catarina, which translates into less incoming radiation and generally lower average air temperature above reservoirs, resulting in lower rates of evaporation. However, it has been observed that the electrical power output tends to present considerable variation between months, having a fundamental effect on water footprint estimates.

The figures presented in this study do not indicate significant correlation between the size of hydropower plants – in terms of reservoir area or installed capacity – and their respective water footprints. However, it has been noted that a power plant with a very low dam height / gross static head relationship is associated with a comparatively extremely low impact in terms of water footprint, which is in accordance with the findings of Gleick (1992).

It should be emphasized that there is currently no consensus over the most appropriate method for estimating the water footprint of hydroelectricity. Therefore, the results presented in the current study are tied to the formula adopted by Mekonnen and Hoekstra (2012), and would likely differ significantly if considerations made by other authors were taken into account (e.g. the incremental flooded area in place of the gross reservoir area, net evaporation instead of gross evaporation, etc.). The scope of this study was constrained by the lack of data availability regarding reservoir properties and electricity generation of smaller facilities. Consequently, the monitoring and disclosure of such data will allow the estimation of the water footprint of a considerably larger amount of power plants. Finally, it is relevant to recap that there are numerous other factors that comprise the overall environmental impact of power plants, and that should also be carefully assessed by decision-makers.

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