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Water-Electricity nexus in Ecuador: The dynamics of the electricity's blue water footprint

S. Vaca-Jimenez, P.W. Gerbens-Leenes, S. Nonhebel

Abstract

Freshwater has spatial and temporal constraints, affecting possibilities to generate electricity. Previous studies approached this from a water perspective quantifying water consumption of electricity to optimize water use, or from an electricity perspective using modeling methods to optimize electricity output. However, power plants consume different water volumes per unit of electricity, depending on the applied technology, and supply systems often include a mix of different technologies with a different water footprint (WF), an indicator of water consumption, per unit of electricity. When water availability varies in time, probably the contribution of different electricity generating technologies also varies in time, resulting in WF fluctuations. Focusing on electricity generation from the water perspective, we assessed how water availability affects an electricity mix's dynamics and its blue WF using Ecuador as a case study. We studied the Amazon and Pacific basins, which have different temporal and spatial water availability fluctuations, assessing monthly water availability, electricity production, and blue WFs per plant. The Amazon basin has smaller temporal and spatial availability fluctuations than the Pacific. The difference between the largest and smallest water availability in the Amazon basin is two-fold, in the Pacific four-fold. Hydropower generation in the Amazon basin contributes more than 60% to the electricity mix. However, hydropower is directly affected by water availability, and its production decreases in water-limited periods. For biomass plants, limited water availability affects the fuel source, sugarcane bagasse. As water availability decreases, other technologies in the mix take over, causing WF variation (from 4.8 to $8.6 \cdot 10^3 \text{ m}^3$ per month). Usually, less water-availability means more water-efficiency, implying fossil-fueled plants in the Pacific take over from hydropower in the Amazon. It is relevant to assess the water-electricity nexus in countries with electricity mixes dominated by hydropower because energy planning needs to consider water availability and electricity mix dynamics.

Keywords

Water-energy nexus; water footprint; water availability; electricity generation; mix dynamics; hydropower

Glossary

BPP: Solid Biomass power plant

DC: Dry cooling system

GHG: Greenhouse gases

HPP: Hydropower plant

NC: No cooling system

OT: Once-through cooling system

OWS: Open water surface

PP: Powerplant

ROR: Run-of-the-river

TPP: Fossil-fueled Thermal Power Plant

WF: Water Footprint

WT: Wet-tower cooling system

1. Introduction

The global electricity sector is aiming to transition from fossil to renewable sources of energy to reduce GHG emissions (Edenhofer et al., 2014; IEA, 2019; IRENA, 2014; The World Bank, 2019). Renewable sources of energy include traditional renewables (hydropower plants, *HPPs*, and solid biomass, *BPPs*), and non-traditional renewables (e.g., solar, wind, biogas, geothermal and tidal energy). Traditional renewable technologies for electricity generation have many advantages in relation to fossil-fueled technologies (e.g., reduced GHG emissions and pollution), and to non-traditional renewables (e.g., larger storage capacities, technology maturity and costs) (Feng et al., 2019b; IEA, 2016; IRENA, 2014). However, they are usually water-intensive, with larger consumptions than fossil-fueled thermal power plants (*TPPs*), and non-traditional renewable technologies, like solar or wind energy (Meldrum et al., 2013). Previous studies, e.g., Gleick (1994), Larsen and Drews (2019),

Macknick et al., (2012) and Meldrum et al., (2013), have assessed average, annual water consumption by power plants in volumes of water per unit of electricity from a static point-of-view for benchmarking purposes. However, power plants' operations are not static but vary over the year. Several factors, including water availability, an important constraint for electricity generation, make their operations dynamic, and thus their water consumption is also dynamic. To define water consumption, many studies used the water footprint (WF) tool to quantify water consumption, estimating freshwater volumes consumed by anthropogenic activities (Hoekstra et al., 2011). The WF includes three components: the green WF, which refers to the use of precipitation, the blue WF, which refers to the consumption of ground and surface water, and the grey WF, which refers to water pollution (Hoekstra et al., 2011).

Water availability has temporal and spatial constraints, which can be observed with the historical trends of the order of magnitude of the difference of the seasonal water availability. Water is not always available, and it is unevenly distributed over the globe. These constraints affect electricity production of power plants (*PPs*) (DeNooyer et al., 2016; Lubega and Stillwell, 2018). For instance, *HPPs* are affected by water availability fluctuations as its production depends on the river flow. *TPPs* are affected as most cooling systems use water. Water availability also affects the fuel of *BPPs*, because it affects crop yields. In principle, the more water-intensive the *PP* is, the more likely its operation is affected by water availability fluctuations. Previous studies, e.g., Carvajal et al. (2019, 2017), Fernández-Blanco et al. (2017), Sesma-Martín (2019), and Sesma-Martín and Rubio-Varas (2017), have assessed the effect volumetric constraints of water availability have on *PPs*, modeling possible water constraints for future electricity production based on benchmarked water consumption values, in the case of *TPPs*, and based on hydrological models to forecast future electricity production from *HPPs*.

Individual *PPs* are often part of larger electricity systems, making an electricity mix with different energy sources, e.g., coal-fired power plants, hydropower, wind, and solar energy. All *PPs* in a certain

area, e.g., a country, together contribute to the electricity supply of the mix. Previous studies have addressed the water-electricity nexus of mixes considering their operation static. For instance, Mekonnen et al. (2016, 2015) have assessed global mixes in order to define WF differences among regions and to assess future WF scenarios for electricity and heat. Huang et al. (2017), Khalkhali et al. (2018), Lv et al. (2018) and Sun et al. (2018) did similar studies for local electricity mixes. However, the operation of individual *PPs* contributing to an electricity mix is dynamic, because certain technologies outperform others during certain periods, generating different temporal WFs. Therefore, WFs of electricity mixes are also dynamic as they have a temporal and spatial distribution based on the *PPs* contributing to the mix (Peer and Sanders, 2018).

Most studies that have assessed the water-electricity nexus focused on water-scarce regions where the relation between water availability and electricity generation is considered critical, e.g., Fernández-Blanco et al. (2017), Lv et al. (2018), Sesma-Martín (2019), Sesma-Martín and Rubio-Varas (2017) and Sun et al. (2018). In general, water-abundant countries have large hydropower and biomass potentials, so these technologies dominate their electricity mixes (Rockwood, 1979). The electricity mix of these countries may be vulnerable to water availability fluctuations as it affects electricity generation of certain technologies in the mix (Carvajal et al., 2019, 2017; Feng et al., 2019a, 2019b). Thus, there is a need to study the water-electricity nexus in a water-abundant country. The study must consider the dynamics of an electricity mix over time, and the dynamics of a WF mix with different technologies, and it must show the consequences of water-availability variation for the electricity mix.

This study aims to answer the following research questions:

1. What are the main characteristics of the temporal and spatial constraints of water availability in a water-abundant country (like Ecuador)?
2. How does temporal and spatial water availability shape and affect the electricity mix in Ecuador?

3. What is the temporal and spatial variation of the blue WF for hydropower, thermal power plants, and biomass power plants in the Ecuadorian electricity mix?

Ecuador is a suitable case for this study because (i) it is a water-abundant country, which internal renewable water resources are 100% from internal sources (FAO, 2015), (ii) water-intensive technologies have historically had a large share of the electricity mix (in 2017, *HPPs* and *BPPs* accounted for 62% of the installed capacity of the country (ARCONEL, 2018a)). (iii) In the mix, *HPPs* are prioritized over *TPPs* and *BPPs* to reduce costs from fuels imports and reduce carbon footprints (MEER, 2017), and (iv) the mix dynamics have been affected by water availability fluctuations (US Army Corps of Engineers, 1998). If water is available, *HPPs* generate 75% of the Ecuadorian electricity (ARCONEL, 2018b). However, when water is limited, electricity generation is constrained (ARCONEL, 2017; MEER, 2017). In our previous study (Vaca-Jiménez et al., 2019), we made a comprehensive inventory of the electricity mix of the country and calculated the average annual direct and indirect WF per unit of electricity of 287 Ecuadorian *PPs* of different technologies. We use our earlier paper as the starting point for this study.

2. Water and Electricity in Ecuador

Ecuador is the case study of this assessment. This section contains the description of the water and electricity systems of the country.

2.1. Hydrography

The Andes mountains divide Ecuador in the Pacific basin in the west and the Amazon basin in the east (SENAGUA, 2002). Population and agriculture are mostly located in the Pacific basin (INEC, 2014). Water availability in the basins has different seasonal fluctuations due to different weather systems (UNESCO, 2010). Freshwater availability is larger in the Amazon basin (88% of the resource) than in the Pacific basin (CEPAL, 2010). The Pacific basin has a wet season from December to May, with 82% of annual precipitation. In the Amazon basin, there are two wet seasons, one from March

to June and one from late October to December with 64% of annual precipitation. Despite large rainfall, there is freshwater competition among users in Ecuador (US Army Corps of Engineers, 1998). Municipal water supply has the priority to access freshwater, next agriculture, and finally industry, including the electricity sector (Asamblea Nacional de la República del Ecuador, 2014). The three sectors have different temporal and spatial blue WF patterns.

2.2. Ecuadorian electricity mix

The Ecuadorian electricity mix was initially built as a series of standalone systems providing electricity for a community (Narváez Avendaño and Tamay Crespo, 2013). The infrastructure was built around cities in the Pacific basin using locally available resources. Most of the times, cities in the Andes used *HPPs*, cities in the lowlands *TPPs*. In the '60s, the government integrated these standalone systems in a national grid (Narváez Avendaño and Tamay Crespo, 2013). The introduction of the national electricity grid (*SNI*) allowed the Ecuadorian mix to use part of the large hydropower potential of the Amazon basin during the following decades. Nowadays, the Ecuadorian electricity mix includes many power plants in both basins, which provide electricity to 97% of the Ecuadorian population (MEER, 2017). There are still off-grid power plants, but they are in remote areas (e.g., the Galapagos Islands) or work as standalone systems to fulfil specific industrial activities (i.e., the oil industry in the Amazon rainforest).

Since the past decade, Ecuadorian policies and national planning have defined energy transition as a national priority aiming to change electricity generation by fossil fuels to renewable sources (SENPLADES, 2017, 2013) and *HPPs* and other renewables are prioritized over *TPPs* (Asamblea Nacional de la República del Ecuador, 2015). Policies aim to reduce oil consumption and GHG emissions (MEER, 2017). This policy has consequences for blue WFs, as *HPPs* have larger WFs than *TPPs* (Vaca-Jiménez et al., 2019), and the overall operation of the national grid. In Ecuador, *HPPs* electricity output is constrained by water availability shortages that occur during seasonal dry periods. *HPPs* electricity production decreases when river water is limited. For instance, in 2017,

Ecuadorian *HPPs* had a capacity factor of 51% (ARCONEL, 2018a), smaller than the average 54% of Latin America and the Caribbean (Kumar et al., 2011). When water for *HPPs* is limited, *TPPs* increase production (ARCONEL, 2018a).

2.2.1. Composition

Electricity generating technologies in Ecuador include *HPPs*, *TPPs*, *BPPs*, and some non-traditional renewables (solar, wind, and biogas), contributing less than 1% to total electricity generation (ARCONEL, 2018a). *HPPs* and *TPPs* produce 97% of the electricity (ARCONEL, 2018a). *HPPs* are majorly in the highlands and produce 71% of the electricity in the country. *TPPs* are majorly in the lowlands and produce 26% of the electricity in the country using crude oil derivatives. *BPPs* are exclusively located in the Pacific basin (ARCONEL, 2016) and produce 2% of the country's electricity using sugarcane bagasse (a residue of the sugarcane industry, which can be stored for later use) as fuel. Their operation depends on the sugarcane seasonality (growing, harvesting, and production). Most electricity is used by the industry itself; the surplus goes to the national grid.

Figure 1 shows the studied system. In it is observed the Ecuadorian basins, sub-basins, and main rivers, and the on-grid connected *HPPs*, *TPPs* and *BPPs* and their location.

Figure 1. Map of Ecuador showing the major basins (Pacific and Amazon), the studied sub-basins, their main rivers, and hydrological stations. It also shows the country's power plants divided into three categories of power plants based on their energy source (Hydropower plants, Thermal power plants, and solid biomass power plants). Note: the larger the size of the circle, the larger the nominal capacity of the power plant.

2.2.2. Hydropower and thermal power plant's types and characteristics

The infrastructure and operating conditions of *HPPs* and *TPPs* in Ecuador have a large variation, which affects the electricity output and their water consumption. On the one hand, *HPPs* can be classified into three types of *PPs*, based on the way they divert the river's flow: (i) *dammed HPPs*, (ii) *run-of-the-river (ROR)* and (iii) *In-conduit HPPs* (Vaca-Jiménez et al., 2019). *Dammed HPPs* use a dam to divert the river flow and store water, enabling them to overcome water availability fluctuations to some extent. The largest reservoirs are located in the Pacific basin, the smaller ones in the Amazon basin (ARCONEL, 2016). *RORs* deviate the river flow by a relatively small weir, creating smaller ponds

before the weirs. When water availability decreases, electricity generation also decreases as they do not have large water storage capacity. *In-conduit* are small *HPPs* located in-between water supply pipelines. Their operation is linked to municipal water supply, which is not affected by water availability because the water supply is prioritized over other users. On the other hand, *TPPs* water-electricity relations are mainly based on their cooling type. Ecuadorian *TPPs* include four cooling types: (i) *once-through* cooling (*OT*), (ii) *wet-tower* cooling (*WT*), (iii) *dry cooling* (*DC*) and (iv) *no-cooling* (*NC*). *TPPs* with *OT* withdraw water from a source and discharge it immediately after use, requiring large water volumes, but with negligible consumption (Meldrum et al., 2013). They use freshwater, saline, or even gray water (Jiang and Ramaswami, 2015). Ecuadorian *TPPs* with *OT* are mainly located near the sea and use saline water (except for one). *TPPs* with *WT* recirculate water in a close loop avoiding large water withdrawal. The cooling water evaporates in a tower, so water must be added regularly. They use freshwater to avoid damage in the cooling system. *TPPs* with *DC* cool by air flowing through heat exchangers. *TPPs* with *NC* work under a Brayton thermodynamic cycle, which is open-loop and self-cooling (without water).

3. Methods

This paper addresses spatial and temporal dimensions of water availability, electricity production for the on-grid electricity mix (using the 2017 composition), and its water consumption in Ecuador. The spatial dimension included Ecuadorian power plants locations in river basins. The temporal dimension included average monthly water availability and monthly electricity production and water consumption.

Figure 2 shows our calculation steps, inputs and results. Three clusters of steps assessed the relationship between monthly water availability, electricity production, and water consumption of the Ecuadorian electricity mix. First, we quantified the *Monthly Normalized Water Availability in the Amazon and Pacific basin* in four steps (**Step 1-Step 4**) where historical data from hydrological stations in the rivers basins are transformed in a *Normalized Water Availability* index that defines

water availability fluctuations. Second, we calculated the *Monthly Electricity Production* in four steps (**Step 5-8**) using historical data of individual power plants. Finally, we estimated the *Monthly blue WF* of the on-grid electricity mix in seven steps (**Step 9-15**) using total monthly blue WFs of the power plants.

This study assessed monthly blue direct and indirect WFs of electricity in Ecuador per *PP* per technology. We used the WF as the indicator of freshwater consumption. The WF is a tool that estimates the volume of freshwater consumed or polluted by anthropogenic activities. We used the definition of WF as described in (Hoekstra et al., 2011), which has been used earlier as standard, e.g., in Liu et al. (2015), Mekonnen et al. (2016, 2015), and Mekonnen and Hoekstra (2012). The WF includes three components: green, blue, and grey WFs (Hoekstra et al., 2011). The WF of a *PP* has an indirect and a direct component (Mekonnen et al., 2016, 2015; Vaca-Jiménez et al., 2019). The indirect WF considers the fuels' life cycle and the life cycle of the plant itself (construction and decommission), which is negligible compared to the fuel's life cycle, or the direct WF (Hogeboom et al., 2018; Mekonnen et al., 2015; Meldrum et al., 2013), so the indirect WF in this study only considers the fuel's life cycle. The direct WF refers to water for *PP* operation.

Figure 2. Methodological Steps and their relation to each other.

3.1. Monthly Normalized Water Availability in the Pacific and Amazon basin

We defined monthly water availability as the monthly availability of fresh surface water in rivers and lakes, considering the natural runoff of the Pacific and Amazon basin with monthly fluctuations. We expressed monthly water availability by normalizing the monthly river flow (m^3/s) by their annual average flow (m^3/s). We calculated the average *Monthly Normalized Water Availability in the Pacific and Amazon basin* using data for the period 1963 to 2017 of 62 hydrological stations (34 for the

Pacific basin and 28 for the Amazon basin). *Appendix A* gives an overview of included rivers and hydrological stations.

Step 1 defined the *Multiannual Average River Flow*, $f_m[r]$ (m^3/s), per river r , per month m . First **Step 1** combined hydrological stations and rivers in sub-basins, next it calculated multiannual average monthly flows per hydrological station per river r . We assessed twelve rivers and their tributaries in the Pacific basin, and eleven rivers and their tributaries in the Amazon basin. We derived data on monthly river flows from INAMHI (2019a, 2019b, 2019c, 2016). *Appendix B* gives the *Multiannual Average River Flow*.

The *Normalized River Flow*, $Nf_m[r]$, shows differences in temporal water distribution availability in rivers. **Step 2** calculated the $Nf_m[r]$ per river r per month m , as the ratio between the $f_m[r]$, and the multiannual average of the annual flow, $f_{yr}[r]$ (m^3/s) of river r as follows:

$$Nf_m[r] = \frac{f_m[r]}{f_{yr}[r]} \quad (1)$$

The $f_{yr}[r]$ was calculated using annual river data for 1963-2016 from INAMHI (2019a, 2019b, 2019c, 2016).

Step 3 quantified the *Sub-basin's Water Availability*, $WA_m[s]$, of month m per sub-basin s , by averaging $Nf_m[r]$ of the rivers per sub-basin. The sub-basins, however, have rivers without hydrological stations. We calculated the $WA_m[s]$ based on the rivers with available data assuming they are representative for the entire sub-basin. In the Pacific basin, the $WA_m[s]$ was calculated for four sub-basins with most of the on-grid *PPs*. In the Amazon basin, we included three sub-basins, with all the on-grid electricity generation. *Appendix C* gives the *Sub-basin's Water Availability* of the seven sub-basins.

Step 4 calculated the *Water Availability in the basins*, $WA_m[b]$ of month m per basin b using the weighted average as follows:

$$WA_m[b] = \frac{\sum_{s=1}^S (WA_m[s] * w[s])[b]}{\sum_{s=1}^S (w[s])[b]} \quad (2)$$

where, $w[s]$ (ha) is the weighted index of sub-basin s , referring to the drainage area of the sub-basin.

We measured the drainage areas of the sub-basins using basin maps from SENAGUA (2002) and ArcGIS Arcmap®. *Appendix D* gives the drainage area of the seven sub-basins.

3.2. Monthly Electricity production of the on-grid electricity mix

Step 5 made an *Overview of the Power Plants*. First, **Step 5** classified *PPs* based on their operating conditions in three categories and eight technologies. The *PPs* were classified depending on their connectivity into on-grid and off-grid, which were excluded from this study. Next, the on-grid were classified into three categories based on the fuel source into *TPPs*, *BPPs*, and *HPPs*. Other renewables like solar and wind were excluded. Finally, *PPs* were further classified into eight technologies. *TPP's* technologies were classified based on the cooling system into *WT*, *OT*, *DC*, and *NC*; *HPP's* based on their infrastructure into *dammed*, *ROR* and *In-conduit*. *BPP's* only have one technology: *solid biomass*. *Appendix E* gives a diagram of the power plant classification. Second, **Step 5** localized the Ecuadorian power plants in basins using ArcGIS ArcMap®. The country's boundaries were derived from IGM (2018) and the basins maps from SENAGUA (2002). We derived the coordinates of Ecuadorian *PPs* and their operating conditions from our earlier study (Vaca-Jiménez et al., 2019). *Appendix F* gives the nominal capacity, classification, location of Ecuadorian power plants.

Step 6 calculated the *Power Plant's Electricity Production*, $E_m[p]$, per month m and power plant p , by averaging multiannual electricity production of plant p in month m . We assessed the $E_m[p]$ for 103 *PPs*. Power production data for the period 1999 - 2018 were derived from (ARCONEL, 2019). Some plants were built after 1999. For those plants we assumed that available data is representative for all plants. *Appendix F* gives the range of years of data available per *PP*, and *Appendix G* gives the *Power Plant's Electricity Production* per month.

Step 7 calculated the *Electricity Generated*, $E_m[b, t]$, of month m , per basin b and technology t , as the sum of the $E_m[p]$ (calculated in **Step 6**) of power plant's technology t in basin b as:

$$E_m[b, t] = \sum_{p=1}^P (E_m[p])[b, t] \quad (3)$$

Step 8 calculated the *On-grid Electricity mix's Average Production* $E_m[b, c]$, per month m , as the sum of the $E_m[b, t]$ of the *PP's* technologies (from $t=1$ to T) of the category c in basin b as:

$$E_m[b, c] = \sum_{t=1}^T (E_m[b, t])[c] \quad (4)$$

3.3. Blue WF of the on-grid electricity mix

The quantification of the on-grid electricity mix's blue WF was based on the blue WF of the power plants in the mix. Depending on the *PP's* category, the assessment of its blue WF varies. The following subsections give the method for the different categories, based on the method described in (Vaca-Jiménez et al., 2019).

3.3.1. Thermal power plants and biomass power plants

Ecuadorian *TPPs* use oil and oil derivatives and *BPPs* sugarcane bagasse. These power plants have different direct and indirect WFs. The WF calculation included two steps:

Step 9 calculated the *Indirect blue WF of Thermal and Biomass power plants*, $WF_{m,i}[p]$ (m^3), per power plant p as:

$$WF_{m,i}[p] = \sum_{d=1}^D (F_m[d] * WF_f[d])[p] \quad (5)$$

where, $F_m[d]$ is the multiannual average volume (m^3_t) of fuel d (or mass, in t_t , of sugarcane bagasse for *BPPs*) consumed by power plant p in month m , and $WF_f[d]$, (m^3/m^3_t or m^3/t_t for biomass), is the

blue WF of fuel d . The $WF_f[d]$ has an annual basis for the fuels used in the *TPPs*, and a monthly basis for the sugarcane bagasse in *BPPs* because it is defined by crop water use, which is dynamic.

Moreover, the $WF_f[d]$ used for *BPPs* already considered the allocation process between the crop's WF and the bagasse. The calculation considered the sum of the product of these variables as many power plants used a fuel mix for their operation. Data on monthly fuel consumption per power plant from 1999 to 2017 were derived from (ARCONEL, 2019). The $WF_f[d]$ s were derived from (Vaca-Jiménez et al., 2019).

Step 10 calculated the *Direct blue WF of Thermal and Biomass plants*, $WF_{m,d}[p]$ (m^3) using the $E_m[p]$ of *TPPs* and *BPPs* (from **Step 6**) as:

$$WF_{m,d}[p] = E_m[p] * WF_{m,t}[t] \quad (6)$$

where, $WF_{m,t}[t]$ (m^3/TJ) is the average monthly blue WF per unit of electricity produced by plants of technology t . Data on $WF_{m,t}[t]$ for each technology of *TPPs* and *BPPs* were derived from (Vaca-Jiménez et al., 2019). *TPPs* direct blue WF is dominated by the cooling system (Meldrum et al., 2013; Vaca-Jiménez et al., 2019). *TPPs* with *DC* and *NC* have negligible direct blue WFs and Ecuadorian *BPPs* have *WT* systems (Vaca-Jiménez et al., 2019).

3.3.2. Hydropower plants

HPPs only have a direct WF as they do not use fuel. *HPPs'* open water surfaces (*OWS*) lose water by evaporation (Mekonnen and Hoekstra, 2012; Vaca-Jiménez et al., 2019). Their direct blue WF is determined by the type and size of the *OWS* (Mekonnen and Hoekstra, 2012; Vaca-Jiménez et al., 2019). *RORs* have smaller *OWS* with smaller blue WFs than *dammed HPPs*. *In-conduit HPPs* do not have *OWS* and no blue WFs. For *dammed* and *ROR HPPs*, we calculated the blue WF in two steps.

Step 11 calculated *Evaporation of the Open Water Surfaces*, $OWS_m[p]$ (m^3), per month and hydropower plant p , as the sum of the evaporation from the *OWS* (from $r=1$ to R). We adopted the gross method from (Mekonnen and Hoekstra, 2012):

$$OWS_m[p] = \sum_{r=1}^R (10 * Ev_m[r] * A_R[r]) \quad (7)$$

where, 10 corresponds to the conversion factor from mm to m^3/ha , $Ev_m[r]$ is the monthly evaporation (mm) and $A_R[r]$ is the surface area (ha). The $Ev_m[r]$ was calculated using the Modified Penman Method (Harwell, 2012) with daily meteorological data. Meteorological data for the places where the *OWS* are located were derived from (INAMHI, 2018) and (CONELEC, 2008). The $A_R[r]$. Data on the *HPP's OWS* were derived from (Vaca-Jiménez et al., 2019).

Step 12 calculated the *Direct blue WF of Hydropower plants*, $WF_{m,d}[p]$ (m^3) per month m and hydropower plant p using the approach of Liu et al. (2015) and Zhao and Liu (2015) as:

$$WF_{m,d}[p] = OWS_m[p] * \eta \quad (8)$$

where, η is the allocation factor (between 0 and 1). The allocation factor is 1 when a *HPP* is the only user of the *OWS* (most of the cases for Ecuadorian *HPPs*). Allocation factors were derived from (Vaca-Jiménez et al., 2019).

3.3.3. Total blue WF per power plant, and the blue WF per technology and basin

Step 13 calculated the *Total blue WF*, $WF_m[p]$ (m^3) of power plant p per month m as:

$$WF_m[p] = WF_{m,i}[p] + WF_{m,d}[p] \quad (9)$$

where, $WF_{m,i}[p]$ were taken from **Step 9**, and $WF_{m,d}[p]$, from **Step 10** and **Step 12**. Appendix H gives the total monthly blue WF per power plant.

Step 14 calculated the *Blue WF per technology and basin*, $WF_m[b, t]$ (m^3) per month m , as the sum of the $WF_m[p]$ (calculated in **Step 13**) of the power plants (from $p=1$ to P) of technology t in basin b as:

$$WF_m[b, t] = \sum_{p=1}^P (WF_m[p])[b, t] \quad (10)$$

3.3.4. Blue WF of the on-grid electricity mix

Finally, **Step 15** calculated the *Blue WF of the On-grid Electricity Mix*, $WF_m[b, t]$ (m^3), per month m , as the sum of the $WF_m[b, t]$ of the PP's technologies (from $t=1$ to T) of category c in basin b as:

$$WF_m[b, c] = \sum_{t=1}^T (WF_m[b, t])[c] \quad (11)$$

4. Results

4.1. Water Availability in Ecuadorian basins

4.1.1. Differences Upstream and Downstream

Water availability fluctuations occur differently upstream and downstream of rivers. Figure 3a and b show some results obtained in **Step 1-2**. They show the *Multiannual Average River Flow* at hydrological stations for locations upstream and downstream of the river and the *Normalized River Flow* of the most-upstream and most-downstream stations. Figure 3a shows this for the Pacific basin, using the example of the San Pedro-Guayllabamba river in the Esmeraldas sub-basin, and Figure 3b for the Amazon basin, using the example of the Quijos-Coca river in the Napo sub-basin.

Figure 3a-b. Variation of the Multiannual Average River Flow at hydrological stations that are in different locations upstream and downstream of two rivers. **a.** The San Pedro-Guayllabamba river in the Pacific basin, and **b.** The Quijos-Coca in the Amazon basin. Note: the legend indicates the altitude of the hydrological station.

There are large differences of the river flow between upstream and downstream locations with a maximum of nine times the volume. The sub-basin in the Pacific basin has a more significant variation between upstream and downstream than the Amazon basin caused by climate differences. The largest precipitation of the San Pedro-Guayllabamba system occurs midway of the river (INAMHI, 2018), with large water input downstream. The precipitation for the Quijos-Coca river has almost a constant spatial distribution along the river path (INAMHI, 2018). Fluctuations of the *Normalized River Flow* of the other rivers in the Pacific and the Amazon are likely the same.

4.1.2. Monthly Normalized Water Availability the Pacific and Amazon Basin

When aggregated, the local temporal and spatial river water availability fluctuations define the temporal and spatial fluctuations of the basins. Figure 4 shows the average monthly *Normalized Water Availability* in the Pacific and the Amazon basin.

Figure 4. Variation of Water Availability in the Amazon and Pacific basin relative to the annual average.

Figure 4 shows large differences in the *Normalized Water Availability* between the Amazon and Pacific basin and the different monthly fluctuations. The Pacific basin has more water available in the first semester of the year, the Amazon basin in the middle of the year. Between September and November, the basins have relatively small water amounts available compared to the rest of the year. River water availability in the Amazon basin has smaller annual fluctuations than availability in the Pacific. The difference between the largest and smallest availability in the Amazon basin is two-fold, in the Pacific basin four-fold.

Water Availability in the Pacific basin has a larger volumetric temporal and spatial fluctuation (also upstream and downstream, as seen in Figure 3a) than availability in the Amazon basin. This implies a possible tradeoff for *HPPs* in the Pacific. If *HPPs* are upstream, they have a more constant, but smaller electricity production potential than *HPPs* downstream due to smaller river flows, something that does not occur in the Amazon.

4.2. Mix dynamics and its relation to water availability

4.2.1. Electricity generated per technology and basin

Figure 5a and b show the *Electricity Generated per Hydropower technology and basin*. The Pacific basin is shown in Figure 5a, the Amazon in Figure 5b. In both basins, *Dammed HPPs* are most affected by water availability and have larger temporal fluctuations than *ROR*. The production peak

of *dammed HPPs* coincides with the water availability peak in each basin (June and July for the Amazon basin, March and April for the Pacific basin). Their storage capacity is observed in the output after those periods. In the Amazon basin, *dammed HPPs* have large outputs in August, despite smaller water availability. The same occurs in the Pacific basin, where the large production continues until May. Figure 5a shows that the temporal fluctuation in the Pacific basin is similar with a production peak from March to July, and a small production from August until November. Conversely, Figure 5b shows that the temporal fluctuation of technologies in the Amazon basin is different. The *ROR* production fluctuates less than *dammed HPPs*. Moreover, Figure 5a shows that *In-conduit HPPs* electricity production is small in comparison to other *HPP* technologies. Their electricity production does not have the same temporal fluctuations, as the other technologies, as their output is a by-product of water supply, which is not affected by water availability fluctuations, especially during the dry periods as water supply is prioritized over other users, namely electricity.

Figure 5a-b. Monthly electricity generation by hydropower technology in the Pacific and Amazon basins, including Hydropower plants with dams, run-of-the-river and In-conduit. Note: There is a difference in scale between figures **a.** and **b.**, and the In-conduit hydropower plants are only present in the Pacific Basin

Figure 6a and b show the *Electricity Generated* per Thermal power technology and basin. The Pacific basin is shown in Figure 6a, the Amazon in Figure 6b. It shows that *TPPs* in both basins have the smallest production from May to July and then the largest from October to March. Water-intensive cooling systems, like *WT*, have larger fluctuations than water-efficient systems as dry cooling. Figure

6a shows that *TPPs* with *WT* in the Pacific basin have a significant reduction in their output in August and September, while the other *TPP* technologies have an increase. As the *WT* system requires water, it is also constrained by water shortage in those months in the Pacific basin.

Figure 6a-b. Monthly electricity generation by thermal power plant's technologies in the Pacific and Amazon basins, including Thermal power with Once-through cooling, Dry-cooling, No-cooling, and Wet-tower cooling. Note: There is a difference in scale between figures a. and b., and the Once-through and No-cooling technologies are only present in the Pacific basin.

4.2.2. Monthly Electricity production of the on-grid electricity mix

Figure 7 shows the *Monthly Electricity production of the on-grid electricity mix*, presented in terms of the average monthly contribution to the mix by the different *PP*'s categories (1999-2018). It indicates the mix dynamics of the different categories and how these vary depending on their location (Amazon and Pacific basin).

Figure 7. Contribution of the various power plant's categories (hydropower plants, thermal power plants, and biomass power plants) and basins to the On-grid Electricity Mix's Average Production over the year (average data over 1999-2018).

There is a large difference between the electricity output of the Amazon and the Pacific basin. Every month, between 1999 and 2018, the Amazon basin produced more than 60% of Ecuador's electricity, the Pacific basin produced the rest. *HPPs* are the largest electricity producers in the Amazon basin, while in the Pacific the *TPPs* are the largest producers, followed by *HPPs*. *BPPs* contribute little. The electricity production shows monthly fluctuation. Power plant production in the Amazon basin is largest in June and July. The fluctuation is driven by the *HPPs* generation (*TPPs* generation in the Amazon is almost negligible). The largest production in the Pacific basin occurs in November and December, mainly driven by the *TPPs* when they replace the reduced production of Amazon's *HPPs*. The *HPPs* in the Pacific have the largest production in March and April, and the smallest in September and October. The difference between the largest and smallest production of *HPPs* in the Pacific is twofold, while for the *HPPs* in the Amazon basin, the difference is only 25%. The Amazon basin has smaller water availability fluctuations, with *HPPs* that have more constant electricity production than *HPPs* in the Pacific basin. *BPPs* operated from June to December during sugar production in the Pacific basin.

Water availability in the two basins (see Figure 4) explains the electricity mix dynamics shown in Figure 7. The largest volumes of water in the Amazon basin are observed in June and July when

electricity production of *HPPs* is largest; the largest electricity production from *HPPs* in the Pacific basin occurs in March and April, which coincide with the period with the largest water volumes available. Water availability in the Amazon basin is the main driver of the dynamics of the Ecuadorian electricity mix. Figure 4 shows the reason behind the electricity peak of *HPPs* in the basins from March to July when water is abundant in both basins. The first part of the period coincides with the wet season in the Pacific basin; the second part with the wet season of the Amazon basin. The large *HPP* electricity production is first caused by large water availability in the Pacific, next by availability in the Amazon. It seems unlikely that the mix can include only traditional renewable generation, *HPPs*, and *BPPs*, considering the current electricity mix dynamics and the dependency on *HPPs*, in which *TPPs* balance the grid when less water is available from September to November.

4.3. Monthly blue WF of the on-grid electricity mix

Figure 8 shows the *Monthly blue WF of the On-grid Electricity Mix* of Ecuador, including power plants' categories (*HPPs*, *TPPs*, and *BPPs*) for the Amazon and Pacific basin. The blue WF differences between basins are large. The Pacific basin consumes six times more water than the Amazon basin, where *HPPs* and *BPPs* are the largest water consumers. *HPPs* in the Amazon basin are more water-efficient than their Pacific counterparts. They have smaller reservoirs per unit of installed capacity and smaller evaporation losses. The fluctuation of blue WFs also differs largely between the basins. The Amazon basin's blue WF is nearly constant, while in the Pacific, the largest blue WF occurs in August and October due to *BPPs*. Without *BPPs*, the largest consumption occurs in March and April, the smallest in June and July coinciding with the largest and smallest water availability. *BPPs'* blue WF is also an indication of the prioritization of water for agriculture over industry. Freshwater is used to irrigate sugarcane in the dry season of the Pacific basin despite smaller water availability and impact on *HPPs* electricity production upstream.

Figure 8. Blue WF of the Ecuadorian on-grid electricity mix over the year, and the contribution of the different power plant's categories to this total. Note: The blue WF of Thermal Power plants in the Amazon basin is so small in comparison to the blue WF of other power plant's categories that it is not easily observed.

The blue WF of BPPs is large but linked to sugar from the sugarcane industry. Electricity from BPPs is a byproduct of sugar production. Blue WFs of TPPs and HPPs are entirely related to electricity production. When blue WFs of BPPs are excluded, the blue WF peak of the electricity mix occurs from April to May, and the smallest blue WF is from June to September. The shape of the monthly blue WF of the electricity mix coincides with water availability in the Pacific basin. Hence, the electricity mix becomes water-efficient when less water is available.

5. Discussion

5.1. Water-electricity nexus at the country level

The water-electricity nexus in Ecuador is defined by the spatial and temporal fluctuation of water in its basins. First, the spatial fluctuations have shaped the electricity mix (e.g., the distribution of the PPs in the territory) as there are large differences in water availability between basins and in the basins (upstream and downstream differences). Second, the temporal fluctuations constrain the country's electricity generation as water availability is the main driver behind the electricity mix. We discuss some of the connotations of the water-electricity nexus in Ecuador further below.

5.1.1. Water availability affecting the Ecuadorian electricity mix's dynamics

Our results show how the dynamics of power plants in the Ecuadorian electricity mix are affected by the temporal distribution of water availability. For *HPPs*, the mix's dynamics main driver is water availability in the Amazon basin. When less water is available during certain periods, the other producers in the mix take over. When water is available in the Pacific basin (first quarter of the year), *HPPs* in the Pacific back up part of the reduced production from Amazon's *HPPs*. However, when water is not available in neither of the basins (last trimester of the year), *TPPs* take over. *BPPs* also produce during this period, but they are constrained by the temporal distribution of the sugarcane industry.

Our results also show that the effect that water availability has on the electricity mix dynamics is intrinsically defined by the climatic seasonality of the country's basins, and therefore, water availability fluctuations affect future Ecuadorian electricity mixes. An Ecuadorian *HPPs*-based electricity mix has little options to stop using *TPPs* as a backup when less water is available. For instance, more *HPPs* could be built in both basins, but new *HPPs* have similar water availability fluctuations. A new mix requires a larger installed capacity of hydropower than the ones they replace to guarantee the electricity production even in dry periods in the Amazon basin. However, in the last trimester of the year, when water is less available in both basins, *HPPs* are still constrained and backup still needed.

5.1.2. Water availability affecting electricity's blue WFs

Power plants decrease their production when water availability goes down. This affects the mix's total monthly blue WF. Usually, when water is available, water-intensive *HPPs* and *TPPs* maximize production, consuming more water. However, when less water is available, more water-efficient technologies replace water-intensive technologies. *HPPs* are replaced by *TPPs*, and *TPPs* with water-efficient cooling systems (once-through and dry cooling) replace water-intensive cooling systems (wet-tower cooling). This is not the case for *BPPs*. They have large blue WFs in the dry season,

because agriculture is favored, and sugarcane receives irrigation water. *BPPs* contribution to the mix is small, and its blue WF is irrelevant, because the bagasse for *BPPs* is a residue of the sugarcane industry, and therefore, the blue WF remains regardless whether the residue is used or not for electricity.

There are water-efficient *HPPs* technologies in the mix, the *ROR* technologies, but they are phased out in dry periods due to limited river water availability. Their infrastructure has no (or limited) water storage capacity. This suggests that the addition of water-efficient *HPP* technologies does not guarantee a water-efficient electricity mix throughout the year.

5.1.3. Electricity production and blue WF variation of Amazon and Pacific basins

Electricity production and blue WFs of power plants of the same technology in the Amazon and Pacific basin show large variation. *HPPs* in the Amazon basin produce more electricity and have smaller blue WFs than *HPPs* in the Pacific basin. The seasonal variation of river flows of the Amazon basin is smaller than variation in the Pacific basin. The Amazon has: (i) larger electricity productions and *HPPs* with larger capacities. (ii) *HPPs* with smaller reservoirs and smaller WF per unit of electricity generated than *HPPs* with larger reservoirs in the Pacific. *TPPs* blue WF is dominated by their electricity output and fuel consumption as they consume water only when they operate (in contrary to *HPPs* that consume water as evaporation from their reservoirs even when they do not produce electricity). Therefore, the WF difference between *TPPs* in the Pacific and Amazon basins is mainly caused by saline water availability at the Pacific coast. This alternative water source permits once-through saline water cooling, which is impossible in the Amazon basin. Saline water is always available and has no blue WF, permitting relatively large electricity production.

5.2. Implications for the water-electricity nexus

Temporal variation of water availability in a country affects the spatial distribution of power plants contributing to an electricity mix, also affecting blue WFs. Water availability fluctuations limit a larger contribution of traditional renewable sources, and fossil-fueled *TPPs* need to balance the grid when

less water is available. Considering that the energy transition is likely to go towards water-intensive mixes (Mekonnen et al., 2016), this implies that the feasibility of a global energy transition is linked to water availability, even in water-abundant countries.

Previous studies (Hoekstra and Mekonnen, 2012; Vaca-Jiménez et al., 2019) have shown that water consumption by the electricity sector (or the larger sector, industry) is small compared to agriculture. Our results indicate that the blue WF of the electricity sector is significantly linked to water availability. Even when the WF of power generation does not affect annual water resources in a country volumetrically, it can still affect agriculture or municipal water supply or industry when water is limited, affecting one, or more, of the cornerstones of a national economy.

Moreover, until now, the existing knowledge has shown how intrinsically connected are water and electricity from a static point, and mostly at a power plant level. So far, we know how certain technologies are more water-efficient than others (e.g., (Macknick et al., 2012; Meldrum et al., 2013; Vaca-Jiménez et al., 2019)), and how water scarcity may affect electricity production in the future based on modelling scenarios of the electricity output of certain type of *PP* (e.g., (Carvajal et al., 2019, 2017)). Our study shows the water-electricity nexus at the country level, taking into consideration the historical dynamics of an on-grid electricity mix and the interaction of all the power plants in this mix, and their relationship with water availability. Our results indicate that the WF of individual technologies is of limited interest for future electricity planning in a water and carbon-constrained world. The water-electricity nexus should be addressed from the point-of-view of the mix's dynamics and its relation to the water availability in the region, as this is the real limitation to surpass to have a water-efficient and carbon-neutral electricity generation. For instance, in previous studies (i.e., (Mathioudakis et al., 2017)), the water-electricity nexus of BPPs has been defined as one of the most important to be addressed for their large WFs and their dependency on water. The WFs of *BPPs* are large, mainly due to the fuel source, which usually comes from agricultural residues. This implies that the WF comes from the allocation of the WF of the main agricultural product. Thus, the

consumption of water will happen whether the residue is used or not. Moreover, the BPPs electricity output is small in comparison to other technologies, and it only occurs during certain periods through the year, so their contribution to the electricity mix is insignificant. Therefore, the *BPPs'* water-electricity nexus is not relevant when the electricity mix dynamics is considered and can be neglected in future studies.

5.3. Approaches for the Water-Electricity nexus

Several studies have quantified the water-electricity nexus of electricity generating technologies. For example, Gerbens-Leenes et al. (2009), Liu et al. (2015), Mekonnen et al. (2016, 2015), Mekonnen and Hoekstra (2012) and Vaca-Jiménez et al. (2019) have quantified WFs of electricity generating technologies based on rough estimates, often generating global annual averages or benchmark values per technology, country or region. Those studies have left the system dynamics out. Other studies modelled water-electricity relationship for future situations, for example, Feng et al. (2019b, 2018). Our study includes a dynamic perspective, not only considering water consumption of electricity generating technologies, but also showing how water availability shapes and defines the dynamics of electricity generation, and how this dynamic behavior from the mix translates into a dynamic water consumption of the power plants in the mix.

Different approaches to address the water-electricity nexus correspond to different applications and goals and use different methods. The water-electricity nexus is a multidisciplinary issue. Existing scientific knowledge has applied several methods to address this nexus. The assessments have different aims and perspectives and include two categories that (i) try to understand the system, and (ii) aim to optimize the system.

The first category addresses the water-electricity system as a static system and aims to understand how the system works and to identify important factors in the operation of the system. This category helps to conclude about current operations based on historical data, and, if possible, gives suggestions on how to improve the system. Research in this category is not able to predict

operations for different situations or optimize the system. Examples of studies in this category are Liu et al. (2015) that studied the WF of China's hydropower, Mekonnen et al. (2015) that assessed the WF of electricity generation and heat on a global scale, Mekonnen and Hoekstra (2012) that quantified the WF of the largest hydropower plants of the global mix, Sesma-Martín (2019) that estimated the water needs for thermoelectric generation in the Ebro basin in Spain, and Vaca-Jiménez et al. (2019) that quantified the WF of the Ecuadorian electricity mix. This paper falls in this category because it shows the system's dynamics of electricity generation in Ecuador.

The second category models and predicts the water-electricity system for different scenarios. It involves mathematical modeling and computational simulations. Those studies suggest ways to optimize the system or to identify which scenario is the most suitable for a certain outcome (i.e., which policy is the most water-efficient from a range of possibilities). However, the modeling of the system can become complex as more variables and actors are considered, and the simulations may require large computational capacities (Feng et al., 2019a). Examples in this category are Carvajal et al. (2019, 2017) who have assessed for the first time the impact of climate change on long-term hydropower generation in Ecuador (2017), as well as, the cheapest way for the hydropower sector to adapt to climate change (2019). Fernández-Blanco et al. (2017) modelled a hydropower-thermal power system to provide stability to the Greek mix, and Feng et al. (2019b, 2018) proposed methods for the optimization of hydropower production in China (2018), and to optimize operation of thermal plants to provide flexibility to hydropower (2019b). At the end of the day, the two categories complement each other. The results obtained by the first category usually serve as the starting point for the modeling in the second category.

6. Conclusions

Our analysis of the electricity generating system in Ecuador, using historical weather data, electricity production per power plant and water use estimations, shows that: (i) Water availability in the Amazon and Pacific basin in Ecuador has different temporal and spatial fluctuations in different

locations in each basin. The Pacific basin has more water available in the first semester, while the Amazon basin has more water in the middle of the year. Moreover, water availability in the Amazon basin has smaller annual fluctuations than availability in the Pacific. (ii) These temporal and spatial water availability fluctuations define the electricity mix's composition and dynamics. Ecuador has a hydropower-based electricity mix, which dynamics are determined by water availability at hydropower plants' locations and forces other technologies to accommodate to the hydropower plants' production. (iii) Water availability fluctuations indirectly and directly affect the different electricity generating technologies. Thermal power plants, especially in the Pacific basin, are indirectly affected by water availability fluctuations as they are used to balance hydropower plants decreased production in water-limited periods. Biomass power plants are indirectly affected by water availability, but differently than the other technologies. For biomass power plants, limited water availability does not affect the power plant's operation, but the fuel source, sugar cane that needs irrigation. However, the bagasse has an advantage over hydropower, because the fuel can be stored, while hydropower's water storage is limited. Our findings suggest that when countries rely on water-intensive technologies for their electricity generation, like HPPs and BPPs, water availability is likely to be the main driver of the mix dynamics. (iv) The electricity mix's water footprint has temporal fluctuations based on different spatial locations. As water availability fluctuates, other technologies in the mix need to take over, causing water footprint variation. Usually, when less water is available, efficiency becomes more important, and the electricity mix becomes more water-efficient. However, this implies the use of fossil-fueled power plants. Moreover, our study suggests that the addition of water-efficient HPP technologies does not guarantee a water-efficient electricity production as they are phased out in dry periods due to limited river water availability.

Even though these four findings are relevant for the Ecuadorian case, they can serve as an indication for other countries. They show that it is relevant to address and quantify the water-electricity nexus in not so evident countries, especially those that are water-abundant, and with that large temporal variation of water availability in their basins. This study indicates that the effect of water availability

variations can be reduced by the optimization of the water resources available in the country by understanding the spatial differences of the basins of the country. Even when we cannot change water availability in a country as it is determined by factors out of human control, when a power grid is available, we can select the places where to put the power plants to reduce the effect of water fluctuations.

The study has shown how the aim towards a renewable electricity mix is curtailed by seasonal water availability fluctuations, and that this displaces water-efficient technologies. Therefore, future decision-making and energy planning need to consider the water-electricity nexus from the mix dynamics perspective, and not only focus on water-efficient technologies.

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Graphical abstract

Highlights

- Even in water-abundant countries, water availability shows variation over the year
- The spatial and temporal variation in water availability affects electricity supply
- Water availability affects Hydropower directly, and Thermal and Biomass indirectly
- Thermal plants compensate the decreased Hydropower production in dryer months
- A hydropower-based electricity supply system needs back up systems for dry periods