GREEN WATER FOOTPRINT AND SUSTAINABILITY FOR ESPÍRITO SANTO STATE

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ABSTRACT

Water footprint is a relatively new concept of freshwater appropriation that considers its direct and indirect use by a consumer or producer and used as a comprehensive indicator of the appropriation of water resources. The objective of this study was to estimate the green water footprint and evaluate its sustainability in the state of Espírito Santo, using the land use information and indicators of water scarcity. The total green water footprint was estimated by the sum of the green water footprints of pasture, forest, coffee cultivation, forestry, and other agricultural uses. The state’s total green footprint estimated was 47.5 billion m³/year, and the pasture class represented 48.5% of this total, followed by forest (29.8%), coffee cultivation (10.1%), forestry (6.4%), and other crops (5.2%). The ratio between the mean annual total volume of precipitated water and the green WF in the state was 80%. The environmental sustainability assessment shows that the green footprint was unsustainable for most of the year, on average, mainly in the May to September.
INTRODUCTION

Despite being renewable, water is considered a limited natural resource. Because of the limitation on the availability of water, in quantity and quality, especially fresh water, it is necessary to use it rationally, in order to ensure its sustainable supply. The use of tools and indicators allows a better understanding of the functioning of water dynamics in the hydrological cycle, especially in its terrestrial phase, as well as assisting in decision making related to water resources management. In this sense, one indicator that has been used is the water footprint.

The concept of water footprint (WF) encompasses both direct and indirect use of water by a consumer or a product. This is considered a broader indicator of appropriation of water resources, which differs from the traditional and restricted concept of water intake (consumption), as it also allows the quantification of the volume required for the dilution of pollutants. This indicator separates water consumption into three components: blue WF, which refers to the consumption of fresh, surface or groundwater from its direct catchment in springs; green WF represents the evapotranspiration (consumption) of water temporarily stored in soil and vegetation; and gray WF, the volume of water needed to dilute pollutants (HOEKSTRA et al., 2011; MEKONNEN & HOEKSTRA, 2011; EMPINOTTI & JACOBI, 2013; SILVA et al., 2013; BLENINGER & KOTSUKA, 2015; SCHYNS et al., 2015; BLENINGER; KOTSUKA, 2015).

In terms of global average values, the total WF of the Earth, from 1996 to 2005, was distributed as follows: 74% green WF; 15% gray WF and 11% Blue WF (MEKONNEN & HOEKSTRA, 2011a). In the state of Espírito Santo, specifically in the Itapemirim river basin (IRB), green WF also had the highest proportion of total WF with 86%, followed by blue and gray WF, with 9% and 5%, respectively, in 2007 to 2012 period (LEAL et al., 2018).

Regarding agricultural production (excluding livestock), in relation to the sum of green and blue WF, green WF represented, in general 86% on Earth (MEKONNEN & HOEKSTRA, 2011a); 93% in the European Union (VANHAM & BIDOGLIO, 2013); 92% in Brazil and 95% in the Paraná River Basin (MEKONNEN & HOEKSTRA, 2011b); and 91% in IRB (LEAL et al., 2018).

According to MEKONNEN & HOEKSTRA (2011b), green water is often the most significant in general consumption, even in regions with irrigated agriculture, with higher consumption of blue water. SCHYNS et al. (2015) state that it is necessary to better understand the aspects related to the availability of green water, so that it can be better managed, since, surprisingly, studies and discussions about water scarcity have been mainly focused on blue water.

There are several studies on WF on a global scale, but few on a regional and local scale. In addition, considering the importance of green water in terrestrial water availability, this study was carried out with the objective of estimating green WF and evaluating its sustainability in the state of Espirito Santo.

MATERIAL AND METHODS

The study area comprises the state of Espirito Santo, in the southeastern region of Brazil, with a territory of 46,052.64 km². The state covers 78 municipalities, with a population of approximately 4 million inhabitants (IBGE, 2018). According to the Köppen classification, the state has four predominant climates: 53.3% Aw and 14.3% Am (humid tropical); 14.9% Cfa and 10.4% Cfb (hot temperate) (ALVARES et al., 2013).

Land use survey

The land use survey conducted in this study was based on the orthophoto mosaic with 1-m spatial resolution, generated from the aerophotogrammetric...
survey conducted in the state of Espírito Santo in 2007/2008 by the STATE INSTITUTE FOR ENVIRONMENT AND WATER RESOURCES (2008). This represents the last available complete survey of the vegetation of the state, containing 25 classes (Figure 1). Based on this delimitation, combined with the official map of the state political division (Figure 2), the corresponding types and areas of each type of existing land use were computed for each municipality.

Figure 2. Political division of the state of Espírito Santo (municipalities and macro-regions), and grid with the monthly average precipitation points used in the study. Source: Adaptation of GEOBASES and XAVIER et al. (2016).
Accounting of the Green Water Footprint

Green WF was accounted by using the methodology established in the Water Footprint Assessment Manual (HOEKSTRA et al., 2011), adapted for each crop under study (native vegetation, pasture, coffee, forestry and other agricultural crops). Green WF was spatially calculated for the entire state, in 1 x 1-km pixels, based on the Climatic Water Balance (CWB), using the method of THORNTHWAITE & MATHER (1955), from which the actual crop evapotranspiration (ETR) was obtained using control rainfall and evapotranspiration data (ET0). The elements of CWB were spatially calculated following an adaptation of the methodology presented in CECÍLIO et al. (2012). The description of the data used and the calculation procedures performed are described below.

Green WF was calculated in the same way for all land use classes according to Equation 1.

\[
WF_{\text{green}} = 10 \times ETR \times \text{Area}
\]  

Where,

\(WF_{\text{green}}\) = monthly green water footprint, m³;

ETR = monthly average actual crop evapotranspiration, mm; and

Area = cropped area, hectares.

In the native vegetation class, all natural vegetation was considered by joining the areas of native forest, vegetation in the early stage of regeneration, swamp, sandbank and mangrove. In the forestry class, the areas of eucalyptus, pine and rubber tree were considered together.

Data on rainfall and evapotranspiration

The average monthly rainfall data from 1980 to 2013 were obtained from the work of XA VIER et al. (2016), with spatial resolution of 0.25º (Figure 2). The interpolators indicated by SILVA et al. (2011) for downscaling the monthly precipitation maps to spatial resolution of 1 km.

The monthly average potential evapotranspiration data were calculated using the method of Hargreaves and Samani (HARGREAVES & SAMANI, 1985), Equation 2, by correcting the values through the adjustment proposed by ZANETTI et al. (2019), for Espirito Santo, Equation 3:

\[
ET^0_{0.81} = 0.0023R_a \left(T_{\text{max}} - T_{\text{min}}\right)^{0.5} \left(T_{\text{med}} + 17.8\right)
\]  

\[
ET^0 = \left[1.08ET^0_{0.81} - 0.81\right] NDA
\]  

Where,

ET^0 = potential evapotranspiration, daily average of each month, calculated by the method of Hargreaves and Samani, mm;

ET^0 = monthly potential evapotranspiration, mm;

\(T_{\text{max}}\), \(T_{\text{min}}\) and \(T_{\text{med}}\) = monthly maximum, minimum and average temperatures, respectively, ºC;

Ra = extraterrestrial solar radiation, daily average of each month, mm day⁻¹; and

NDA = number of days of each month in the year.

The maximum and minimum temperature data were obtained from the application of multiple linear regression equations (Equation 4), in which \(T_{\text{med}}\) was determined by the mean between \(T_{\text{max}}\) and \(T_{\text{min}}\).

\[
T_i = \beta_0 + \beta_1 Alt + \beta_2 Lat + \beta_3 Long
\]  

Where,

\(T_i\) = maximum and minimum regular monthly temperatures, ºC;

Alt = altitude, m;

Lat = latitude, decimal degrees;

Long = longitude, decimal degrees; and

\(\beta_0\), \(\beta_1\), \(\beta_2\) and \(\beta_3\) = parameters of the equation.

The parameters used in Equation 4 to estimate monthly maximum and minimum air temperatures were those proposed by CASTRO et al. (2010).

Altitude data were obtained from the TOPODATA Digital Elevation Model, developed by the National Institute for Space Research (LIU et al., 2009), which represents a refinement of the MDESRTM, with a spatial scale of 30 meters. For the use of this DEM, a reclassification with a spatial resolution of 1 km was previously performed.

Calculation of climatological water balance

The CWB was calculated using monthly average crop evapotranspiration (ETc) and monthly average rainfall data. The ETc was obtained by multiplying the values of ET0 and the crop coefficient (Kc) shown in Table 1.
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Table 1. Mean values of crop coefficients (Kc) and effective depth of the root system (Z)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Kc</th>
<th>Source</th>
<th>Z (m)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pineapple</td>
<td>0.37</td>
<td>a</td>
<td>0.45</td>
<td>a</td>
</tr>
<tr>
<td>Banana</td>
<td>0.98</td>
<td>a</td>
<td>0.70</td>
<td>a</td>
</tr>
<tr>
<td>Coffee</td>
<td>1.01</td>
<td>a</td>
<td>1.20</td>
<td>a</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>0.80</td>
<td>a</td>
<td>1.60</td>
<td>a</td>
</tr>
<tr>
<td>Coconut</td>
<td>0.80</td>
<td>a</td>
<td>1.00</td>
<td>c</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>0.82</td>
<td>b</td>
<td>1.50</td>
<td>a</td>
</tr>
<tr>
<td>Papaya</td>
<td>0.87</td>
<td>a</td>
<td>0.30</td>
<td>c</td>
</tr>
<tr>
<td>Pasture</td>
<td>0.80</td>
<td>a</td>
<td>1.00</td>
<td>a</td>
</tr>
<tr>
<td>Rubber tree</td>
<td>0.98</td>
<td>a</td>
<td>1.50</td>
<td>a</td>
</tr>
</tbody>
</table>

a: ALLEN et al. (1998); b: ALVES et al. (2013); c: MIRANDA et al. (2007).

For native vegetation classes (native forest, vegetation at early regeneration stage, sandbank, mangrove and swamp), pine, temporary and permanent crops, the Kc equal to 1.00 was adopted and for thick vegetation it was used 0.80 (same pasture value). There are uncertainties about these values due to unavailability of specific data in the literature.

Available water capacity (AWC) was determined by multiplying the AWC per unit depth and the effective depth of the root system (Z) of the crops (Table 1).

For native vegetation (native forest, early stage of regeneration, sandbank, mangrove, swamp and pine), it was used Z equal to 1.5 m. For temporary crops, 0.30 was adopted, and for permanent crops and thick vegetation, it was used 1.00. Similarly, there are uncertainties about these values due to unavailability of data in the literature.

The AWC per unit depth was determined according to the average physical properties of the soils, using the values shown by PEREIRA et al. (2002):

- Heavy textured soils: 200 mm/m;
- Medium textured soil: 140 mm/m;
- Coarse textures soils: 60 mm/m.

The average soil texture classes were obtained as performed by SILVA et al. (2011):

- Medium textured soils: Ultisols and Litolic Neosol;
- Coarse textured soils: Spodosols, Quartzarenic neosol and Fluvic Neosol.

The soil map used in the study (Figure 3) was obtained from the database of the Integrated System of Geospatial Bases of the State of Espírito Santo (GEOBASES).

By using the calculation of the BHC, the values of real evapotranspiration (ETR) were obtained, in monthly and annual scales, for each pixel (1 km x 1 km) in the state of Espírito Santo.

The areas of rocky outcrop, built-up area, rupestrian field/altitude, mining extraction, water mass, exposed soil and others were not accounted for in the green PH calculations, considered unproductive areas.

Green water footprint

The green WF sustainability assessment was based on the Water Footprint Assessment Manual (HOEKSTRA et al., 2011), based on the interpretation of water scarcity (WS) indicators per municipality:

\[ WS_{green} = \frac{\Sigma WF_{green}}{WA_{green}} \quad (5) \]

where,

\( \Sigma WF_{green} \) = sum of the green WF of the different vegetable cover; and

\( WA_{green} \) = green water availability.
Figure 3. Soil classes mapped in the state of Espirito Santo. Source: Adapted from GEOBASES.
Green water availability (WA\textsuperscript{green}) was set by Equation 6 (HOEKSTRA et al., 2011):

\[
\text{WA}_{\text{green}} = \text{ET}_{\text{green}} - \text{ET}_{\text{env}} - \text{ET}_{\text{unprod}}
\] (6)

In which,

- \(\text{ET}_{\text{green}}\) = volume corresponding to the evapotranspiration of all rainfall, \(\text{m}^3/\text{month}\);
- \(\text{ET}_{\text{env}}\) = volume corresponding to environmental evapotranspiration, that is, native vegetation, \(\text{m}^3/\text{month}\), and
- \(\text{ET}_{\text{unprod}}\) = volume corresponding to the evapotranspiration of unproductive areas, \(\text{m}^3/\text{month}\).

The \(\text{ET}_{\text{green}}\) was considered as equivalent to the total rainfall in each municipality, using the monthly average rainfall data.

Environmental evapotranspiration was calculated by summing the evapotranspiration of native forest areas, early stage of regeneration, sandbank, mangrove and marsh (wetland).

The unproductive areas, referring to rocky outcrop, built-up area, rupestrian/altitude field, mining extraction, water mass, exposed soil and others, were not considered in the green WF sustainability calculations. Since the values of these areas were not calculated for their WF\textsuperscript{green}, this was not subtracted from WA\textsuperscript{green}, therefore, making no difference in the calculation of WS\textsuperscript{green}.

Green water scarcity is considered environmentally sustainable when it has a value of up to 1 (100%), meaning that only available green water is consumed. Consequently, values greater than 1 represent a scarcity considered unsustainable (HOEKSTRA et al., 2011).

**RESULTS AND DISCUSSION**

Figure 4 shows the green WF values calculated for the principal vegetation cover (native vegetation, pasture, coffee, forestry and other agricultural crops) in Espírito Santo. The average green WF totaled 47.5 billion \(\text{m}^3/\text{year}\) in the state. The volume with the highest use occurred in the pasture class, followed by native vegetation, coffee, forestry and the total of other crops with smaller area (papaya, pineapple, banana, sugar cane, coconut and other temporary and permanent crops).

LEAL et al. (2018), in a study in the Itapemirim river basin, obtained similar results, by observing that the pasture class represented 54% of total green WF, followed by native vegetation with 26% and agriculture representing 20%.

The pasture class resulted in higher green WF due to its larger coverage area, representing 46% of the state territory. Similarly, the other classes also followed the magnitude of their coverage areas (Table 2).

When using Equation 1 to calculate green WF, the values tend to follow the magnitude of the area of municipalities as the calculation is performed in units of volume of water consumed as

![Green Water Footprint](image)

**Figure 4.** Water footprint of the main types of land use in the state of Espírito Santo in 2007/2008.

| Green WF (10\textsuperscript{9} \(\text{m}^3\) year\textsuperscript{-1}) |
|------------------|------------------|------------------|------------------|------------------|------------------|
| Pasture          | 22.7             |
| Forestry         | 13.9             |
| Coffee crop      | 4.7              |
| Agro-forestry    | 3.8              |
| Other crops      | 2.4              |
recommended in the Water Footprint Assessment Manual (HOEKSTRA et al., 2011). This method, while consistent, is not effective for comparing different areas such as municipalities or regions. In this case, it was decided to present the results in a relative manner, based on the availability of the main source of water for the occurrence of green WF, that is, rainfall.

Therefore, Figure 5 shows the average relations between the green WF of the principal land uses and the volume of precipitated water in the municipalities of the four macro-regions of the state. The areas considered unproductive (rocky outcrop, built-up area, rupestrian /altitude field, mining extraction, water mass, exposed soil and others) were excluded from the calculation.

In both results, using absolute as well as the relative value (Figures 4 and 5), the green WF of each type of land use, in addition to the area of occupation and regional rainfall, also depends on the characteristics adopted in the calculation of evapotranspiration and water balance (Kc, Z and AWC). As the mean values found in the literature have been adopted, and as in some cases, arbitrary values have been adopted due to unavailability of specific data in the literature, there are some uncertainties related to the results, and the estimates obtained are more appropriate for regional comparisons.

As shown in Figure 5, whose values were calculated in a relative manner, pasture remains the class that most incorporates green water in the North (53%), South (41%) and Central (36%) macro-regions. The regions with the lowest rainfall and the largest pasture area, such as the Northern macro-region (Table 2), have the highest proportion of green WF.

In the Metropolitan macro-region, the largest consumer is the native vegetation class, with 25% of all average rainfall. The native vegetation class also has a significant representation (second largest) in the other macro-regions of the state, with about 21% in the southern macro-region, 28% in the central and 18% in the north.

LEAL et al. (2018) also analyzed the relationship between rainfall and green water footprint. Although the calculation procedures were relatively different, the results were similar, with pasture representing about 40% of the average rainfall depth, followed by native vegetation.

Figure 6 presents the results of the total percentage of precipitated water that is converted into green footprint consumed for each municipality of the four state macro-regions.

The municipalities Presidente Kennedy (South), Laranja da Terra (Metropolitan), Marilandia (Central) and Mucurici (North) represent the largest consumers of the total volume of rainwater in each macro-region they are inserted.

Regarding macro-regions, the largest consumer of rainwater by WFgreen is the Northern macro-region, with about 89%, which can be explained by the occurrence of lower annual average rainfall,
higher pasture percentage and higher annual average real evapotranspiration (higher WF\textsubscript{green}), followed by Central with 84%, South with 76% and Metropolitan with 73%.

Rainwater consumed for the use of vegetation cover represents an average percentage of 80% of the total rainfall in the state, that is, green WF is the main consumer of surface water in the state. Thus, much of the water available in the soil is absorbed and used by vegetation, leaving less water for underground water recharge.

Several studies report that agricultural production is the main consumer of green water, which shows the importance of the green water component (LEAL et al., 2018; LIU et al., 2009; MEKONNEN & HOEKSTRA, 2010, 2011b). According to VANHAM & BIDOGLIO (2013), campaigns for water use awareness focuses on water use for the domestic and industrial sectors. However, more attention should be given to water consumption in agricultural production processes. SCHYNS et al. (2015) report that studies on water scarcity should be focused not only on blue water, but mainly on green water, as it plays an important role in crop production, pasture, forestry, as can be analyzed through this study.

**Green water footprint sustainability**

Green WF sustainability is calculated according to water scarcity (WS) indicators. These indicators are based on green water availability (WA) and total green WF (green WF) used monthly. This availability (WA) comes from the process of total evapotranspiration of the rain water (ET\textsubscript{green}), except the natural vegetation evapotranspiration (ET\textsubscript{env}) and the evapotranspiration of unproductive areas. Figure 7 shows the results for green monthly environmental sustainability in the state of Espírito Santo.
Figure 6. Relationship between the average total volume of rain water and the green water footprint in the state of Espírito Santo.

Figure 7. Monthly environmental sustainability of the green footprint in the state of Espírito Santo.

According to the results shown in Figure 7, the green footprint was unsustainable in most months of the year. From May to September, this unsustainability was more significant, especially in June, with scarcity index close to 1.6, due to the lower rainfall rates that occur during this period (drought).

Regarding the availability of green water, the months with the highest rates were January, March, November and December, with 7.2; 6.2; 8.4 and 9.2 billion m$^3$/month, respectively. An excess was found in seven months of the year in relation to
the green footprint and availability, especially the months of February, June, July and August, which showed higher indices.

This unsustainability behavior was also analyzed by LEAL et al. (2018), in the Itapemirim river basin, which obtained relatively similar results: seven months of the year with the highest representativeness of green water scarcity, also highlighting the month of June, with the highest value.

When the water scarcity values are compared, it is clear that LEAL et al. (2018) obtained, especially in the months with less precipitation (May to September), higher EA values than those obtained in this study. This was due to the fact that ETR was considered in this study, while LEAL et al. (2018) used potential evapotranspiration (ETP) to calculate green WF of crops, using ETR only for pasture and native vegetation. In addition, LEAL et al. (2018) also used a different database from this study regarding evapotranspiration values. That is, the estimates of the crop’s green footprint were made by LEAL et al. (2018) as if irrigation was used in all crops. However, because most of the crops are not irrigated in the state, only the ETR was used in this study, aiming to obtain better estimates.

CONCLUSIONS

• In estimating the total green WF in the state of Espírito Santo, it was found that pastures had the highest percentage of participation in water consumption, followed by native vegetation, coffee, forestry and other agricultural crops. This sequence followed the same order of magnitude of area of the main classes of land use in the state.

• The green WF represented about 80% of the total annual average volume of precipitation in the state over the studied period. Such relationship was greater in the North (89%) macro-region, followed by the Central (84%), South (76%) and Metropolitan regions (73%)

• Water consumption by green WF was unsustainable, that is, it exceeded the availability of water (rainfall) in six months of the year (February, and from May to September), corresponding to the least rainy months in the state of Espírito Santo.

REFERENCES


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