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Agricultural development in Ecuador: a compromise between water and food security?

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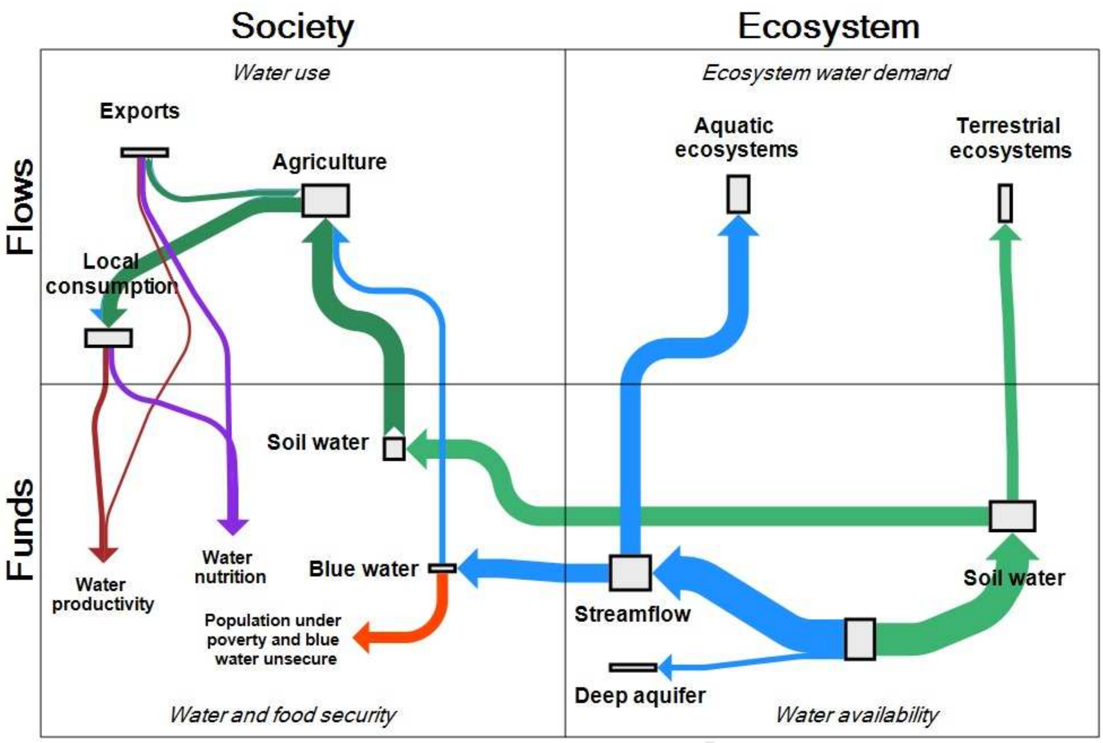
Abstract

Ecuador is facing several threats to its food and water security, with over a tenth of its population currently undernourished and living in poverty. As a response, its government is incorporating new patterns of land use and developing regional water infrastructure to cope with the related challenges. In this study, we assess to what point these efforts contribute to integrated water and food security in the country. We investigated the period 2004-2013 in the most productive agricultural region - the Guayas river basin district (GRBD) - and analysed the impacts of different scenarios of agricultural change on local water security. Our approach integrates MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) with the hydrological SWAT model. Freshwater allocation is evaluated within all the water cycle from its source (natural systems) to the final users (societal systems). Water security is assessed spatiotemporally in terms of water stress for the population living in poverty. Water productivity is obtained in relation to agricultural production and nutrition. The multi-scale analysis shows that whereas at national level the median annual streamflow has a similar magnitude than rainfall stored in soil, these two parameters differ spatiotemporally at subbasin level. The study finds the greatest challenges in achieving water security is the south-east and central part of the GRBD, due to water scarcity and a larger population living in poverty. However, these areas are also simultaneously, where the greatest crop water productivity is found. We conclude that food production for both domestic consumption and market-oriented exports can be increased while meeting ecosystem water demands in all the GRBD regions except for the east. Our integration of methods provide a better approach to inform integrated land and water management and is relevant for academics, practitioners and policymakers alike.

Keywords: irrigation; national development policy; SWAT; water metabolism; Socio-Ecosystems.



Society
Ecosystem
Flows
Funds
Water use
Ecosystem water demand
Exports
Agriculture
Local consumption
Aquatic ecosystems
Terrestrial ecosystems
Soil water
Blue water
Water productivity
Water nutrition
Population under poverty and blue water unsecure
Streamflow
Soil water
Deep aquifer
Water and food security
Water availability

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1. Introduction

Ecuador faces an important food security challenge, where approximately two million people - 11% of its population - are undernourished (FAO, 2017). In response, the government has implemented a legal reform that enshrines food sovereignty in its Constitution (República del Ecuador, 2008) following the principles of the National [Development] Plan for Good Living[1] –NPGL– (SENPLADES, 2013). The NPGL principles were incorporated into the Food Sovereignty Regime Organic Law of 2009, which sought to avoid further monocultures and provides support for local farmers in the country. It has resulted in a raise of public investment in agriculture from $93 million to $268 million in the period 2003-2009 (Nehring, 2012). Despite legal efforts, public investment has not achieved local food security. On the contrary, it resulted in an increase in food production for export – a similar trend to other Latin American countries (Falconí et al., 2017).

The country has a large water endowment (average runoff of 1,275 mm), but it also presents an unequal distribution of water throughout regions and dry-wet seasons (CISPDR, 2014). A number of studies assess the physical and social drivers of Ecuador's water allocation within the water cycle. These include the effects of land use change (Espinosa and Rivera, 2016) and climate change (Molina et al., 2015) over freshwater provision or the contribution of paramo and aquifers retention capacity to baseflow (Guzmán et al., 2015). Research has also addressed the role of water user organisations in water management (Hoogesteger, 2013) and how institutional reforms strengthen water rights (Cremers et al., 2005) of local irrigation communities. Those studies focus mainly on small (i.e., <500 km^2) highland catchments from the Andean region, but to date and to the

[1] The National Plan for Good Living (Plan del Buen Vivir) comes out at four-year intervals (2009–2013 followed by 2013-2017). It is based on the indigenous Quechua concept of Sumak Kawsay (Buen Vivir) - a social paradigm - with objectives to 'better the quality of life of the population, develop their capacities and potential'.

best of our knowledge there are no detailed spatiotemporal assessments of Ecuador that cover the distribution of available water resources, land use distribution (including irrigated areas) and their assigned water demand. More importantly, there are no studies on the areas with larger population densities of people living in poverty and where the most valuable crops are produced.

Distribution of available water resources will also likely be affected by future political decisions, related to changes in agricultural land patterns and water infrastructure, to ensure local and global food demand. The National Hydraulic Plan (period 2014-2035) and the National Plan for Irrigation and Drainage foresee an increase of the irrigated area by 53% (from 941,000 to 1,443,000 ha) (MAGAP, 2013) and the existing reservoir volume by 90% (from 7,690 hm^3 to 14,672 hm^3) (CISPDR, 2014), showing a strong connection between food and water security. Thus, for successful implementation over time, both agricultural development and water resource management must be coherent.

Integrated Land and Water Resources Management (ILWRM) is a scientific approach that highlights the connections between land and water management with the purpose of strengthen their interaction (Falkenmark et al., 2014). ILWRM builds on Integrated Water Management principles, but it provides a further step to environmental evaluations due to the considerations of water-land interactions at the local level (*ibid*). Indeed, local issues are more tractable because the systems co-exist in space (de Loë and Patterson, 2017). Despite the scientific consensus on the usefulness of the approach, ILWRM has had limited practical applications by water practitioners and lacks explicit consideration on environmental policies and development plans. For example, in Europe, the Water Framework Directive does not mention the relevance and effects of land use changes and practices on available water resources, which has resulted in a disconnection between agricultural and water policy objectives (Cabello and Madrid, 2014). Moreover, certain agricultural policy measures also determine land use management practices with effects on water allocation (Salmoral et al., 2017). This has also been the case in Ecuador, where national development plans, aim to increase food provision by including additional irrigated areas and changing crop patterns distributions, but there is no evaluation on the implications of such decisions on local water resources.

We focus on the Guayas river basin district (GRBD), as it is central to Ecuadorian water and food security. The study aims to answer the following questions: 1) What are the water needs for food security in the GRBD? 2) How does food security and the related agricultural development affect water security? The paper is organized as follows. Section 2 describes the selected case study and the ILWRM method, which combines MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) (Giampietro et al., 2009) and the hydrological model SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998). The applied indicators for food and water security links and water productivities are described and scenarios towards water and food security aims presented. Section 3 shows the main results, also including an evaluation of water and food security changes under the proposed scenarios. Section 4 discusses the relevance of our method and obtained multi-level results, and highlights the pressures on local water resources as well as the related implications of national development strategies for water and food security.

2. Materials and methods

2.1. The Guayas river basin district

The Guayas river basin district (GRBD) has a land area of 44,532 km^2 (i.e., 16% of the country surface) and provides water resources for about 6 million inhabitants (i.e., 40% of the national population (INEC, 2015)). In 2010, the GRBD contained 380,840 ha irrigated land, which holds 57% of the national agricultural irrigated area (CISPDR, 2014; CISPDR, 2015). The GRBD is a humid tropical system comprising a rainy season from December to May and a wet one for the remaining months. There are precipitation variations from the north (2,900-3,100 mm) to the south (300-700 mm) (CISPDR, 2015). The GRBD contains the largest share of the national agricultural area for the region's most significant crops i.e., rice (96%), banana (68%), sugar cane (97%), corn (55%) , coffee (33%) and palm oil (19%) (MAGAP, 2015) (Fig. 1; Table A1).

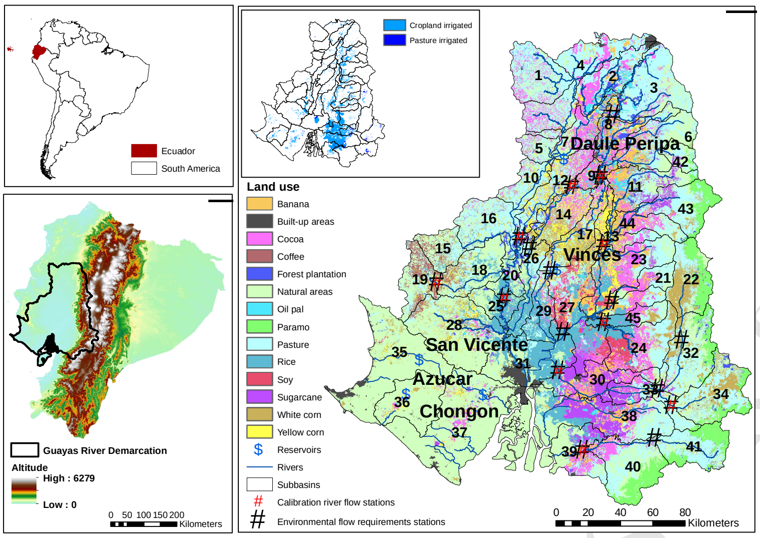

Fig. 1. Location of the Guayas river basin district. Main land use classifications and irrigated areas are shown.

2.2. Studying the water metabolism within ILWRM

ILWRM analyses face an important 'issue of scale' (Cumming et al., 2006) because joint water-land analyses require the simultaneous adoption of different spatial-temporal scales. These differences are marked by water and land dynamics, with differing cycles and geographical boundaries. To address these factors this study assesses the water metabolism of socio-ecological systems from an ILWRM perspective using MuSIASEM (Giampietro et al., 2009).

MuSIASEM is a very powerful framework for the analysis of water use and its resulting impacts (Madrid-López et al., 2014; Madrid et al., 2013; Serrano-Tovar et al., 2014). However, it needs to be adapted to soil and land use dynamics for its application to ILWRM. Fig. 2 shows a chart that summarizes the adaptation and how the water metabolism of socio-ecosystems is conceptualized. The upper part connects the flows of water that reach the land surface and are available at the ecosystem level with those water flows used for food production. The lower level shows the structural organization of each system and the factors that transform them: climate change, ecosystem water requirements and food provision. Policy making is an important part of the metabolism, as it guides the biophysical flows that and has a direct influence over water and food security. Current policy goals have been used in the analysis to build scenarios. They are further developed in Section 2.5.

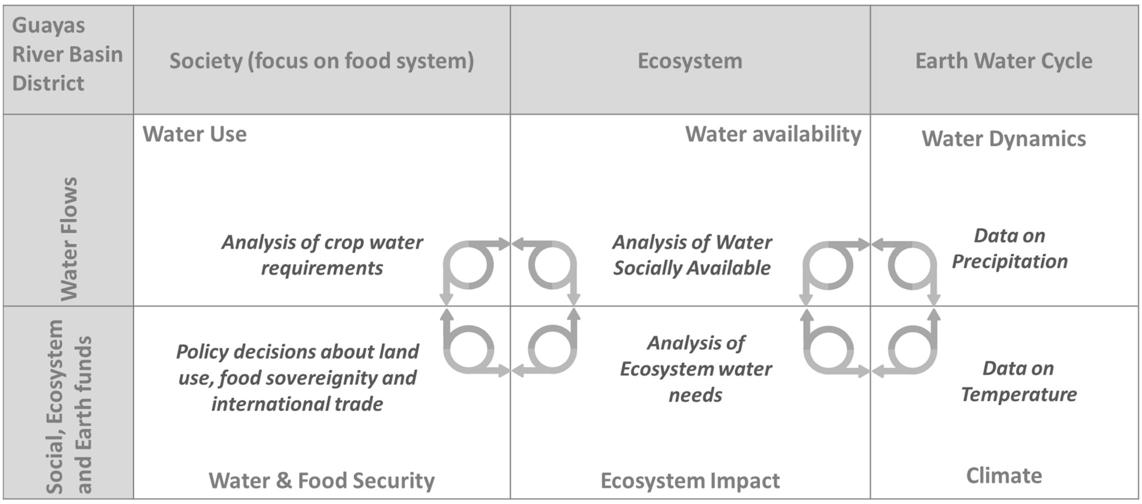

Fig. 2. The water metabolism of the food socio-ecosystem of the Guayas river basin district. Adapted from (Madrid-López and Giampietro, 2015).

2.3. MuSIASEM-SWAT integration

In this study, MuSIASEM serves as a framework in which (1971) Georgescu-Roegen's 'flow' and 'fund' concepts are used to structure the analysis. Funds refer to the components of the socio-ecosystems, which must be maintained (trees, people, river patterns, etc.) In general terms, a specific analytical tool is chosen according to the type of flow to be studied. The results of this analysis are contextualized with a study of the fund elements. As this study focuses on a river basin district, we use the hydrological model SWAT (Arnold et al., 1998). SWAT is able to simulate ecosystem water funds and societal water flows and integrate different spatiotemporal levels of water-land links. The model presents the capacity to combine hydrological components with a plant growth module, which is essential for the assessment of agricultural production in our study. However, it fails to tell the story behind those flows, thus the fund description of MuSIASEM is used for their contextualization.

We use SWAT parameters as proxies for the estimation of five different water metabolism semantic categories[2], as presented in Madrid-Lopez and Giampietro (2014) (Table 1):

- *Ecosystem water funds* refer to the natural runoff (R_{nat}) and soil water storage ($SWS_{ecosystems}$) patterns. R_{nat} and $SWS_{ecosystems}$ are calculated following Salmoral et al. (2017).
- *Ecosystem water flows* refers to the water demand from terrestrial and aquatic ecosystems for their proper functioning.
- *Societal available water* (*SAW*) is the amount of water that can be used by society taking into account constraints of ecosystem water demands and available infrastructure.
- *Gross water appropriation* (*GWA*) includes the consumptive (i.e., evaporation, transpiration, integration into a product, or release into a different drainage basin or the sea) and non-consumptive (i.e., water used for cooling or polluted water) water used for human activities.
- *Net water use* (*NWU*) considers only consumptive water that has actually been used (excluding losses).

We perform a monthly step analysis during the period 2004-2013 for each subbasin generated by SWAT. The outputs are later summarized by the total river basin district and at yearly steps. The detailed information required to run SWAT, design the model and evaluate its performance is included in the Supplemental Material.

Table 1. Water metabolism semantic categories adapted from Madrid-Lopez and Giampietro (2014) and the proxies estimated with SWAT.

Water function	Water metabolism category	Water types	SWAT parameter
Fund	Ecosystem water	Natural runoff (R_{nat})	Streamflow without human abstractions
		Soil water storage ($SWS_{ecosystems}$)	At annual step: evapotranspiration without irrigation practices At monthly step: sum of the soil moisture and effective precipitation at the beginning of each month
Flow	Ecosystem water	Environmental flow requirements (*EFR*)	River flow left to the aquatic ecosystems
		Evapotranspiration	Evapotranspiration from terrestrial ecosystems

[2] More details in Supplemental Material

			from the environment	
Fund	Societal available water (*SAW*)	Blue water (SAW_{blue})	Available streamflow ($R_{nat} - EFR$)	Water yield without human abstractions minus environmental flow requirements. It only considers surface water connected to active shallow aquifer.
			Reservoirs (ST_{res})	Water stored in reservoirs
		Green water (SAW_{green})	Soil water storage for human purposes (SWS_{human})	At annual step: evapotranspiration without irrigation practices for croplands and pasturelands At monthly step: sum of the soil moisture and effective precipitation at the beginning of each month for croplands and pasturelands
Flow	Gross water appropriation (*GWA*)		Households water abstractions	Gross water withdrawn
			Industry water abstractions	Gross water withdrawn
			Surface water evaporation	Evaporation losses from surface water bodies
			Agricultural irrigation water abstractions (1)	Gross irrigation from surface water and reservoir sources
			Agricultural soil water flows	Evapotranspiration in agricultural areas, excluding irrigation
	Net water use (*NWU*)	Blue water (NWU_{blue})	Households water consumption	Net water withdrawn
			Industry water consumption	Net water withdrawn
			Surface water evaporation	Evaporation losses from surface water bodies
			Agricultural irrigation water consumption(1)(2)	Net irrigation from surface water and reservoir sources
		Green water (NWU_{green})	Agricultural soil water flows(2)	Evapotranspiration in agricultural areas, excluding irrigation source

(1) It does not consider losses during water distribution
(2) Part of the water consumed for local agricultural production will be exported in the form of virtual water

2.4. Evaluating food and water security links and water productivities

The evaluation of food and water security has been assessed with three different approaches[3]:

- Water security can be framed focusing on quantity and availability of water (Rodrigues et al., 2014), which in the end is also related to food security to meet agricultural needs (Cook and Bakker, 2012). *Blue flow/fund* shows the water stress

[3] See Supplementary Material for more details regarding methods and data used.

by subbasin *s* and month *m* and is quantified as a ratio of water consumed to water available:

$$blue\ flow/fund_{s,m} = \frac{NWU_{blue}}{SAW_{blue}} \quad [1]$$

Where, NWU_{blue}: net water use in streamflow (volume time^{-1}); SAW_{blue}: societal available water in streamflow (volume time^{-1})

Similarly, *green flow/fund*:

$$green\ flow/fund_{s,m} = \frac{NWU_{green}}{SWS} \quad [2]$$

Where, NWU_{green}: agricultural soil water consumption from rainfall source (volume time^{-1}); *SWS*: soil water storage (volume time^{-1})

NWU_{blue} and SAW_{blue} are calculated as the sum of the flows and funds for all subbasins upstream of the subbasin under study. In contrast, NWU_{green} and *SWS* only refer per subbasin.

- Blue water security is also evaluated with a weighted population under poverty by the volume of unavailable water per unit of drainage area (*Poverty water unsecure* $_{s,m}$, in inhabitants m^3/m^2), when net blue water use exceeds societal available water:

$$Poverty\ water\ unsecure_{s,m} = \frac{Population_{poverty} \times (NWU_{blue} - SAW_{blue})}{drainage\ area} \quad \text{if } NWU_{blue} > SAW_{blue} \quad [3]$$

Where, $population_{\ poverty}$: population under poverty for each drainage area; *drainage area*: sum of the total upstream subbasin area for each under study (m^2)

In the GRBD a total 3,681,472 inhabitants are considered to be living in poverty (INEC, 2011; CISPDR, 2015).

- Crop water productivity (*CWP* in kg/m^3) and crop water nutrition (*CWN*, kcal/L) assess the level of food production in relation to water consumption, including both blue and green water. These are calculated at subbasin level and annual resolution in dry matter content for croplands and pasture. Crops production is first converted into the main food product applying extraction coefficients and later to kcal.

2.5. Scenarios towards water and food security aims

Four scenarios evaluate the implications on local water resources and food provision by 2035 due to changes on water infrastructure and agricultural land uses (Table A6)[4].

"Irrigation": Development of new water infrastructure under current crop patterns

This scenario exclusively shows the planned expansion of irrigated areas (from 413,420 to 814,900 ha) and reservoir storage capacity (from 8,625 to 12,332 hm^3) according to the GRBD Hydraulic Plan. The crop distribution area is the same as in the baseline scenario (Fig. 1).

In the following scenarios, the irrigated areas, storage capacity and water transfers are kept the same as in *Irrigation*. The only condition that changes is crop distributions.

"Exports": Crop pattern changes supporting international exports

Crop pattern changes are justified by the enthusiasm for international exports. Between 2013 and 2035 coffee, cocoa and palm oil areas are annually increased by 1% and the reforested areas by 2%, according to the existing agricultural and reforestation programs. To meet this expansion, pasture land and natural herbaceous vegetation are reduced by 170,283 and 2,090 ha, respectively.

"Sovereignty": Crop pattern changes towards food sovereignty aims

This scenario promotes agricultural production and consumption within the country. Sugar cane, soya and yellow corn are selected towards food sovereignty aims, since these are the main products that Ecuador currently imports. They are increased with an annual growth rate of 1.6%, 2.2% and 2.2%, respectively. To allow this crop pattern change, a total area of

[4] More details about data and methods applied are available in the Supplemental Material.

171,470 ha is reduced, including mainly pasture land, followed by natural herbaceous vegetation, white corn and bush areas.

"Mix": Promotion of both international exports and food sovereignty aims

The last scenario assesses the overall changes from Scenarios 2 and 3, supported by the idea that a mix from previous scenarios might be the most plausible future option.

3. Results

3.1. The water metabolism of the GRBD

The annual median ecosystem blue water fund during the study period (31,793 hm^3 - i.e., 714 mm) is slightly larger than the green water fund (30,553 hm^3 – i.e., 686 mm). At subbasin level both streamflow (between 90 and 1,960 mm) and soil water (between 60 to 1030 mm) funds differ spatially (Fig. A2). At the societal level, streamflow availability is reduced to meet environmental flow requirements, but the presence of reservoirs provide an additional median annual volume of 5,375 hm^3. The agricultural character of the river basin district is shown by the dominance of freshwater water flows for agricultural production. Agricultural production allocates 75% and 64% of the blue and green net water use, respectively. The GRBD is water self-sufficient in food trade because it exports in the international market more virtual water (4,345 hm^3) than it imports (1,064 hm^3). However, the exports depend on a greater extent to blue water, which comprises 30% of virtual water exports, whereas blue virtual water imports only make up 10% (Fig. 3).

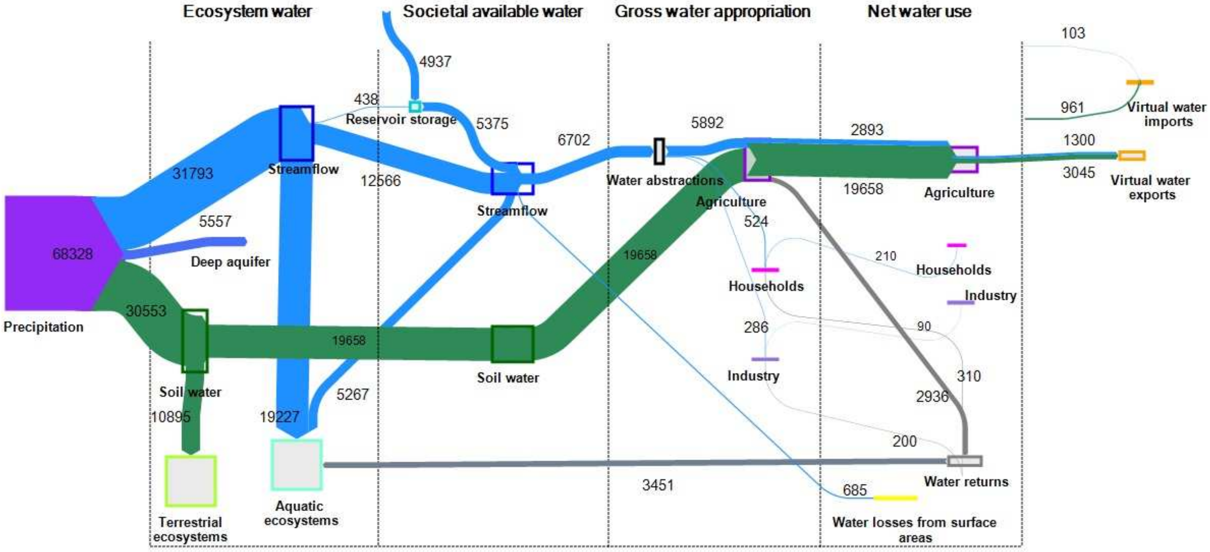

Fig. 3. Links between the water metabolism of ecosystems and society in the GRBD. Annual median values in hm^3 for the period 2004-2013.

The south-east of the basin is where the largest annual net blue water use (i.e., NWU_{blue}) occurs (> 200 mm). In those subbasins irrigation comprises more than 98% of the NWU_{blue}, except for subbasin 31 where 50% of the water consumption refers to urban demand to supply Guayas city. Subbasins with the greatest NWU_{green} (i.e., >800 mm) are located in the centre and north (Fig. 4). The values of these green water flows are shaped by existing land use distribution, and also by climatic conditions and capacity of soils to store water.

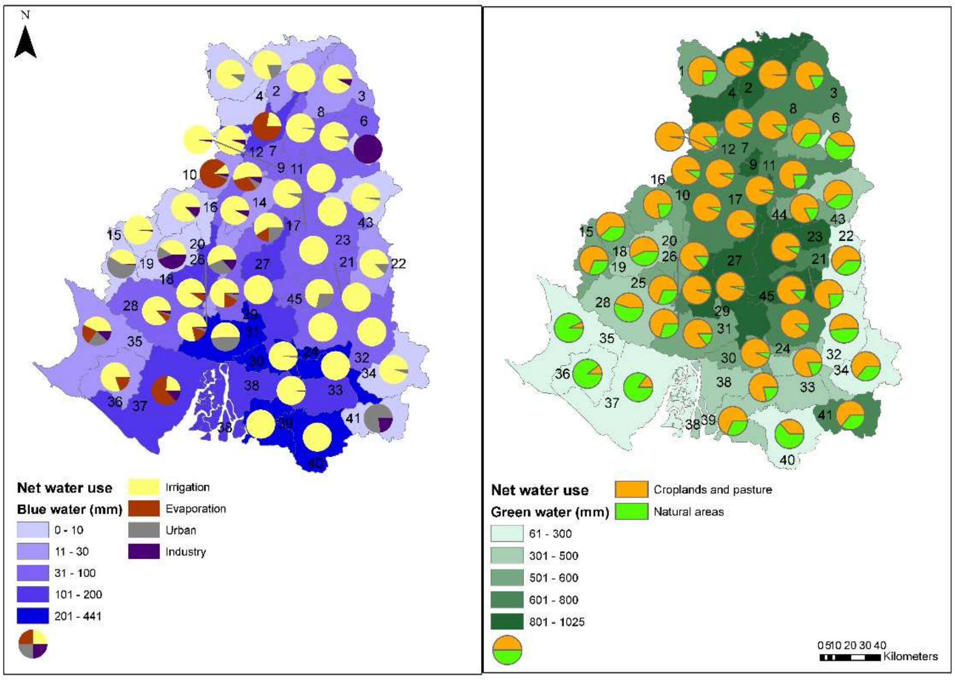

Fig. 4. Blue (left) and green (right) net water use (mm) by subbasin as annual median values for the period 2004-2013. Pie charts show the proportion of main water users.

3.2. Water stress and population under poverty

At subbasin and monthly steps, some regions appear as blue water unsecure due to water scarce conditions. NWU_{blue} exceeds the available blue water for human purposes (i.e., SAW_{blue}) in the south east, central and upper parts (Fig. 5). *Blue flow/fund* takes values > 1 upstream Angas, Cañar, Macul dam and Quevedo monitoring stations. There are also cases (i.e., Babahoyo, Chimbo and Macul dam stations) when even the monthly SAW_{blue} shows negative values (Fig. 5), which means that available streamflow and water stored in reservoirs cannot cover the environmental flow requirements (Table A7). In contrast, Daule Peripa and Vince reservoirs, located at the north-west and central part, allow water savings during the wet period to maintain water demand downstream (i.e., Daule II and Vince stations).

Green flow/fund has the smallest values (i.e., < 0.6) for all subbasins between February and April, which coincides with the rainy season. October and November, is when *green flow/fund* > 0.6 occurs mostly for subbasins located in the centre of the GRBD, whereas in

July, it occurs for subbasins located in the northwest (Fig. A4). This is probably explained by different precipitation distribution in the study area.

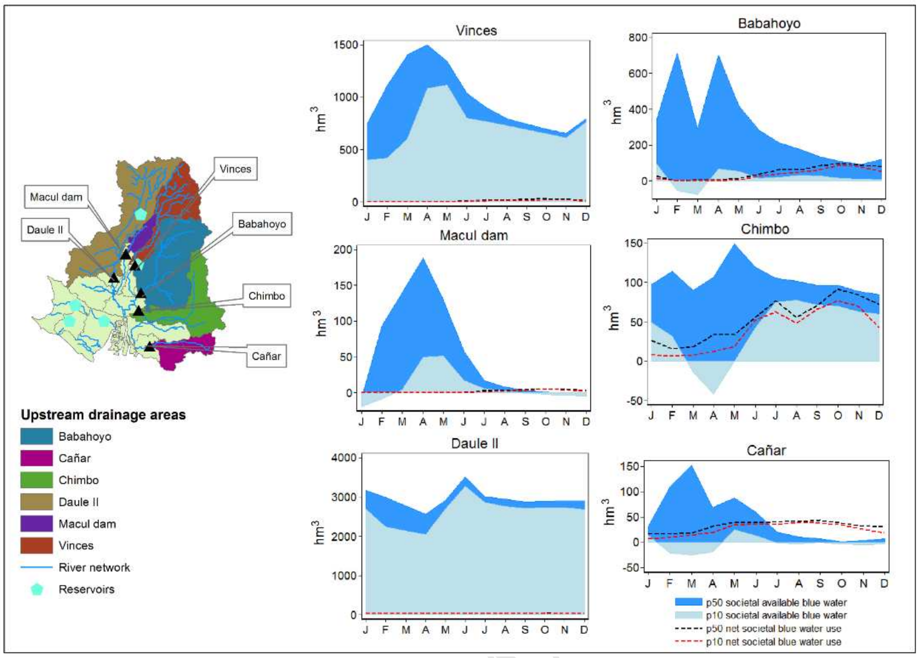

Fig. 5. Median (p50) and 10th percentile (p10) of monthly societal available water (SAW_{blue}) and net blue water use (NWU_{blue}) during the study period 2004-2013 for upstream drainage areas.

Poverty water unsecure (inhabitants m^3/m^2) weights the total population living in poverty by the volume of unsecure blue water per drainage area. East GRBD is where most times NWU_{blue} exceeds the existing fund for human purposes (grey subbasins in Fig. 6). *Poverty water unsecure* shows monthly median values larger than 1,000 inhabitants m^3/m^2 upstream Babahoyo station, Chimbo station and subbasin 38 (Fig. 6). The population under poverty and blue water stress differs greatly from year and month depending on the climatic years (i.e., from zero to a maximum of 1,260,317 inhabitants) (Table A8). Median monthly values of *poverty water unsecure* ranges from 2,057 (February) to 7,522 (September) inhabitants m^3/m^2, considering all the affected areas. A total population of 1,200,996 inhabitants and 51% GRBD's area is under monthly blue water stress (unsecure volume of blue water from 39 to 142 hm^3) (Table A9).

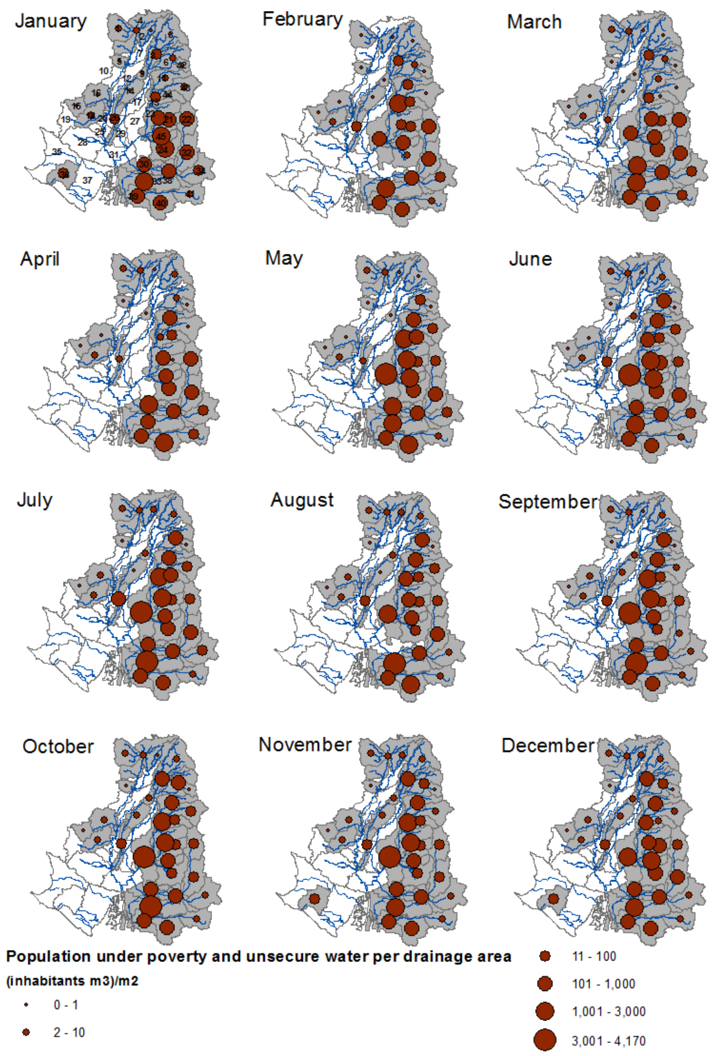

Fig. 6. Population under poverty and unsecure blue water per drainage area (*Poverty water unsecure*, in inhabitants m^3/m^2). The dots refer to the sum of all the upstream population, unavailable water and area.

3.3. Food vs water security

In the GRBD, 28.9 x 10^13 kcal (including pastures) are produced as median annual values for the study period, 31% allocated for crops for exports and the remaining for food sovereignty crops. Regarding blue water, crops for exports account for 53% of the gross water appropriation, whereas sovereignty crops allocate 47%. For green water, the magnitude of sovereignty crops goes up to 72% of the total green water consumption (Table 2).

Table 2. Summary of median annual values of water metabolism variables by crops for exports or food sovereignty purposes.

		Area (ha)	Yield in dry weight (t/ha)	Kcal supplied	Gross blue water flow (hm^3)	Net blue water flow (hm^3)	Green water flow (hm^3)	Crop water productivity (kg/m^3)	Crop water nutrition (kcal/L)
Exports	**Total**	666,470	2.7	8.90E+12	3,140	1,550	5,400	0.26	1.28
	Banana	167,870	8.9	7.80E+12	1,960	990	1,370	0.63	3.31
	Cocoa	408,250	0.3	6.30E+11	1,180	560	3,280	0.03	0.16
	Coffee	38,640	0.2	0	0	0	310	0.02	0
	Oil palm	51,710	4	4.80E+11	0	0	440	0.48	1.1
Sovereignty	**Total**	2,307,960	3.5	2.00E+13	2,730	1,340	14,100	0.52	1.3
	Total (without pastures)	1,227,870	3.4	1.90E+13	2,430	1,190	6,480	0.55	2.48
	Pasture	1,080,090	3.6	7.60E+11	300	140	7,620	0.5	0.1
	Rice	370,010	3.3	5.30E+12	1,070	540	2,390	0.41	1.81
	Soy	52,860	1.2	1.20E+11	20	10	100	0.56	1.04
	Sugar cane	147,270	13.8	1.30E+13	1,120	530	980	1.34	8.58
	White corn	262,010	0.4	5.00E+11	90	40	1,620	0.07	0.3
	Yellow corn	395,730	2	5.10E+11	120	70	1,390	0.54	0.35

The most efficient areas for food production in terms of water consumption (i.e., greater *CWP*, in kg/m^3) are mostly found in the centre and south east, with median values from 0.41 to 2.85 kg m^{-3} (Fig. 7a). High pasture yields generate high *CWP* in some subbasins (e.g., subbasin 18). Larger *CWP* also takes place in subbasins with a dominant presence of sugar cane and banana (e.g., subbasins 23 and 27). In contrast, subbasins within the Andean region have the lowest *CWP* with values below 0.1 kg m^{-3} (Fig. 7a).

In terms of nutritional value, as expected, those subbasins with irrigation can produce larger quantities of kcal too (i.e. greater *CWN*, in kcal/L). *CWN* shows a similar geographic distribution as *CWP*. However, some differences are found due to the existing crops patterns per subbasin and caloric content of the food product they provide (Fig. 7b). For instance, subbasins 42 and 43 has a median of 0.45 and 0.34 kg m^{-3} *CWP*, respectively, but the median *CWN* is 8.3 and 6.3 kcal/L. This is due to the existence of sugarcane in 10% of each subbasin area, which shows both a high crop yield and caloric content (387 kcal/100 grams).

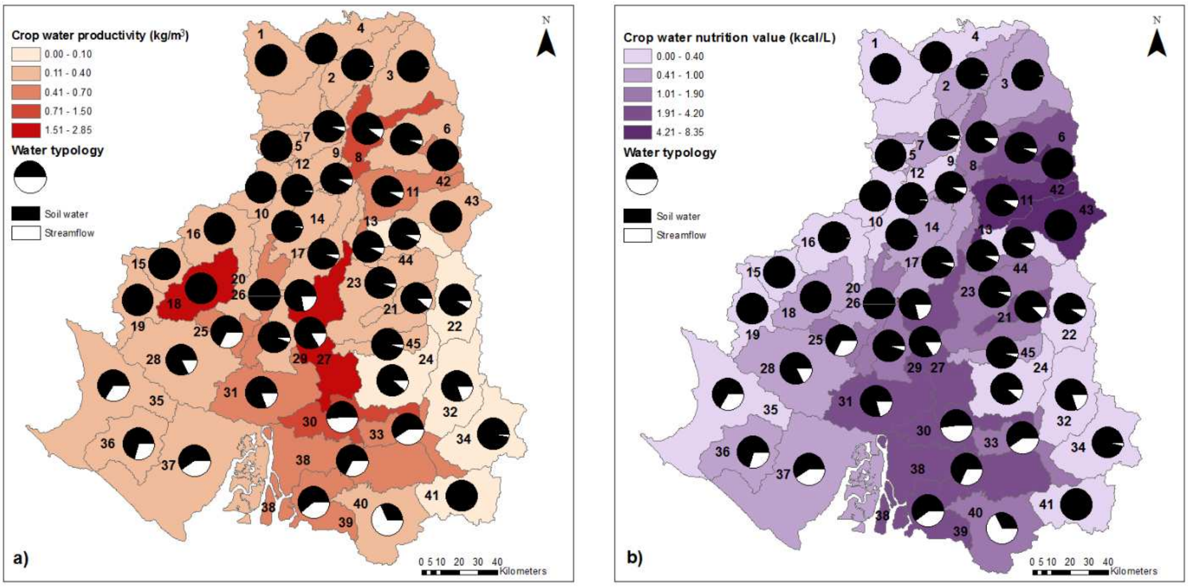

Fig. 7. a) Crop water productivity (kg m^{-3}) and b) crop water nutrition (kcal L^{-1}) as median values per subbasin for the period 2004-2013. The water typologies (soil water and streamflow) are also shown.

3.4. Water and food security changes under 2035 scenarios

In the proposed scenarios, annual median values of societal available blue water (SAW_{blue}) (i.e., natural runoff - environmental flow requirements + reservoir storage) decreased in comparison to *Baseline* (from 17,940 in *Baseline* to 16,130 hm^3 in *Mix*). Available streamflow decreased from 12,565 in *Baseline* to 8,460 hm^3 in *Mix*, but this decrease is offset by providing water from reservoirs. Gross (net) irrigation raises from 5,890 (2,895) in *Baseline* to 10,165 hm^3 (6,135) in *Mix*. In contrast, agricultural green water consumption declines from 19,660 (*Baseline*) to 18,505 hm^3 (*Exports*) (Table A10).

The scenarios show a decrease in NWU_{blue} in relation to existing SAW_{blue}, as additional reservoirs can mitigate water stress that was occurring in some regions in *Baseline*. *Blue flow/fund* is reduced from *Baseline* to proposed scenarios into values < 1 in Macul dam, Chimbo, Babahoyo and Cañar (Fig. 8 for median values and Fig. A5 for 90th percentile). Moreover, with the proposed scenarios, no negative SAW_{blue} takes place as in baseline scenario (Table A7), meaning that available streamflow and water stored in reservoirs can meet the required environmental flow requirements, as long as adequate management of water release from reservoirs is carried out. Nevertheless, upstream Chimbo station still faces water security issues due to water stress in the proposed scenarios. About 95 hm^3

reservoir capacity have been added in Chimbo's upstream subbasins, but blue water stress has worsened due to increased irrigation.

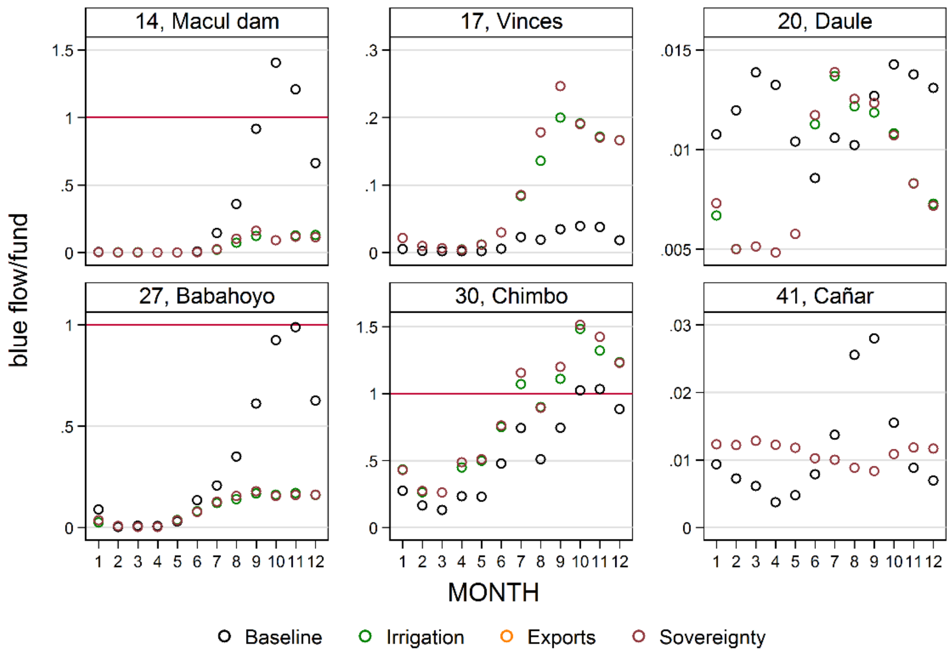

Fig. 8. Changes between *Baseline*, *Irrigation*, *Exports* and *Sovereignty* scenarios for median monthly *blue flow/fund* for selected drainage areas. Median values do not include negative *blue flow/fund* occurred during baseline scenario. See Fig. 5 for location of drainage areas. The number in the headings refer to the subbasin outlet number of each drainage area.

Considering the entire GRBD, the largest increase on agricultural production occurs in the *Irrigation* scenario, which is related to the weight that pasture production provides to the total agricultural production, also reflected in the greatest *CWP* in the *Irrigation* scenario (0.55 kg/m^3). However, the greatest amount of kcal is produced in the *Sovereignty* and *Mix* scenarios, mainly due to sugar cane, soya and corn. Both scenarios also show the greatest *CWN* (1.47 kcal/L in *Sovereignty* and 1.48 kcal/L in *Mix*) (Table A10). At the subbasin level, *CWP* increases in 31 out of 45 subbasins in *Irrigation*, whereas in the *Exports*, scenario only 23 subbasins increment their *CWP*. *Sovereignty* shows the largest number of subbasins increasing their *CWP* with a total of 36 subbasins out of 45, related to the change of crop patterns. In contrast, all subbasins increase their *CWN*. The largest changes take place in *Sovereignty* and *Mix*, where 11 out of 45 subbasins increase the annual median *CWN* by more than 2 kcal/L (Fig. 9).

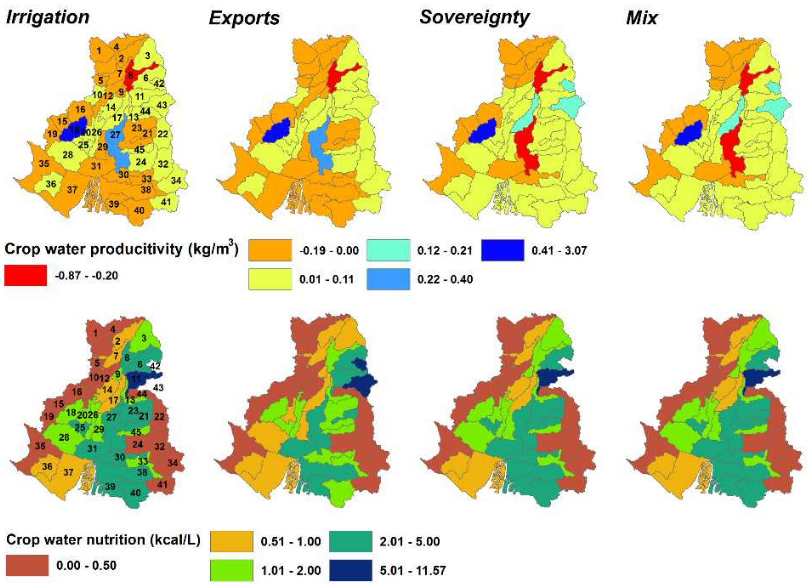

Fig. 9. Changes on median values for crop water productivity (kg/m^3) and crop water nutrition (kcal/L) between the proposed scenarios and baseline scenario.

4. Discussion

4.1. The novelty of water metabolism for assessing water and food security

Within hydrological research, there are many evaluations on the different components of the water cycle (e.g., runoff generation, groundwater recharge, evapotranspiration) and a vast experience in hydrological planning on the allocation of flowing blue water resources. However, approaches that are able to consider in more detail the current links between natural and societal water systems are needed, like the one addressed here. A multi-level visualization to work towards ILWRM approaches is relevant to understand the overall view (from the natural system to final users) of water allocation, considering both streamflow and rainfall stored in the soil. In the GRBD, within the ecosystem water budget, annual streamflow water availability exceeds 1.04 times soil water, which coincides with the 1.05 ratio that has been found in similar subtropical humid conditions (Chen et al., 2016). In contrast, under drier climate conditions, such as in the Mediterranean climate, this value can drop to 0.3 (Salmoral et al., 2017), with this ratio depending on the capacity of soils to store rainfall.

In the GRBD and period under study, green water (as median annual value) comprises the largest water consumption with 29% of the annual precipitation, in comparison to the net blue water with 6% annual precipitation. The high rainfall and runoff generation in some regions of the GRBD accounts for green water consumption values below the 55-60% global estimations, whereas the presence of irrigation makes blue water consumption above the 1% global average of precipitation (Vanham, 2015). Agriculture is the largest water consuming sector, demanding 64% and 75% of the green and net blue water flows, respectively, showing blue water consumption values slightly below the global average of 80-87% (Hoekstra and Mekonnen, 2012; *ibid*). The detailed evaluation of blue and green water flows indicates the dependence on climatic, soil and anthropogenic conditions as well as the relevance of assessing both flows in water and food security evaluations (Veettil and Mishra, 2016).

The GRBD can be considered rich in blue water resources, however, these are spatiotemporally unevenly distributed (i.e., annual median values from 90 to 1,960 mm) making it difficult to meet societal water demand under sustainable boundaries throughout the study area. Our water metabolism approach - with the application of flow/fund ratios - applies a bottom-up process of defining water boundaries at the watershed level (Rockström et al., 2014). It adds value to existing river basin scale studies (Steffen et al., 2015) due to the detailed spatiotemporal assessment of water impacts which occur at more local levels. Our method also shows the value of identifying those populations not achieving water security as well as accounting upstream blue water available to downstream users, as previous global studies have also done (Green et al., 2015). In the GRBD, the greater number of people living under water unsecure conditions are located in the east of the river basin district. This is the area where the central and regional governments will require to put more efforts - in the future - to meet both water and food security for local livelihoods.

Some authors claim that the key for resolving the water-food dilemma is a focus on having more nutritional value per drop of water consumed (Rockström et al., 2014), which we addressed with the application of crop water productivity indicators (i.e., *CWP* and *CWN*). In the GRBD, the increasing order for the *CWN* is: coffee < pasture < cocoa <white corn < yellow corn < soy < palm oil < rice < banana < sugar cane, ranging from 0 to 8.6 kcal/L (Table 2). However, what needs to be highlighted is that the largest crop water productivities are found in subbasins that are water scarce and with a large proportion of the population living in poverty. In contrast, the lowest productivities are found in the lower populated Andean region due to the lower yields produced under harsh climatic conditions. Besides the uneven biophysical conditions in the GRBD, differences in crop water productivities would also be related to the types of irrigators and their purpose. The aims of indigenous farmers located in the Andean region are mainly for local markets and self-sufficiency. Whereas, farmers located close to the coast largely produce for national consumption and exports e.g., rice, and banana. The latter are associated with agricultural producers associations that give them greater access to national and international markets (Gaybor et al., 2008).

4.2. Understanding agricultural water management findings

A general concern in irrigation water management is to reduce pressures on local water resources. Consumptive water savings can be achieved when increasing irrigation systems efficiency, as featured in the National Irrigation Plan in Ecuador, which calls for irrigation technology and system efficiency. At field level, blue water withdrawal (i.e., gross water volume) can be reduced with modernized irrigation systems, which helps to redistribute water between sectors (e.g., agriculture, households, ecosystems), but at catchment level consumptive water (i.e., net irrigation) savings do not take place. Even an increase in blue water consumption can occur with higher irrigation systems efficiency, if additional areas are converted into irrigation (Olen et al., 2016) and/or crop patterns change to more water consuming crops (Rodríguez-Díaz et al., 2011) - and with a related added energy demand from 'technified' irrigation systems (*ibid*; Perez Neira, 2016). `

The study finds that agricultural soil water consumption declines from the baseline to proposed scenarios, because an appropriate irrigation dose has not taken place in relation to crop water requirements. Under auto-irrigation management, SWAT can be set up to a specific irrigation amount when the crop reaches a certain limit of water stress, but this amount must remain consistent, depending on the level of water stress. This leads to: 1) blue water percolation losses, when more irrigation water is applied to what the plant can transpire, and 2) rainfall losses after the irrigation event, because the soil cannot store more water or be used later by the plant. On the field, similar situations can occur. For instance, when land is converted from rainfed to irrigated conditions, crop yield will increase due to a steady application of water throughout the crop development. However, not following an adequate soil water balance and applying an appropriate irrigation dose at a given moment can lead to scarce or excess of irrigation. In the end, appropriate crop irrigation schedules can help farmers to understand crop water requirements and irrigate accordingly. To date in Ecuador, there is still an inadequate water management for irrigation (Espinosa and Rivera, 2016).

4.3. Implications of Ecuadorian national development on food and water security

This study demonstrates how water security is driven not only by agro-climatic and geophysical conditions, but also by policy decisions about land use and food security. Food sovereignty in Ecuador is a national issue that has gained centrality in the political debate (Giunta, 2014), but not every nation can be food sovereign because of restrictions imposed by limited arable land, irrigation water and other resources (e.g., energy, fertilizers), particularly in geographically small countries. Thus trade is necessary to overcome ecological, climatic and other location specificities that make up crop division of global production (Agarwal, 2014). In the country, international trade plays a key role on food security, because of scarcity in specific commodities for the Nation's requirements (e.g. wheat mainly supplied from international trade for broilers feed in Ecuador). In the GRBD, we see that that the region can be water self-sufficient for agricultural production and related food trade. The GRBD exports more virtual water than imports, although exports embed a larger proportion of blue water resources than imports (i.e., 30% blue water in exports against 10% blue water in imports). Nevertheless, the role of primary products exports in the national economy is shown with their significant share of the Ecuadorian GDP; 24% in 2013 (Latorre et al., 2015), particularly relevant in the production of cocoa, bananas and coffee (Burnett and Murphy, 2014).

In Ecuador future irrigation plans will support both local food supply and international exports. Scenarios designed in this study can guide and complement future agricultural and water management decisions, towards achieving water and food security. Currently in the GRBD, about 28.7 million kcal are produced, as annual median values for the study period. In our scenarios, total kcal production is increased with the inclusion of new irrigated areas. Nevertheless, the scenarios with the largest total kcal production are *Sovereignty* and *Mix*, where more kcal for local consumption also take place. In both scenarios, the area of crops for exports (e.g., banana) and pasture reduces, whereas the area of crops that contribute to local consumption (e.g., yellow corn, sugar cane and soya) increases. Another scenario that could increase total food provision in Ecuador is one offered by Knoke et al. (2013). They propose shrinking existing pasture areas in Ecuador to facilitate an increase in cropland area, while total pasture area could still increase through the re-cultivation of abandoned grazing lands.

The planned state driven development of new irrigated areas and crop patterns will influence distribution of available water resources, as illustrated in the scenarios. SAW_{blue} in the proposed scenarios decreases in comparison to the baseline, which is partially offset by a greater reservoir management capacity during dry seasons. The planned reservoirs development will help to alleviate water scarce conditions, as long as all reservoirs can be build (and properly) managed, and their construction not be constrained by an unstable national economy. However, additional reservoir development and irrigated areas do not mean that all farmers will have access to land and water. Development of additional reservoirs is managed by the state, but canalization from new infrastructures to final users has not been considered and there is no a plan to date of how these new infrastructures will reach the final end users. There is a risk that development of new irrigated areas might put the country in a similar situation to that during 80-90’s, when public irrigation systems were created, but only a small part of the population, with better economic and social position, could get access to it (personal communication, 2015).

5. Conclusions

Achieving food security is part of the Ecuadorian political debate and influences decisions around land use and water management. This study provides a detailed spatiotemporal assessment of freshwater resources, and related water security indicators for agricultural production. The importance of catchment approaches is highlighted for balancing human and nature water requirements, and how feasibility of agricultural development needs to address impacts on local water security. Agricultural production allocates the largest freshwater share with 75% and 64% of net blue and green water flows, respectively, and the GRBD can be considered as water self-sufficient in food trade due to the positive virtual water exports (4,345 hm^3) and imports (1,064 hm^3) balance. Nevertheless, a total population of 1,200,996 inhabitants and 51% GRBD's area is under blue water stress, and the study finds water security as a challenge due to the combination of scarce water conditions and population under poverty in the south east and central part of the GRBD. It is in this part of the river basin district, where at the same time, the greatest annual crop water productivity (0.41 - 2.85 kg m^{-3}) and crop water nutrition (1.9 – 8.35 kcal/L) are found. The study also provides a first step towards creating agricultural scenarios in Ecuador for water and food provisioning and can aid in meeting the country's water and food security goals, providing alternatives that lessen the impacts for land and water use. The scenarios reveal that food provision, towards local food consumption or exports market-oriented, can be increased and ecosystem water demand still be met, with the exception of the east of the GRBD.

Future research could build on our study and further consider other drivers that will affect both water and food security, including demographic changes, droughts (Vicente-Serrano et al., 2016), flooding events (Hallegatte et al., 2013), and existing climatic trends (Morán-Tejeda et al., 2015). Moreover, this research could be extended to perform water-for-energy assessments with the consideration of hydropower development in Ecuador. A comparison of the seasonal effects of water-for-food on hydropower production versus the effects of reservoir management on food production could allow this study to provide additional insights to policy makers regarding their proposed national development strategies, including the recent projects on multi-purpose reservoirs. Finally, the flexibility of the methodology adopted in this study may be applicable to a worldwide scale with an integration of the water metabolism approach to global hydrological and crop growth models. Insights from the study can extend beyond academia to practitioners and policymakers in water and land management beyond our case study. Ultimately, the provided alternatives to promote integrated land and water management in Ecuador can aid towards meeting the country's future water and food security needs.

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Highlights

- Ecuador is facing important changes on agricultural land and reservoirs development
- In the Guayas river basin district, agriculture is the main consumer of blue and green water
- Eastern Guayas will increase food production at the expense of ecosystem water supply
- Water security is challenged in areas with scarce water and population in poverty