Environmental Science and Policy 152 (2024) 103656

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Evaluating the impacts of agricultural development and climate change on the water-energy nexus in Santa Elena (Ecuador)

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ARTICLE INFO

Keywords:
Crop irrigation
Water resources
Scenario
WEAP model

ABSTRACT

A combination of a changing global climate coupled with rapid socio-economic development is putting unprecedented pressure on water, energy, and food resources. Addressing these issues within a nexus approach can help to identify appropriate management practices and strategic policies to ensure natural resources are used more sustainably thus avoiding exacerbating issues of water scarcity and food insecurity. In this study, we used an integrated water resource planning and irrigation model (WEAP) to assess emerging water-energy nexus issues on the Santa Elena peninsula in Ecuador. Simulated water demands showed that current water resources availability is insufficient to meet full irrigation requirements, especially during the dry season. Annual average energy demand for water conveyance in the SEP was significantly higher than for irrigation with 94.5 GWh and 13.5 GWh being used, respectively. Future challenges associated with changes in agricultural irrigation and urban demands within the SEP were evaluated using scenario analysis. This included considering various scenarios such as agricultural expansion, climate change, population growth, and a shift to export-oriented agriculture. The study underscores the significance of nexus thinking in guiding policy and decision-making in Santa Elena, although the limited data prevents its use in an operational framework. The benefits of adopting an integrated modelling approach to analyse water and energy nexus trade-offs are also discussed.

1. Introduction

Almost half (47%) of the world's population already lives in water scarce areas (WWAP, 2018), placing water management at the centre of the global agenda for achieving future global food security (Mancosu et al., 2015). Demographic growth, coupled with economic development and rapid climate change, is exerting serious pressure on water resources (Ougougdal et al., 2020), especially in arid and semi-arid regions (Okello et al., 2015; Rishma and Katpatal, 2019a; Rishma and Katpatal, 2019b). Agriculture is the largest global user of water and, thus, it is often perceived as one of the main causes of water stress (Iglesias and Garrote, 2015). In many developing countries, agricultural expansion provides a major opportunity for economic growth (Sanjuán-López and Dawson, 2010). This is particularly remarkable in the case of agro-export production driven by increasing food demand and globalised agricultural trade (Kanianska, 2016; Salmoral et al., 2020). However, agricultural expansion has also been linked to detrimental environmental impacts including deforestation, soil depletion and over abstraction of water; threatening biodiversity in terrestrial and aquatic ecosystems (Hatfield, 2015; Kanianska, 2016). Irrigation abstraction, conveyance (distribution) and application can also account for significant energy consumption (Daccache et al., 2014; Belaud et al., 2020). Without appropriate design and careful planning, agricultural expansion and its related water and energy consumption is likely to become a key geopolitical issue affecting the global economic system (Bogardi et al., 2012). Identifying sustainable pathways for expansion and more efficient use of resources is thus a major priority (Rasul, 2016).

The impact of food production on the water environment is highly variable and depends on crop type, agricultural practices, local climate and resource status (Hess et al., 2014). Moreover, the water, energy and food sectors are tightly coupled. That is, the impacts in one sector directly affect the performance in others. Thus, there is a need for the

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https://doi.org/10.1016/j.envsci.2023.103656
Received 1 April 2022; Received in revised form 7 November 2023; Accepted 12 December 2023
Available online 22 December 2023
1462-9011/

integration of the water, energy and food sectors in both governance and management (Wichelns, 2017; Mahlknecht et al., 2020). Given that the global demand for food, water and energy by 2030 is expected to rise by 35%, 40%, and 50% respectively (NIC, 2012), the linkages between these sectors require an integrated nexus approach to ensure future food and water security, and sustainable agricultural and energy production (Momblanch et al., 2019).

The Santa Elena Peninsula (SEP) in southern Ecuador experiences water scarcity and seasonal droughts (Herrera-Franco et al., 2020). It has an average annual rainfall below 500 mm which is concentrated in a single rainy season (January to April), and suffers from high inter-annual precipitation variability (Cornejo et al., 2006). Agricultural development is dependent on supplemental irrigation (MAGAP, 2014) enabled through major water infrastructure which has supported agricultural transformation and expansion of irrigated crop production over time (MAGAP, 2011). There are many large farming enterprises in the SEP focusing on agro-export production which heavily rely on water and energy use for high-value crop production. This has brought into question the long-term sustainability of agriculture in the region (Cornejo et al., 2006). The aim of this paper is, therefore, to critically evaluate these issues in the SEP using a nexus approach. A scenario-based modelling methods are used to evaluate the water-energy trade-offs arising from a shift from traditional farming to agro-export production, in combination with the potential impacts of climate change and population growth.

2. Materials and methods

2.1. Case study description

The SEP is located in western Ecuador and extends over approximately 6400 km^2 with a population of 308,693 (CISPDR, 2015). It is bounded by Manabí province to the north, the Pacific Ocean to the south and west and the Guayas River basin to the east. The proximity to the Pacific Ocean and the local undulating topography result in significant climatic variability in the SEP. Most water resources for domestic use in the SEP come from water transfers from Daule River, enabled by the development of the PHASE irrigation scheme. This scheme, which was built in the 1980's, includes several reservoirs, canals and pumping stations. The PHASE scheme was designed to benefit local communities by increasing the productive potential of land, thereby, expanding livelihood opportunities and enhancing food security. The scheme includes the lower (zones 1 to 5) and upper (zones 6, 7 and 8) irrigation sectors (Fig. 1). Zones 9 and 10 were not in the original plan but they were incorporated later to be part of the upper zone (MAGAP, 2015). Water is drawn from the Daule River and pumped at the Daule pumping station to the Chongon Reservoir. From there, a portion of the water is released for natural gravity-based distribution in the lower sectorwhich are then pressurised for their application at field scale. The remaining reservoir releases are pumped to a final diversion point (Leoncito pumping station) where part of the water continues by gravity to zones 7 and 8, while the rest is pumped with diesel pumps to zones 9 and 10.

The irrigated area has increased 10-fold since the inception of the PHASE project with drip irrigation now constituting the main irrigation method (Cornejo et al., 2006). The SEP has a total irrigated area of 23, 000 ha which includes 43 different crop types; being maize (24% of total irrigated area), cocoa (19%), mango (16%), banana (8%), sugarcane (3%), chia (3%), lemon (2%), pepper (2%), passion fruit (2%) and papaya (1%) the ten most important crops in extension (Table S1 in supplementary material). Domestic water demand in the two most populated districts (i.e., Playas and Santa Elena) was estimated to be 250 litres/person per day (CISPDR, 2015).

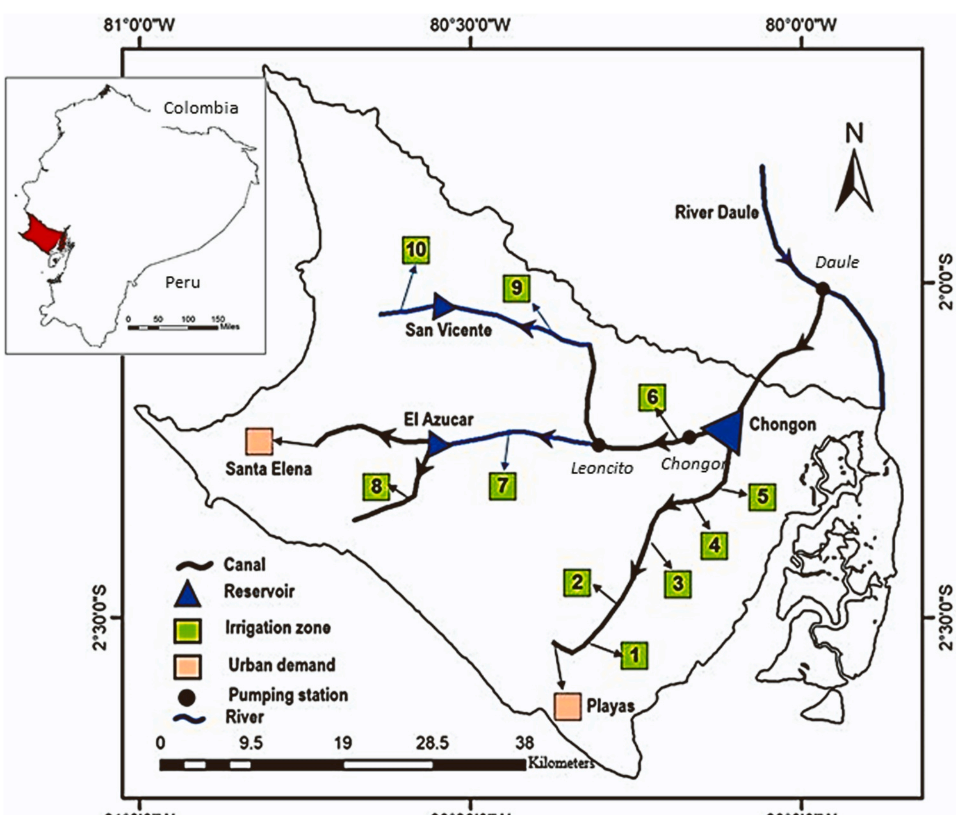

Fig. 1. Schematic representation of water infrastructure including reservoirs, irrigation zones, pumping stations and urban water demand sites across the Santa Elena Peninsula (based on CEDEGE (2001)).

2.2. Water-energy nexus modelling

This study estimated the current and future changes in water demand and energy use in the SEP for selected scenarios using the integrated Water Evaluation and Planning (WEAP) system. Simulated monthly average flows and water volumes from WEAP's application to the SEP were used as an input into an energy model to simulate energy demands to pressurise the water distribution (conveyance) and irrigation application systems for current (baseline) and future agricultural and socio-economic scenarios.

2.2.1. Reservoir simulation model

WEAP is a generalised simulation model for the analysis of water resource systems, which can be used to solve multi-sector water allocation problems based on demand priority and supply preferences. The ability to adopt an integrated approach to simulating water demands, including water consumption as well as environmental requirements, (Sieber and Purkey, 2015), makes WEAP a well-suited model for this study. WEAP is based on the principle of a water balance, and uses a link and node structure to represent system components, processes, and their spatial dependencies (Momblanch et al., 2019). It can be applied to urban and agricultural systems, at a catchment scale or for multiple river systems (Sulis and Sechi, 2013), and allows the user to evaluate a range of issues through a scenario-based approach (Naranjo et al., 2023). Previous studies have demonstrated its capability for water resources management analysis in North Africa (Allani et al., 2020; Ougougdal et al., 2020), India (Momblanch et al., 2019), Argentina (Salomón-Sirolesi and Farinós-Dasí, 2019), Tanzania (Miraji et al., 2019), Iran (Shahraki et al., 2016) and Ethiopia (Arsiso et al., 2017), among others. Specifically, WEAP has been previously used to evaluate domestic and agricultural water demands and supplies (Asghar et al., 2019; Ougougdal et al., 2020), as well as water transfers (Yates et al., 2009).

Climate data to run WEAP were obtained from Ecuador's Meteorological and Hydrological National Institute (INAMHI) for the period 2014–2019. The INAMHI station within the study area is located at Santa Elena University and was assumed to represent typical conditions across the SEP. Hourly rainfall, temperature, relative humidity and solar radiation data were converted to a daily time-step series, with missing data replaced using average monthly values. Fig. 2 shows the strong seasonality in monthly rainfall and reference evapotranspiration (ETo), which emphasised the importance of irrigation during the dry season. The relevance of local hydrology in the area with respect to imported water volumes was considered negligible and, therefore, not included in the WEAP model. Technical details regarding the location and capacity of reservoirs, canals and pumping stations were obtained from the Public Water Company in Ecuador (EPA) and used to model water storage and conveyance, as well as transfers. Net evaporation from reservoirs and canals was estimated by the WEAP model as the product of the surface area (related to the stored volume through volume-elevation curves), the net evaporation rate (evaporation minus precipitation depths), and the time step duration. Seepage losses from canals were estimated at 7% of the flow (Cornejo, 2003), while a reasonable value of 10^6 m^3/month for seepage losses from all three reservoirs was assumed, regardless of their size or soil type.

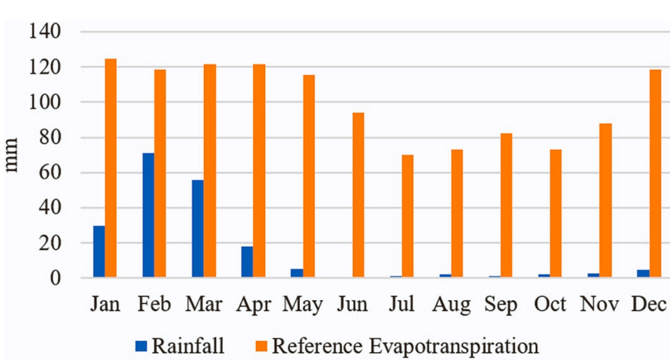

Fig. 2. Average monthly rainfall and reference evapotranspiration (ETo) measured at Santa Elena University (2^{0}13'S, 80^{o}51'W) for the period 2014–2019
Source: INAMHI.

Irrigation needs were estimated using the MABIA module in WEAP, which is a daily water balance method considering evapotranspiration, crop development, soil characteristics and irrigation schedules (Sieber and Purkey, 2015). The dominant irrigated crops were identified for 2014 from Ecuador's Ministry of Agriculture, Livestock, Aquaculture and Fisheries (MAGAP) statistics (MAGAP, 2014). Cropping characteristics including development calendars, crop coefficients, depletion factors, and rooting depths were available within the crop library in WEAP, which relies on Food and Agriculture Organisation data. Typical planting dates for each crop were provided by MAGAP. Due to the lack of information on crop parameters for chia, the equivalent parameters for sorghum were used given their similar cropping phenology (a summary of crop parameters is provided in Table S2). Soils data were obtained from the Ecuadorian Space Institute, from which soil types associated with each irrigation zone were identified.

All flows within the SEP (Fig. 1), including reservoir discharges and water distribution through the canal network to the individual irrigation zones and urban areas were modelled within WEAP. As a general rule, urban areas have higher supply priority than irrigation demands. The other operation rules of the system were adjusted during calibration. The model was calibrated against daily observed storage volumes for each of the three main reservoirs by varying the operating rules in WEAP (including top of conservation, top of buffer, buffer coefficient, reservoir filling priority and buffer-zone-filling priority) for the period 2016–2019. Statistical tests including Pearson's correlation factor (r), percent bias (PBIAS), and normalized root-mean-square error (NRMSE) were used as model performance indicators. They show the proportion of variability in an observed variable that can be explained by the model output, and the average tendency of the simulated variable to be larger (or smaller) than its respective observed value (Moriasi et al., 2007). As with other studies that have applied WEAP to represent the engineered and water demand components of water resource systems rather than the hydrology (e.g. Azari et al., 2018; Ngo et al., 2018; Sahoo et al., 2020), the time series used for calibration period was short. To compensate for this, the model was further evaluated using information on annual crop water requirements (Table S3) and discontinuous observations of water pumped at different locations in the system to ensure that key model components relating to water and energy requirements were realistic.

2.2.2. Simulation of energy demands for water conveyance and irrigation application

Energy demands were calculated for the conveyance of water to and within the peninsula, and for the operation of the irrigation systems at plot level (application). The monthly energy demand to pressurise the system for water conveyance was calculated based on Shammas and Wang (2015):

$$E_{pump}(kWh) = \frac{Q \times \rho g\left(H + h_f\right)}{1000 \times \eta_{motor} \times \eta_{pump}} \times 24 \times N \tag{1}$$

Where Q is the simulated monthly average flow (m^3/s), ρ the fluid density (kg/m^3), g the gravitational acceleration (m/s^2) and N the number of days in a given month. Electric pumps with 90% motor efficiency and 80% pump efficiency were assumed. H is the head (m) that the pump has to overcome and h_f the friction losses (m) was also calculated based on Shammas and Wang (2015):

$$h_f = f \times \frac{8 \times L \times Q^2}{\pi^2 \times g \times D^5} \tag{2}$$

Where f is the friction factor (dimensionless) and was assumed to be 0.025 which is typical for industrial steel pipes ranging from 0.01 to 0.04 (Shammas and Wang, 2015), L is pipe length and D the pipe diameter (m). The energy required to pump irrigation water for each crop within each irrigation zone was calculated based on FAO (2007):

$$\boldsymbol{Energy}(\boldsymbol{kWh}) = \frac{\boldsymbol{Volume}(\boldsymbol{m}^3) \times \boldsymbol{Pressurehead}(\boldsymbol{m})}{367 \times \eta_{motor} \times \eta_{pump}} \tag{3}$$

Where *Volume* represents WEAP simulated irrigation volume; η_{motor} and η_{pump} represent efficiencies of the motor and pump, respectively. A typical value of 80% for pumping efficiency was assumed (Daccache et al., 2014). Electric irrigation pumps were assumed in the lower sector (zones 1 to 5) and diesel engines used in the upper sector (zones 6 to 10). Diesel and electric motors were assumed to be 40% and 90% efficient, respectively (Daccache et al., 2014). Operating an irrigation system also requires taking into account nominal pressure and friction losses (f_{Losses}) within the distribution system. Typical operating pressure for drip of 1 bar and friction losses representing 20% of the nominal discharge were assumed (Daccache et al., 2014). As water is abstracted from surface sources, no pumping lift was assumed. Thus, the total pressure head was:

$$\boldsymbol{Pressurehead}(\boldsymbol{m}) = \boldsymbol{OP}(\boldsymbol{m}) + \boldsymbol{f}_{Losses}(\boldsymbol{m}) \tag{4}$$

Where $\boldsymbol{OP}$ is the operating pressure.

2.3. Scenario modelling: water and energy trade-offs

Through previous engagement with key informants, it was reported that stakeholders in the SEP use projections for the middle of century in their current water resource planning and management. Hence, to understand future water and energy trade-offs in the SEP by 2050, a scenario modelling approach was developed. Three scenarios based on the existing water distribution infrastructure, expected trends in irrigation expansion and cropping patterns, and plausible future climate changes were analysed in WEAP to explore potential implications for the water and energy nexus. A brief description of each scenario is provided below.

(a) *Scenario 1: Agricultural expansion continues as per the original PHASE irrigation scheme design*. The scheme was designed to ultimately supply water to 40,000 ha transferring resources from Daule River using four pumps (with a capacity of 11 m^3/s each). However, at present only half the area (20,000 ha) is under irrigation and just two pumps operating at Daule pumping station (although only one is currently in use). This scenario assumes the irrigated area is increased to 40,000 ha (as originally planned) and four pumps are operational. It assumes Daule River has sufficient water to allow 44 m^3/s withdrawal and irrigated areas are increased at a growth rate of 2.5% per annum between 2020 and 2050 (Ilbay-Yupa et al., 2021). The crop mix remains the same as the 'baseline' scenario.

(b) *Scenario 2: Irrigated production shifts to export-oriented agriculture*. Ecuador has markedly transformed its agricultural sector over the last 20 years. To strengthen the local economy, the Ecuadorian Ministry of Agriculture had promoted an economy based on agricultural exports, encouraging producers to focus more on international markets to improve profitability and livelihoods. As a consequence, it is envisaged that almost 25% of the current maize irrigated area will be converted for export crops including banana, cocoa and mango. To simulate this shift in agro-economic production in WEAP model, a proportion of the maize area in each irrigated zone was replaced by export-oriented crops depending on the current crop mix. For example, if maize, banana, cocoa and mango were already grown in a zone, then 10% of maize was converted to banana, 10% to cocoa and 5% to mango. If maize and only one export crop were present, then 25% of the maize area was converted to the export crop. If only export crops were present in a zone, then no change in cropping was made. As in the baseline scenario, one pump was assumed to be operating at Daule River pumping station.

(c) *Scenario 3: Assessing impacts of population growth and climate change*. By downscaling two AR5 general circulation models for two emission scenarios (RCP4.5 and RCP8.5), Vera et al. (2020) projected average annual rainfall and temperatures in Ecuador to increase by + 22% and + 2.8 °C, respectively. The projected increase in the Latin American population was similar for the two most extreme Shared Socio-economic Pathways SSP1 (sustainability) and SSP5 (conventional development)(van Vuuren et al., 2017; Kriegler et al., 2017) corresponding to an overall + 20% growth by 2050 (Riahi et al., 2017). These changes in climate and population were applied to the baseline values and used as inputs for the WEAP model assuming per capita water demand remained the same as the baseline. The crop mix and irrigated areas were the same as the baseline, with one active pump at Daule River pumping station.

3. Results

3.1. WEAP model 'goodness of fit'

Fig. 3 indicates a suitable goodness of the model for the three reservoirs in SEP. The estimation of irrigation water requirements and the volumes of water pumped in the system also reinforced the good

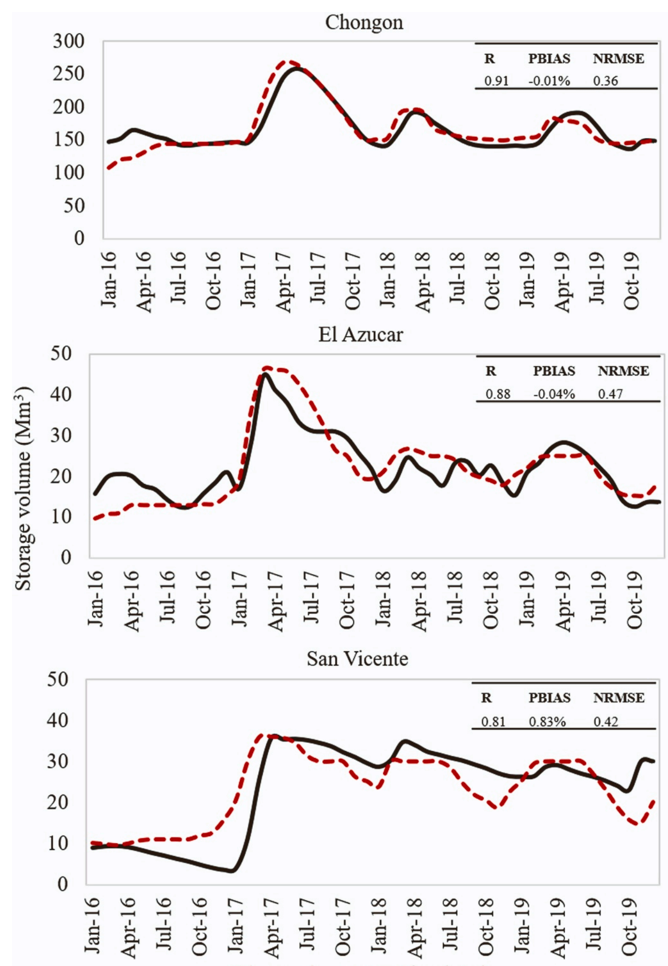

Fig. 3. Comparison of WEAP simulated (dotted line) and observed (solid line) monthly reservoir storage volumes (Mm^3) for each reservoir in the SEP.

performance of the WEAP model. The model performance for reservoir storage was strongest for Chongon reservoir with slightly reduced levels of statistical significance for El Azucar and San Vicente reservoirs. This could be explained by missing hydrological variables including runoff produced within the peninsula which was not taken into account in the WEAP model.

3.2. Current water and energy demand in the SEP

Irrigation water demand is the highest during the dry season (May to November) as opposed to urban (domestic) demand which is constant throughout the year and represents 13% of annual water demand in the system (Fig. 4a). Maize and cocoa are the two most important crops in the SEP by area, and together they account for half the annual volumetric irrigation demand, followed by banana and mango (12% and 6%, respectively). Unsurprisingly, the crop mix has a strong influence on water demand. For example, Zones 2 and 5 have similar irrigated area (Table S1) but irrigation demand in Zone 2 is more than double that of Zone 5 due to differences in crop type (Fig. 4b). Water demand is not evenly distributed spatially across the SEP and marked differences are apparent both within and between the two main sectors of the water infrastructure system.

Water demand coverage, which represents the ratio of the volume delivered (supply) to meet sector water demands, is shown in Fig. 5. On average, coverage is similar across all irrigation zones (Fig. 5a) as they have been assigned the same priority in WEAP. However, the model outputs show that the system is unable to fully meet irrigation requirements between March and July (Fig. 5b). The buffer zone to control water releases included in the model for urban (domestic) water supplies explains this, forcing the reservoirs to be filled at the expense of meeting crop water requirements.

Energy demands for both water conveyance and irrigation application across the SEP (Fig. 6) were calculated using simulated diverted flows in the WEAP model considering water is being transported for both irrigation and domestic supply needs. The annual average energy demand at Daule River pumping station matches with available data from the EPA.

As with water demand, the cropped area has a strong influence on energy demand when comparing irrigation zones that rely on the same energy source (electricity or diesel). Since the pressure head and pump efficiency are kept constant, energy demand is proportional to water demand for all zones with different proportionality depending on the energy source. The efficiency of diesel pumps is lower and so the irrigation systems in the upper sector (Zones 6 to 10) have generally higher energy demand. For example, the total irrigation demand in Zone 8 has a similar magnitude as Zone 3 (Fig. 4b) but requires almost double the amount of energy (Fig. 7b). On average, annual energy consumption for water conveyance (sum of Fig. 6b columns; i.e., 94.5 GWh) is significantly larger than for irrigation application (sum of Fig. 7b columns; i.e., 13.5 GWh).

3.3. Scenario modelling to assess future water and energy demands

When we simulate agricultural expansion based on the original PHASE project (scenario 1), the irrigated area is expected to nearly double so the corresponding increase in both water and energy demand is evident (Table 1). However, water demand coverage decreases markedly during late summer meaning the system is unable to meet demands for the full irrigation command area, even with four pumps in operation (Fig. S1). With the conversion from traditional to export-oriented cropping, the simulated water consumption for Scenario 2 shows a slight increase in water demand in most irrigation zones (Table 1), whilst the proportion of crop water requirements met (i.e., coverage) are similar to the baseline (Fig. S1). In Scenario 3, water demand increases due to a combination of population growth and a changing climate. However, the overall water supply for irrigation is reduced since the supply to urban areas and net evaporation from reservoirs increase, resulting in less water availability for irrigation. This implies the system is unable to meet future demands with supply coverage decreasing for almost all demands and becoming much lower during dry season compared to the baseline (Fig. S1). As the modeling approach followed a general rule of prioritizing urban supply over irrigation, it can be seen that all the urban demands (Playas and Santa Elena) are met without any decrease in the coverage in any of the scenarios.

4. Discussion

4.1. Water and energy demand in the SEP

This study estimated the current and future spatial and temporal distribution of water and energy demands for irrigated agriculture in the

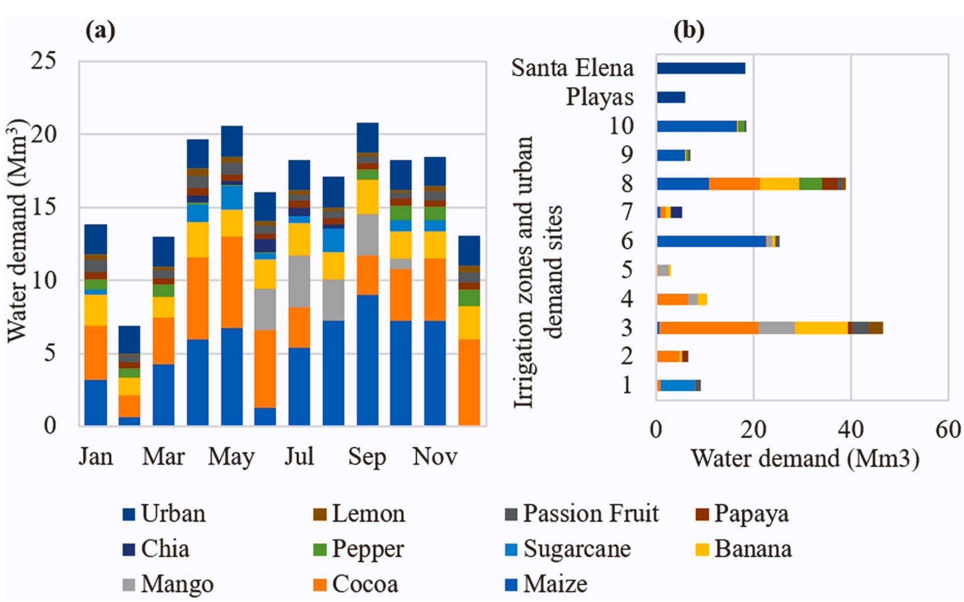

Fig. 4. Simulated monthly average irrigation water demand (Mm^3) by crop (a) and annual average water demand for each irrigation zone, by crop type including urban demand (b).

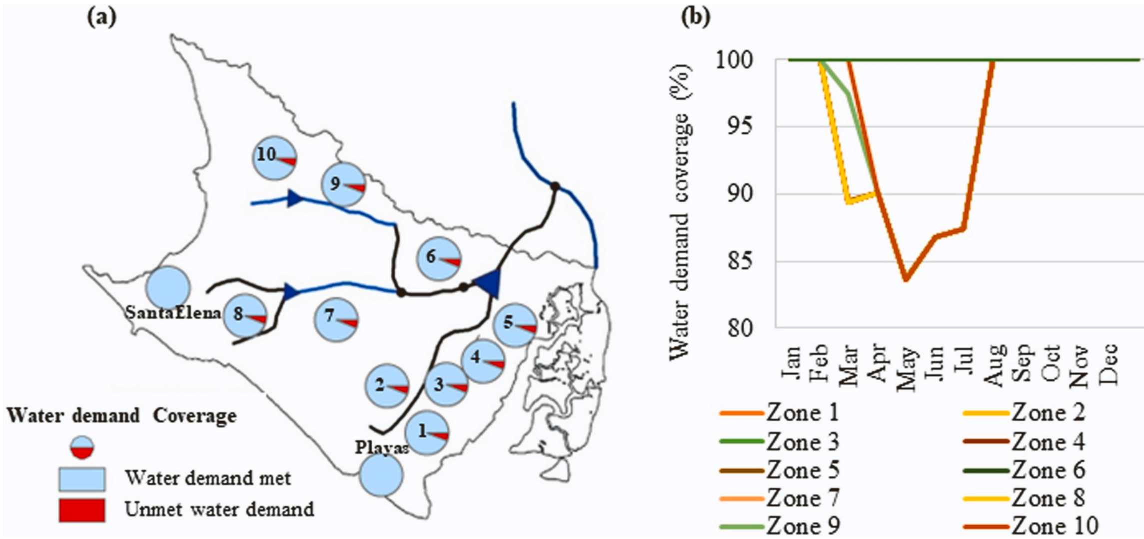

Fig. 5. Simulated annual average water demand coverage (spatial analysis) (a) and monthly average water demand coverage (temporal analysis) for each irrigation zone and urban demand site (b).

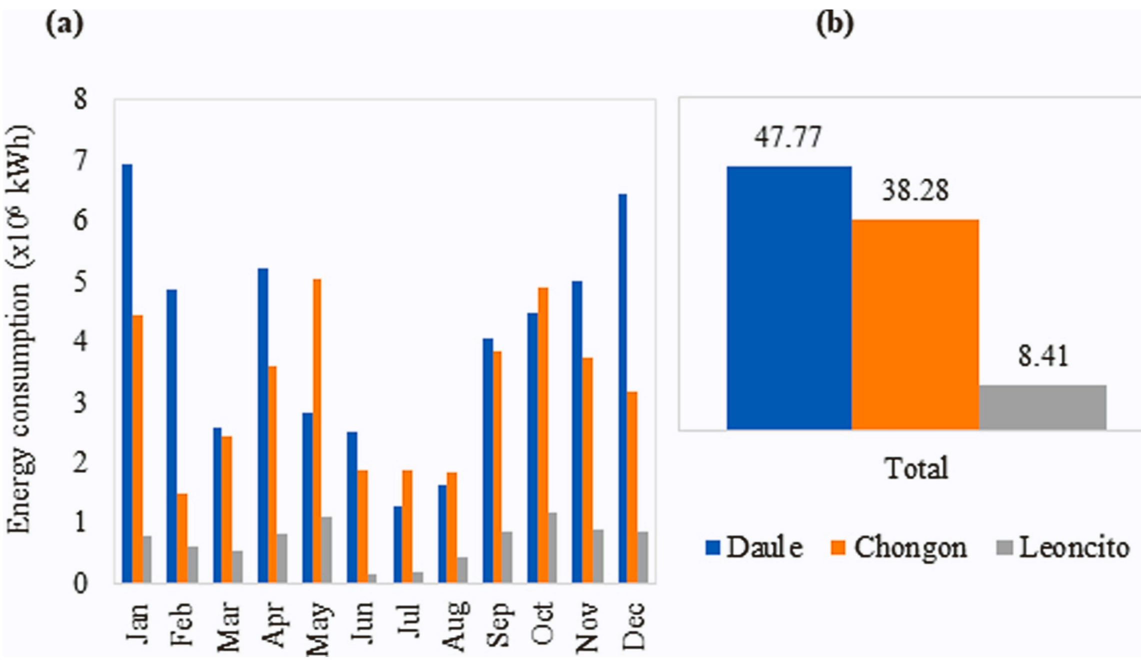

Fig. 6. Simulated monthly variation in energy consumption (left panel) and annual energy use at each pumping station (right panel) in million kWh.

SEP. The modelling outputs shows a high risk of failure to supply the volumes of water demanded for irrigation during the dry season in SEP under baseline conditions. This is supported by previous research by Cornejo (2003) and Morstadt et al. (2016). The existing water supply system in SEP is highly sensitive to future changes in cropped and irrigated areas. In spite of this, national development plans in Ecuador aim to increase irrigated areas and changing crop pattern to meet local and global food demands (MAGAP, 2011). The target is to have 1.6 million hectares under irrigation by 2027. However, there are no plans to evaluate the implications of such decisions on local water resources (Salmoral et al., 2018) or the environment.

In all the future scenarios simulated, water demand is projected to increase. Despite increased transfers from Daule River considered in Scenario 1, the coverage of supply to the irrigation zones reduces with respect to the baseline scenario. Moreover, it is questionable whether the flows in Daule River would be able to provide sufficient volumes of water needed to meet future peak water withdrawals in response to a changing climate and increased agricultural and domestic demand (Vera et al., 2020; Carvajal et al., 2017). Assessments of future seasonal weather patterns on the local hydrology suggest more extreme wet and dry seasons resulting in larger variations in river flows (Crespo et al., 2019). Water supply in the SEP is also constrained by physical limitations of the infrastructure including the capacity of the canals and pipeline distribution network. Palazzo et al. (2019) reported the need of new irrigation infrastructure worth $2.7 billion per year over the next 40 years in Latin America and the Caribbean under socio-economic developments and climate change scenarios, to meet future food demand.

When export-oriented crops are promoted (Scenario 2), the system is under less stress and the demand for water can almost be fulfilled, although coverage is still lower than in the baseline. This scenario has implications for local development and food security. Studies have already reported that, due to globalisation and neoliberal policies,

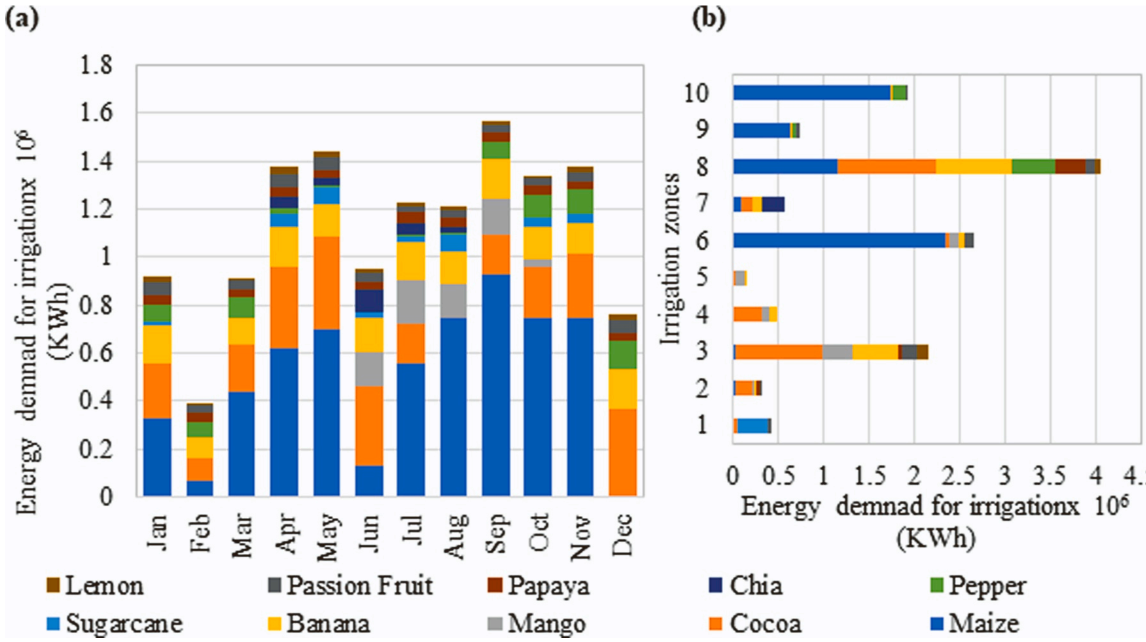

Fig. 7. Simulated average monthly energy consumption by crop type (a) and annual average energy consumption (kWh) for each irrigation zone (b).

Table 1
Potential water demand (D), supply (S) and coverage (C) expressed as percentage changes (%) relative to the baseline for each irrigation zone and scenario.

Irrigation Zone	Scenario 1: Agricultural expansion continues as per the original PHASE irrigation scheme design			Scenario 2: Irrigated production shifts to export-oriented agriculture			Scenario 3: Assessing impacts of population growth and climate change		
	D	S	C	D	S	C	D	S	C
1	84%	80%	-6%	0%	-1%	-1%	13%	2%	-6%
2	94%	84%	-6%	-1%	-1%	-1%	4%	-1%	-6%
3	79%	71%	-6%	0%	-1%	-1%	5%	-2%	-6%
4	93%	82%	-6%	2%	1%	-1%	7%	1%	-6%
5	88%	79%	-6%	2%	1%	-1%	2%	-9%	-6%
6	86%	69%	-7%	-1%	-2%	-1%	2%	-6%	-6%
7	82%	83%	-7%	0%	0%	-1%	5%	2%	-6%
8	62%	49%	-7%	0%	0%	-1%	2%	-4%	-6%
9	83%	65%	-7%	4%	4%	-1%	3%	-5%	-6%
10	86%	81%	-1%	5%	5%	0%	3%	3%	0%
Playas	0%	0%	0%	0%	0%	0%	15%	15%	0%
Santa Elena	0%	0%	0%	0%	0%	0%	15%	15%	0%

>75% 21 to74% 11to 20% 1 to10% 0% -1 to -10%

*Note: Energy demand is proportional to water demand and, hence, values also represent the energy changes for the selected scenario.

support for powerful companies to accumulate water rights in legal and illegal ways has increased more than ever before (Solanes and Jouravlev, 2007; Hendriks and Boelens, 2016). Increased competition for the access to limited resources linked to an imbalance of power result in socio-economic inequalities. Jarosz (2012) argued that actions built upon existing socio-economic and political inequalities will only reinforce unequal access and control of resources in rural areas.

In Scenario 3, rainfall increased by 22%, but this mainly affected the rainy season which occurs for a short period at the beginning of the year. The changing climate accentuated evapotranspiration during the dry season thus increasing crop water demand. Although the hydrology of the SEP was not simulated in this study, recent research has indicated that surface water resources will likely decrease (Barrera Crespo et al., 2019; Carvajal et al., 2017). Moreover, this scenario assumed that urban (domestic) water demand increased by 15% due to population growth and transfers from Daule River would remain similar to the baseline. As a result, water demand coverage in Scenario 3 was found to reduce by 6% as compared to the baseline when the system was subject to a changing climate and growing population. Vera et al. (2020) corroborated this result as they showed that a combination of increasing water demand and climate change will also impact the supply side due to water sources being insufficient to meet projected areas of irrigation expansion, although there was much climate uncertainty linked to the projections. According to Bellfield (2015), integrating national and local climate change adaptation plans within and across sectors offers an urgent entry point to avoid maladaptation and negative externalities.

Results for all simulated scenarios indicate that irrigated agriculture in SEP could be threatened by a more uncertain and reduced supply of water in the area. This reveals a potentially unsustainable management in the long-term if infrastructural and efficiency measures are not implemented.

The energy consumption estimated for water conveyance and irrigation application represents 25% of the total energy consumption in SEP (ARCERNNR, 2020). The source of energy is an important factor driving energy demand for irrigation. Switching from diesel to electric pumps can help reduce energy demand at the farm level as electric pumps have the potential to support agricultural growth with less energy (Buisson et al., 2021). Nevertheless, it should be noted that the total energy required for conveyance far exceeds (seven-fold) the total energy demanded for irrigation application. According to our results, the total energy demand in SEP is estimated to be proportional to water demand. However, despite the clear need for an integrated approach, national governance strategies continue to address water, energy and food policy in isolation (Bellfield, 2015).

4.2. Supporting sustainable irrigated agricultural development

Securing reliable and affordable water supply for agriculture is a major challenge, with water, energy and climate-related risks expected to increase in both frequency and magnitude in the future. Holistic approaches considering multi-level (such as national and local, macro and micro level) challenges and interdependence of resources are key to ensure sustainable development of agriculture without compromising natural resources availability (Pahl-Wostl et al., 2021). In many cases, nexus approaches are implemented as reactive responses to emergency situations and, hence, nexus trade-offs only emerge when one element of the nexus is impacted or at risk (Bellfield, 2015). Recent research is increasingly pointing at the need to embed the nexus approach in longer-term planning processes to better understand and address synergies and trade-offs among linked resource systems is increasingly (Liu et al., 2018; Pahl-Wostl, 2019). In Latin American countries, the focus of water-energy nexus discussions and applications have mainly taken place at the national level, macro-level drivers or large infrastructure developments (Mahlknecht et al., 2020); overlooking the fact that major nexus challenges are faced at the local level (Mpandeli et al., 2019). To promote long-term sustainable agricultural expansion and transformation, a more integrated approach to natural resources management at the local level is much needed, with approaches as the one described in this study providing a framework for such assessments elsewhere.

The current water resources system in the SEP is unable to meet both current and future demands for irrigated cropping. Future scenarios point at increased energy demand which may reduce profitability of irrigated agriculture and further exacerbate climate change. Such production will therefore not be sustainable in the long-term, unless management actions and policies to address the identified water-energy nexus issues are implemented (Naidoo et al., 2021). However, examining water demands within the constraints of existing water distribution infrastructure is complex and, hence, a long-term strategic water management decision-making is highly needed (Rising, 2020). For emerging markets and economies, it remains difficult to design and enforce effective policies to achieve sustainable development targets. In response to these challenges, the Ecuadorian government have moved towards new irrigation management approaches in which greater emphasis on local level decision-making is encouraged. Water management is, thus, decentralised and local governments assume responsibility for irrigation management and investment. In this context, the national irrigation and drainage plan (MAGAP, 2011) defined targets for extending the irrigation command areas and improving irrigation infrastructure, as well as establishing mechanisms to inform stakeholders regarding available water resources, the state of supply sources and impacts of consumption from different sectors. Aligned with the national and local irrigation plans (GADP Santa Elena, 2017; MAGAP, 2011) this study provides valuable new insights on the trade-offs between water and energy demand in the region under future contrasting agro-economic and climate scenarios.

Land use changes and their impacts on water and energy requirements will drive water related decisions, demonstrating the importance of addressing these challenges within a nexus approach. Irrigation development needs to be considered in environmental policies and development plans to promote synergies and avoid negative externalities. The price per unit of water, including electricity to pump water and market value of irrigated crop is another factor that plays a decisive role in irrigation and agricultural development. However, increasing agricultural water prices can positively influence the environment with farmers saving water and improving its management by reducing the demand (Aidam, 2015). Subsidies are already in place to access water from the system and to reduce its price, including the price for pumping. Ensuring effective irrigation strategies while developing climate change adaptive solutions will be essential to achieve food security, access to clean water and sustain a healthy environment.

4.3. Limitations and recommendations

This study provides clear insights on the significance of a nexus framework at local level in terms of sustainable agricultural expansion and reconciling policies to resolve mounting socio-economic and environmental challenges. However, the study has some limitations which should be considered when interpreting the results. Firstly, we assumed crop type and irrigated area, identified for the year 2014 from MAGAP statistics, remains the same throughout the study period, which might not assess the water-energy nexus dynamically. If there were more accurate local data with yearly variations of cropped area and cropping pattern, the model could represent the system more precisely. Secondly, due to lack of information we assumed a single irrigation system; i.e., drip irrigation. Although drip irrigation is dominant in the region, this assumption might under-estimate the water and energy demand. The study also makes an assumption that the Daule River can accommodate maximum water withdrawals. However, this assumption relies on the local hydrology of the upstream basin, which has not been taken into account. Moreover, the weather time series used to run and calibrate the model just contained 6 years. Even though the lack of long-term data may hinder the practical application of this study into an operational framework (Albrecht et al., 2018), as a test of the water-energy nexus approach under different future scenarios, this study has value as it demonstrates the workability of this methodology on a regional level, and builds the basis for management strategies to transform rural livelihoods.

5. Conclusions

This paper aimed to explore the benefits of scenario-specific integrated modelling approach to analyse the water-energy nexus in the peninsula of Santa Elena, Ecuador. Modelling the engineered water resources system allows essential understanding on the current water demand, its coverage and the energy requirements to operate irrigation and conveyance systems in the region, as well as their future changes. The three scenarios selected provide a clear insight of the unsustainability of agriculture in the area in the long term, and highlights the future challenges for the region in the next few decades. A balance will then have to be found between agricultural and infrastructure developments, which highlights the importance of the nexus approach. Moreover, the study showed that if the any of the analysed scenarios of future agricultural demands materialise, expansion of available infrastructures and promotion of efficient agricultural practices will be needed to achieve sustainable management.

Through an integrated approach and case study analysis, this study shows the significance of nexus thinking in a real-life situation to guide policy and decision-making in formulating informed strategies that lead to sustainable development. Besides the envisaged importance of nexus planning, the study highlights the need of formulation of pathways to overcome the barriers impeding nexus operationalisation to mitigate trade-offs and enhance synergies of resources for long-term sustainability. While limited data restricts the immediate applicability of these results in the case study, integrated approaches like the one presented here have broader relevance in agricultural development, particularly in regions characterized by strong engineered functioning.

CRediT authorship contribution statement

Rishma Chengot: Conceptualization, Software, Writing – original draft preparation. **Raphael Zylberman:** Conceptualization, Methodology, Software. **Andrea Momblanch:** Conceptualization, Supervision, Writing – reviewing & editing. **Tim Hess:** Writing – reviewing & editing. **Jerry W Knox**: Writing – reviewing & editing. **Oswaldo Viteri Salazar:** Validation of results, Writing – reviewing & editing. **Dolores Rey:** Conceptualization, Supervision, Writing – reviewing & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dolores Rey Vicario reports financial support was provided by Natural Environment Research Council.

Data availability

The authors do not have permission to share data.

Acknowledgements

We acknowledge the UK Natural Environment Research Council (NERC) for supporting this research as a part of NEXT-AG project (Nexus thinking for sustainable agricultural development in Andean countries) (grant number NE//R015759/1). The funding agency have no involvement in the design of the study or interpretation of the result. No new data were collected in this research.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2023.103656.

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