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Bayesian belief networks for the analysis of the controversial role of hydropower development in the antagonistic agrofood-fisheries nexus: A potential approach supporting sustainable development in the Guayas river basin (Ecuador)

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Increasing anthropogenic activities are affecting water quality and related ecosystem services in river basins worldwide. There is a need to identify and act on synergies between the water-energy-food (WEF) elements and the other Sustainable Development Goals (SDGs) while mediating trade-offs. The Guayas river basin (GRB), one of the major watersheds in Ecuador, is being affected by increasing urbanization, agricultural and industrial activities. In this perspective paper, we indicate the WEF interactions in the GRB linked to the SDGs. A major challenge is the geographical distance between pressures and impacts, for which environmental and agricultural governance are key to support the needed change towards sustainable development. In particular, the realization of measures to reduce the pollutant input in upstream systems will need both legislative and financial means to solve downstream water quality problems. A Bayesian belief network (BBN) framework was developed in order to support sustainable decision making in the GRB. The discussed concepts can be applied to other river basins worldwide since, in many basins, very similar food production challenges need to be addressed.

KEYWORDS

WEF, public health, economic development, conflicts, geographical distribution, sustainable development, decision support framework, BBN

Introduction

The direct and indirect connections among water, energy, and food systems have given rise to the concept of the water-energy-food (WEF) nexus (Hoff, 2011). Water, energy, and food are fundamental elements of sustainability and are included as three of the 17 Sustainable Development Goals (SDGs) of the United Nations (Huntington et al., 2021). To accomplish a global agenda of sustainable development, it is needed to identify and act on synergies between the resources and the other SDGs while mediating trade-offs (Hopkins et al., 2021). Hydropower is the most important renewable energy source to date and dams are being developed in an upward trend (Gernaat et al., 2017). However, research has shown that hydropower dams and reservoirs can negatively affect ecosystems (Ren et al., 2019; Swanson & Bohlman, 2021). There is a need for models incorporating the nexus elements to approach the interactions and challenges in an integrated way (Leng et al., 2017).

Bayesian Belief Networks (BBNs) are frequently used to model socio-ecological systems and have demonstrated effectiveness in the support of river management decisions (Stritih et al., 2020; Leone et al., 2022). BBN is a probabilistic graphical model consisting of two structural components: (1) the causal network, generally referred to as the directed acyclic graph (DAG), and (2) the conditional probability tables that quantify the relations among the variables. The DAG comprises a set of nodes, which represents the variables of interest, and a set of arrows, which indicates the causal relationships among these variables (Forio et al., 2022; Landuyt et al., 2015; Van Echelpoel et al., 2015). BBN models can provide a quantitative indication of uncertainties and can integrate various empirical data sources and expert knowledge (Forio et al., 2020). BBNs can be applied in a broad range of topics and areas and it has been shown that those models are able to learn complex relationships with reasonable precision (Ahmad et al., 2021).

In this perspectives paper we discuss the controversial role of hydropower development in the antagonistic agrofood-fisheries nexus in the Guayas river basin (GRB) and how models can serve to gain insights in the improved management of environmental and natural resources. The Guayas river basin in Ecuador is used to provide cultivated foods and water supply for human use. It is of major importance to mitigate effects of anthropogenic pressures on the ecosystem's quality and functioning (Arias-Hidalgo et al., 2013). The goal of this paper is twofold. Firstly, we determine the key interactions of the water-energy-food (WEF) system of the GRB linked to the SDGs. And secondly, a concept Bayesian belief network (BBN) framework of the WEF nexus is developed in order to support sustainable decision making in the GRB. The WEF interactions in the Guayas river basin have not been previously studied and identified, despite its urgency. Due to the complex spatial situation of the WEF nexus and the limited data availability in the GRB, the BBN approach can be advantageous when modeling the WEF nexus in the system. The BBN famework based on the interactions in the GRB will, as a novel methodology, create insights that can provide support to river managers, policymakers, and other stakeholders at a national and international level. The concepts introduced in this perspective paper have major potential for application in other river basins worldwide where very similar food production challenges occur.

Study area

The GRB is one of the major watersheds in Ecuador (Supplementary Figure S1), where increasing human activities (i.e. hydroelectric dams, agriculture, industrial plants), increasing urbanization, and expansion of aquaculture are affecting water quality and related ecosystem services (Damanik-Ambarita et al., 2016). Like many freshwater systems worldwide, these developments have led to needs in protection measures and restoration policies (Maasri et al., 2022). This is also reflected in the status of the basin, where biodiversity loss, unsafe potable water, eutrophication and reduced water availability are among the key consequences of poor water management to address the many land-use changes (Forio et al., 2015; Forio et al., 2020). The GRB is located in central-western Ecuador. With 33,700 km^2 land surface area, it is the largest watershed in South America west of the Andes mountains (Gobeyn et al., 2017). The river basin is considered of major importance in Ecuador due to the agro-industrial and economical values and exploitation. Population growth throughout Ecuador has been occurring (i.e., from 4.5 million inhabitants in 1960 to 17.6 million inhabitants in 2020 (World Bank, 2020)). Specifically, one-fourth of the Ecuadorian population (4.4 million inhabitants) resides in the GRB (INEC, 2020). The basin receives an average annual precipitation of 1,662 mm and discharges on average 835 m^3/s into the Gulf of Guayaquil. The basin drains the water towards the Gulf of Guayaquil and the two main rivers are the Daule and Babahoyo rivers which merge into the Guayas river near Guayaquil, the largest city of Ecuador (Damanik-Ambarita et al., 2016; Deknock et al., 2019). The streams of the GRB enrich the region with soils carried down from the Sierra, making it Ecuador's most fertile agricultural zone (Buckalew et al., 1998). In the Daule and the Babahoyo rivers, the main anthropogenic activities are residential and agricultural (Damanik-Ambarita et al., 2018). The high population density has been intensifying anthropogenic activities such as urban construction, industry and agriculture in the GRB. The major environmental pressures on the freshwater ecosystems today are pollution from sewage (due to limited wastewater treatment coverage) and agriculture, changes in land use and two hydro-electrical power dams located in the upper catchment of the basin (Alvarez-Mieles et al., 2013; Nguyen et al., 2015).

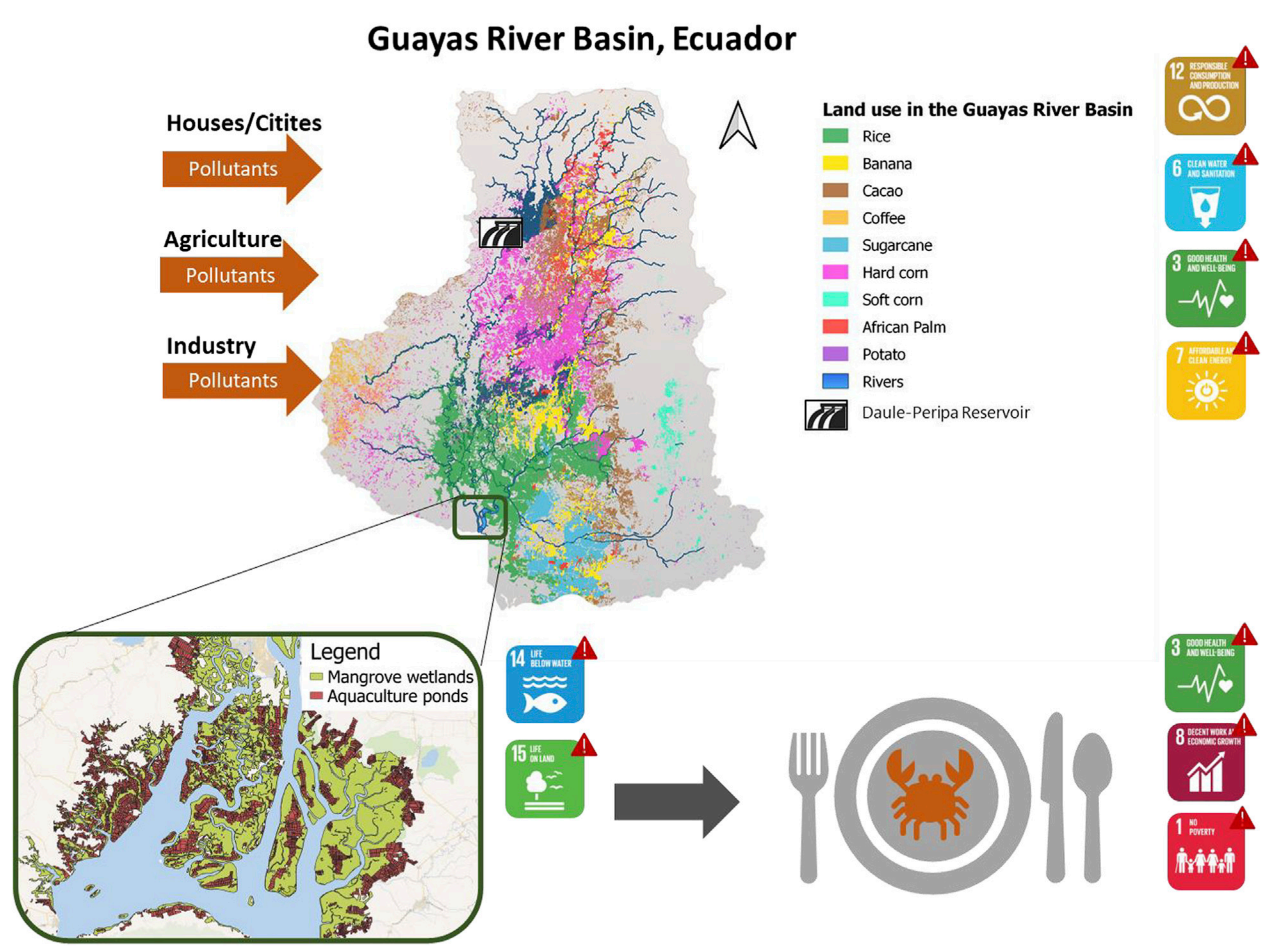


FIGURE 1
Land use and water-energy-food nexus and interactions with SDGs in the Guayas River Basin (GRB), Ecuador. Source SDG symbols: https://sdgs.un.org/goals.

Food production challenges and controversial effects of hydropower dams linked to SDGs

River basins worldwide serve as regions for integrated planning and management of watersheds, groundwater, land use, river regulation, food security and healthcare development (Langat et al., 2019). Food systems worldwide have the capacity to emend human health and support environmental sustainability; however, they are currently pressuring both (Willett et al., 2019). Global agriculture and food production release more than 25% of all greenhouse gases (GHGs), pollute fresh and marine waters with agrochemicals and use about half of the ice-free land area as cropland or pastureland (Tilman & Clark, 2014). River-based agricultural and other developments upstream often generate hydrological transitions downstream, a situation which has become prevalent in recent years (Langat et al., 2019). In the GRB, the main economic activities are agriculture, fisheries and hydropower generation (Deknock et al., 2019). Banana, rice, maize, sugarcane, potato, African palm cultivation, cocoa, and coffee productions are important agricultural activities in the basin as well as aquaculture and fisheries (Alvarez-Mieles et al., 2013; Damanik-Ambarita et al., 2018) (Figure 1). The previously mentioned crops represent 36% of the total land use (LU) in the basin (Forio et al., 2020). The most prevalent crop is maize (12% of total LU), followed closely by rice (9%) and cacao (9%). The areas of banana and sugar cane are considerably less (both 3%). It has been shown that various sources of pollution pass through the basin and accumulate in the Guayas estuary (De Cock et al., 2021a; De Cock et al., 2021b). Agricultural intensification has resulted in the use of pesticides and chemicals to ensure healthy crops and food production in the GRB. Consequently, rivers receive chemical runoff as a result of agriculture production which eventually ends up in the Guayas estuarine system, located at the delta of the GRB. Studies have shown that pesticide contamination of the freshwater environment is widely occurring in the GRB and estuary (Deknock et al., 2019; De Cock et al., 2021b). This is detrimental not only for aquatic health but also for human health as fishing is a primary commercial activity in the Guayas basin and estuarine system. The latter is well known for its shrimp aquaculture (Hervé Lucien-Brun, 2017) and crab fisheries (Pontón-Cevallos et al., 2021). The estuary is the habitat of a nutritious and very popular national dish and has both a high economic and cultural value (De Cock et al., 2022). More specifically, the red mangrove crab is a species of considerable economic significance in the Guayas estuary. It is not only part of the local culture as a delicacy, also thousands of artisanal fishermen rely on it for their monthly income. In the Gulf of Guayaquil, 13% of the families depend directly on the harvest of the red mangrove crab (Flores, 2012). Recently, researchers have provided evidence of the presence of metals and pesticides in the red mangrove crabs and they indicate a maximum of eight crabs per month to prevent adverse health effects (De Cock et al., 2021a; De Cock et al., 2021b). The shrimp aquaculture industry in Ecuador is one of the mayor players in the world. In 2017, almost 185,000 thousand hectares of ponds were provided for shrimp production mostly located around the city of Guayaquil (Hervé Lucien-Brun, 2017). A triple food nexus can be identified in the GRB, since also aquaculture production forms part of the nexus. Aquaculture activities are active near the estuarine system. The water quality in the GRB can potentially influence the quality of the aquaculture ponds, which in turn could influence the quality of the sediments in the estuarine system. Previously, variability in the water quality throughout the GRB was reported, with good water quality at (upstream) forested locations, while moderate and poor water quality was found at sites close to arable land and residential areas, respectively (Damanik-Ambarita et al., 2018; Damanik-Ambarita et al., 2016). Aquaculture activities have been reported to cause numerous environmental problems, such as the excretion of chemicals, e.g. antibiotics, in the aquatic environment (Liu et al., 2016; Tian et al., 2021). Consequently, the use of pesticides for food production in the GRB could potentially threat the quality of the aquaculture end products, which are mostly produced for an international market, with consequent impacts on local economy. Additionally, the use of antibiotics and other chemicals in aquaculture ponds can end up in the water and sediments of the mangrove ecosystem (Liu et al., 2016). Biota, such as the red mangrove crab, the mangrove cockle, and fish species nursering and living in the mangrove ecosystem can potentially accumulate those pollutants. This eventually can harm the aquatic and human health of the biota and consumers of those species, respectively. Thus, antagonistic effects can be identified in the agrofood-seafood nexus in the GRB. It can be said that the use of chemicals in agriculture assures healthy and productive crops thereby promoting social and economic activities (SDGs one and 8). However, the other side of the medal is the consequent negative impact on life below water (SDG 14), life on land (SDG 15), responsible consumption and production (SDG 12), good health and well-being (SDG 3), and clean water and sanitation (SDG 6) in the GRB, and in particular in the downstream areas where these pollutants are received from these diverse sources, leading towards impacts on the economic growth for fishermen (SDGs one and 8) (Figure 1).

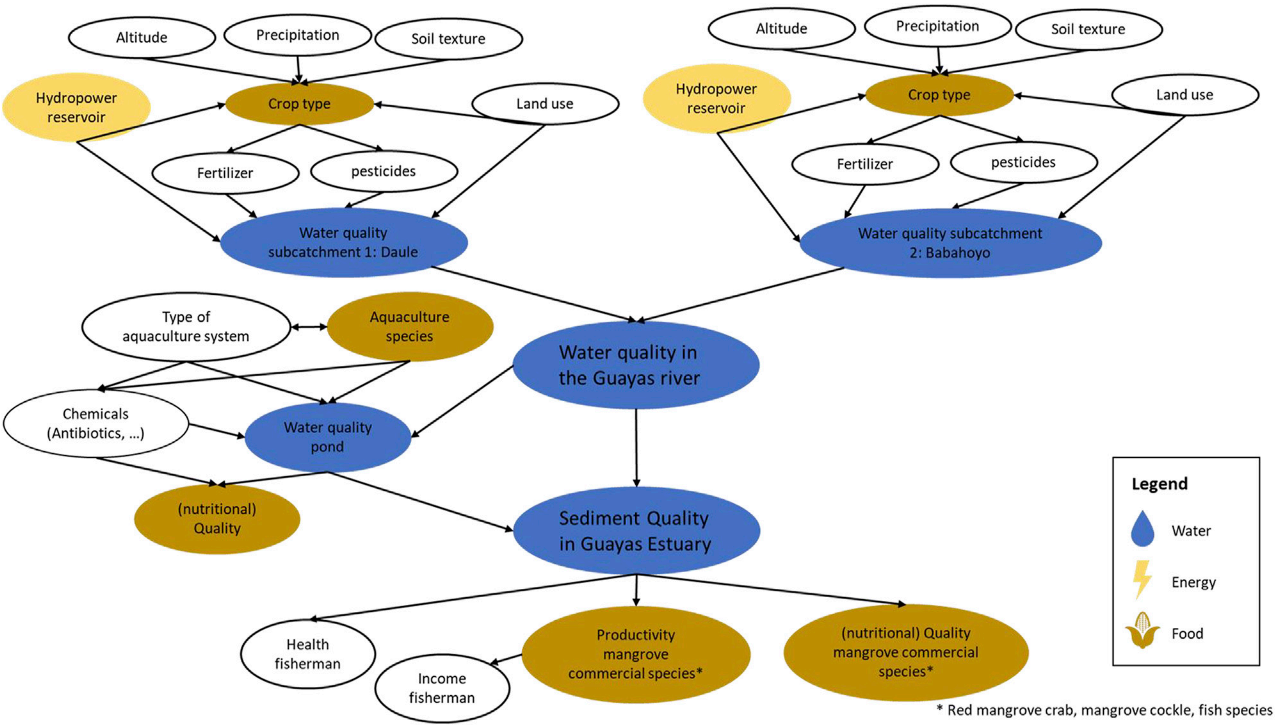
Researchers have shown that Latin America has only 25% potential to build hydropower dams in terms of suitable sites (Gernaat et al., 2017). However, the hydropower production installations are affecting aquatic biodiversity and agricultural production in river basins worldwide (Yoshida et al., 2020; Swanson & Bohlman, 2021). Apart from the antagonistic agrofood-fisheries nexus previously discussed, also energy plays a role in the sustainable development of the GRB. One of the two hydro-electrical projects in the basin is the Daule-Peripa multi-purpose reservoir, situated in the north of the basin at the Daule river, that is used to provide electricity, water for irrigation and drinking water (Damanik-Ambarita et al., 2016) (Figure 1). The Daule-Peripa reservoir has a surface area of approximately 30,000 ha, six billion m^3 of water storage capacity and 14,350 m^3/s spillway natural maximum discharge. The reservoir was built in 1987 to generate electricity, supply water for irrigation, control floods and supply drinking water (Nguyen et al., 2015). In contrast to intensive agriculture and pesticide use, the impact of the dam on the aquatic ecosystem in the GRB is less straightforward, with both negative and positive consequences. On the one hand, there is a drastic negative impact resulting from a change in habitat (Damanik-Ambarita et al., 2018; Damanik-Ambarita et al., 2016; Nguyen et al., 2015), mainly resulting from the increased depth, longer residence time and reduced flow velocity in the reservoir. This resulted in the growth of invasive water hyacinth species that proliferated in the reservoir, threatening water quality and navigation among remote communities. Ironically, the generation of power through the dams goes accompanied by energy loss and additional operational costs as the water hyacinth species have to be continuously removed in order to prevent damage to the turbines and to assure safe navigation of water transport (Nguyen et al., 2015). On the other hand, the dam also serves as a large 'settling' system for sediments and the intensive hyacinth growth has an additional water purification effect and improves the surface water quality, in particular through a severe decrease in nutrients. In addition, this nutrient retention at the upper basin could promote a higher demand for artificial fertilization of agricultural crops located at the lower basin. Nevertheless, anoxic conditions can be observed near the bottom. The cover moreover leads to a very stable and extremely transparent water system. Further WEF interactions exist between the unsustainable use of energy (fossil fuel) in agriculture, food production, water sanitation and the production of biodiesel from sugarcane, a crop that can be used for human food production, animal feed production and energy generation. In that sense, SDG 7 (assure affordable and clean energy) can be influenced by previously indicated interactions in the Guayas river basin.

The need for integrated WEF-nexus policies

It is evident that aquatic and human life need to be protected as industries and agriculture are growing in the GRB whilst agricultural fertilizers and pesticide use are incrementing. Monitoring and assessment can provide insight into the changes in the aquatic ecosystem and its status over time and the severity of the impacts. Identifying measures is the first step, nevertheless, the most critical step is to convince the relevant actors to implement these measures in the basin. This can be achieved, among other things, through raising awareness as well as showing quantitative results based on model-based scenario analyses which provide a holistic view of the costs and benefits of implementing these measures, which can contribute to the development of relevant policies. For example, the pesticide contamination in the freshwater systems may be attributed to both high consumption rates and non-specific application methods, such as aerial spraying of banana plantations and application directly into the water layer of irrigated rice fields (Deknock et al., 2019). Therefore, technical advise and awareness campaigns regarding pesticide application methods are suggested to prevent environmental pollution and accumulation of pesticides. Furthermore, the implementation of suitable policies in combination with efficient and effective WEF-governance are needed to address the complex challenges of basin management in an integrated perspective, to ensure a more sustainable development in the basin and country (Villa Cox, 2021). A major challenge is the geographical distance between pressures and impacts, therefore, a realization of measures/ responses to reduce the pollutant input in upstream systems will need both legislative and financial means to solve downstream water quality problems that affect the food generation *via* fisheries and aquaculture in the downstream estuarine system. The challenges and importance of implementing various policies regarding agriculture, water, energy, fisheries, aquaculture at different scales, as well as the effect of hydropower on pollutant removal, uptake, and ecosystem transformations are indicated by the scheme in Supplementary Figure S2 (Lawford, 2019; Mersha, 2021). As indicated in Supplementary Figure S2, many water-energy-food interactions exist in the Guayas river basin. For example, energy is becoming a more and more essential element in food production and processing, and thus agriculture. It can be noticed that every action and manner of resource use in one sector affects other sectors and their resources use, thus calling for an integrated approach of the WEF nexus (Zarei et al., 2021). Mohtar et al. (2020) indicated that a blend of monitoring data, coordinated research, public policy, and governance are needed at the national and global scales to help set goals to encourage the sectors to work together to address broader integration as needed (Vannevel & Goethals, 2021). Furthermore, Koehn et al. (2022) indicated the need for more coherent policies among sectors that provide clear procedures connecting fish production and distribution to consumers to increment the contribution of aquatic foods to food security. Also, Arthur et al. (2022) indicated that the development of policies and management resolutions to allow fisheries to make positive contributions to food systems and nutritional security, while achieving global sustainable development objectives, is a significant challenge. Thus, for future research, we recommend to extend the water-energy-food nexus by integrating the essential elements of ecosystems and public health (WEFEH), as part of one health studies and models. Studies have further demonstrated that data combined with new technologies (tools and models) can support better decision-making when adopted by governments and the management framework for each of these sectors (Farinosi et al., 2018; Mohtar et al., 2020).

Modelling the WEF nexus and the potential role of BBN's

Using integrated models, such as Soil and Water Assessment Tool (SWAT) (agro-environmental models) with urban water cycle models, ecological models, and socio-economic models to generate potential solutions for an improved balance among basin uses and the different SDG's, can support the sustainable development in the GRB (Forio & Goethals, 2020; Larsen & Drews, 2019). However, the limited availability of field data frequently restricts the use of these data-driven or complex modelling techniques to support water resource management (Forio et al., 2015). As a result, the use of Bayesian belief networks (BBN) is increasing as a decision-making tool for river basin management due to their flexibility with input data, spatial scale, model complexity and structure. BBNs are probabilistic graphical models that utilize causal interpretation (Coccoli et al., 2018; Leone et al., 2022). This modeling approach is able to work with limited and incomplete data and can combine knowledge-based (qualitative) and evidence-based (quantitative) information (Coccoli et al., 2018; Forio et al., 2015). Furthermore, they are also transparent and easy to interpret (Forio et al., 2022). Due to the complex spatial situation of the WEF nexus and the limited data availability in the GRB, the BBN approach can be advantageous when modeling the WEF nexus in the system. We developed a BBN conceptual diagram to model the WEF nexus in the GRB and its estuarine system, integrating the (sea)food security aspect (Figure 2), based on expert knowledge. This framework can be implemented to analyze the effects and trade-offs of agriculture and aquaculture (inputs) on the estuarine systems and its fisheries (output). The three food production systems (agriculture, aquaculture, and fisheries) are interconnected with the hydropower reservoir as a mediating factor in the two main catchments. The proposed BBN structure consists of 29 nodes in total, in which data can be gathered from different sources to populate the conditional probability tables. The construction of a BBN and selection of nodes have been explained using case studies by Forio et al. (2020) and Leone et al. (2022). In the



* Red mangrove crab, mangrove cockle, fish species

FIGURE 2
Conceptual diagram of the Bayesian Belief Network for the water-energy-food nexus, from an ecosystem perspective, in the Guayas river basin, Ecuador.

case of the GRB, it is important to consider interactions across space and time at different levels. Thus, the spatial aspects such as the subbasin and basin scales were explicitly represented in the conceptual diagram. To incorporate changes over time, the conceptual diagram can be implemented as a causal network in a Dynamic Bayesian Network (DBN) model instead of an ordinary BBN model to explicitly model influences over time (Chee et al., 2016). Importantly, for further research, the performance and interpretation of a BBN sensitivity analysis should be performed (Ahmad et al., 2020). Smith et al. (2018) have proven the effectiveness of BBNs for facilitating decision making through the exploration of outcomes when working with stakeholders. Thus, the implementation of the developed Bayesian belief network (BBN) framework could support sustainable decision making in the Guayas river basin by providing information and quantifying the potential trade-offs and synergies among the WEF elements.

Conclusion

Global food production, as well as the development of hydroelectric power plants, are crucial activities. There is an obvious need for a sustainable approach in the Guayas river basin considering the spatial distribution and planning. Due to the complex spatial situation of the WEF nexus and the limited data availability in the GRB, the BBN approach can be advantageous when modeling the WEF nexus in the system. This perspective paper has shown the potential of applying the WEF nexus approach to facilitate a sustainable development of the Guayas river basin. Furthermore, a high potential of implementing the developed Bayesian belief network (BBN) framework exists to be used as trade-off tool for attaining the SDGs and to support informed decision making in the Guayas river basin by linking diverse data, information and knowledge sources. The framework can be implemented to analyze the effects and trade-offs of agriculture and aquaculture on the estuarine systems and its capture fisheries. Furthermore, the BBN framework should be implemented and further developed in future research with the support and input from experts and stakeholders. The implementation and development of the BBN model and the consequent regulations can safeguard public health and economy of the local communities and support the sustainable development at a national and international level. Nevertheless, the link with human health, ecosystems and their life-contributing services and SDGs is crucial (Mersha, 2021; Yadav et al., 2021). Thus, for future research, we recommend to extend the water-energy-food nexus by integrating the essential elements of ecosystems and public health (WEFEH), as part of One Health studies and models.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material further inquiries can be directed to the corresponding author.

Author contributions

AD, MF, and PG contributed to conception and design of the study. AD wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.980442/full#supplementary-material

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