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EDITED BY
Nirmali Gogoi,
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Bombay, India
Robin Mahon,
The University of the West Indies, Cave
Hill, Barbados

*CORRESPONDENCE
Katherine Vammen
katherinevammen@yahoo.com.mx

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Water and climate: Global environmental sustainability and the current state in a developing country, Nicaragua

Katherine Vammen[1]* and Elizabet Peña[2]

[1]Institute of Interdisciplinary Research in Natural Sciences of the University of Central America (IICN/UCA) and Co-Chair of the Water Program of the Inter-American Network of Academies of Sciences (IANAS), Managua, Nicaragua, [2]Institute of Interdisciplinary Research in Natural Sciences of the University of Central America, Managua, Nicaragua

Environmental sustainability means taking steps to secure adequate management of natural resources in all human productive and livelihood activities. These steps involve a strategy of rational sustainable exploitation and the introduction of effective conservation measures which means integral management on all levels, national, regional and global. The specific situation of Nicaragua, as a prime example of a country in development with a vast richness in natural resources is analyzed. To name a few, in total renewable water resources the country has the 14th highest total yearly internal renewable water resources per capita (24,161/capita/year) in the Americas and as a tropical country has a large variety of biodiversity and ecosystems such as tropical dry and humid forests and 910 km of coastal area in the Caribbean and Pacific coast. These natural resources and more could bring potential to promote its own development. In spite of this, the country is on an unsustainable path as many parts of the world but with even greater challenges due to limited economic sustainability, high vulnerability to climate change and the lack of institutional capacity to establish better management. Unsustainable practices ranging from over-exploitation of resources to drastic land use changes have created environmental problems which consequently affect human wellbeing and health. Additionally, ecosystems and the quality of resources are under pressure which lead to a reduction in quality of water, forests and biodiversity. For example, the dry tropical forests have been reduced in 90% from 2000 to 2011 in the Pacific and Central areas and humid tropical forests are constantly being invaded and converted to agricultural and pasture lands. Water quality has been affected from contamination from agriculture, industries and the natural volcanic geology (arsenic) in groundwater as well as eutrophication and increased sedimentation from the watersheds of both lakes and rivers. Climate change is exacerbating these problems and causing new ones. After illustrating the present state of resources in Nicaragua, strategic suggestions of needed components to introduce an integral and improved management of the water resources have been laid out as a proposal for the future that include improvement in institutional capacity and governance to promote better management.

KEYWORDS

water, natural resources, Nicaragua, environmental sustainability, developing country, climate change

Introduction

Good environmental management and especially the integral management of resources should be approached on the bases of interdisciplinary knowledge and information in order to elaborate diagnosis of the current state of resources which are importantto create plans to protect natural resources and convert the exploitation of ecosystem services into a direction that secures their sustainability. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Intergovernmental Science-Policy Platform on Biodiversity Ecosystem Services-IPBES, 2019) "the health of ecosystems on which we and all other species depend is deteriorating more rapidly than ever. We are eroding the very foundations of our economies, livelihoods, food security, health and quality of life worldwide." These foundations include multiple dimensions such as water security of sufficient quality and quantity, energy security based on renewable resources, food security and the protection of biodiversity, all which contribute to a "life-supporting safety net" to sustain human life (Intergovernmental Science-Policy Platform on Biodiversity Ecosystem Services-IPBES, 2019).

The global demand for water, energy and agriculture are constantly growing. The accelerated expansion of agriculture and animal husbandry into areas of intact ecosystems is a global phenomenon and the majority is observed in the tropics where habitats have the highest level of biodiversity on the planet (Vammen, 2018; Raven et al., 2020). Latin America is the region with the highest loss of biodiversity globally where an alarming decline of 94% in wildlife in the populations of mammals, birds, amphibian, reptiles and fish was observed between 1979 and 2016 [World Wildlife Foundation (WWF), 2020].

Between 1900 and 2000 the global population quadrupled but the extraction of fresh water increased by 9 times. It has been predicted that the world population will increase to over 10 billion in 2050; if this tendency continues, the extraction of water will reach unsustainable levels in 2030 (World Economic Forum Water Initiative, 2011). Water does not have substitutes nor alternative forms to produce the adequate quantity and quality of water for the future without reverting to extremely high costs of infrastructure associated with the transport, storage and desalinization of water (Inter-American Network of Academies of Sciences-IANAS, 2018). Currently agriculture represents ~3,100 billion m^3 or 70% of the total extraction of water globally. According to The World Bank (2020) "due to population growth, urbanization and climate change, competition for water resources is expected to increase, with a particular impact on agriculture. Combined with the increased consumption of calories and more complex foods, it is estimated that agricultural production will need to expand by approximately 70% by 2050." Climate change exacerbates the need for water not only in water-stressed regions but "also in regions where water resources are still abundant today" (United Nations Educational, Scientific and Cultural Organization-UNESCO, 2020).

Nicaragua is a country in development with a great richness in natural resources including abundant water resources, biodiversity due to a large variety of ecosystems and potential for renewable energy. Nevertheless, as a country in development, it has not achieved progress in the sustainable use of these resources partly due to a large deficiency in the conditions for an adequate application of science, technology and innovation that can promote better protection and development plans for the integral management of its resources. Precisely due to these immense problems in securing economic sustainability, the country has not yet advanced in building up human and institutional capacity and needed plans to effectively take advantage of these favorable natural conditions for their own development. Of equal importance, there exists an urgent need to establish and adequate strategy of adaptation, taking into consideration its particularities in confronting the challenges of climate change expected in the future.

The purpose of this article is to examine the present state of natural resources and the environmental situation of Nicaragua in a global, regional and national context. The richness in natural resources and their ongoing deterioration will be analyzed considering the limits and deficiencies in the process of developing a sustainable resource management as one of the principal factors in its own national development. This has been limited due to economical and institutional aspects such as the generation and organization of information that can be applied to up-to-date diagnostics and failure to build sufficient institutional capacity to adequately manage the state of resources and regulatory processes in appropriate governance. Of course, this runs parallel to promoting the necessary economic resources needed to support these processes. The urgent need to initiate a process of environmental sustainability through the improved development and application of science will be stressed in order to avoid an increase in the current situation of environmental imbalance (Cornejo et al., 2020).

Situation in Nicaragua

Nicaragua is the second poorest country in the Americas by nominal GDP (International Monetary Fund-IMF, 2019). It has a population of 6.7 million inhabitants where 57% live in urban areas and 43% in rural zones. There is a surface area of 130,370 km^2 whereas 7.8% are lakes. The population is characterized by an uneven distribution where 51% is located in the Pacific Zone, 34% in the Central and North Zone and only 15% in the Caribbean zone (Instituto Nacional de Información de Desarrollo-INIDE, 2020). The principal productive sectors of the economy are agriculture and cattle breeding (13.7% of GDP) and manufacturing has grown to 16% in 2021. Mining activities are also increasing and have reached 2.4% GDP in 2021 (Banco Central de Nicaragua-BCN, 2021).

The country has also been evaluated by the International Water Management Institute (Seckler et al., 2007) as a country with economic scarcity of water meaning that it has sufficient renewable water resources but requires investment in infrastructure to guarantee better availability of water for the population. Since this time there has been no further evaluation of economic scarcity of water for the country but important projects in infrastructure such as the Integral Sectorial Program of Water and Human Sanitation (Programa Integral Sectorial de Agu y Saneamiento Humano-PISASH) have been carried out supported by a group of international organizations of cooperation from 2014 to present which has benefited the urban population of Nicaragua with improved access to potable water and sanitation systems. This project is managed by the National Company of Aqueducts and Sewers (ENACAL).

Central America is a unique climate region due to its geographical position and narrow isthmus shape with a highly variable topography and located between two marine areas, Pacific and Caribbean which have strong influence on its climate variability and change with the occurrence of extreme events. "It is common to classify the climate into having predominantly Pacific or Caribbean slope features" (Hidalgo, 2021). There are comparatively low levels of greenhouse emissions but the region has been categorized as vulnerable to climate change (Eckstein et al., 2021) as extreme events such as hurricanes and tropical storms have been growing in intensity (Hidalgo, 2021) and extended dry periods have been observed in the Central America Dry Corridor (Pascale et al., 2021), in Nicaragua mainly in the Pacific and Central regions.

Temperature trends are increasing constantly and have been predicted to grow even more in the future (Hidalgo, 2021). According to the last Climate Risk Index evaluation from German Watch (Eckstein et al., 2021), Nicaragua ranks as the 49th nation globally.

Water resources

Nicaragua has a wealth of water resources; according to Food Agriculture Organization of the United Nations (FAO-AQUASTAT) (2022), in the year 2018, inhabitants had 25 446 m^3 per year as Total Renewable Water Resources. A comparison of the Total Renewable Water Resources per Capita in different global regions demonstrates the natural favorable conditions of water resources in Nicaragua and Central America (Table 1) and Nicaragua has the 14^{th} largest IWRW of all countries of the Americas [Food Agriculture Organization of the United Nations (FAO-AQUASTAT), 2022] (Table 2).

The Pacific Zone has an IRWR of 3,493 m^3/inhabitants /year as 51% of the total population is concentrated here. This is still above the limit of 1700m^3/inhabitants /year which is the limit of hydric stress according to the Falkenmark Water Stress Indicator (Falkenmark et al., 1989).

TABLE 1 Total internal renewable water resources (m^3/capita per year) [Food Agriculture Organization of the United Nations (FAO-AQUASTAT), 2022].

Regions	Total internal renewable water resources (IRWR) m^3/capita per year
World	5,829
Oceania	29,225
Americas	19,725
North America	15,845
Mexico	3,220
Central America	13,922
Nicaragua	24,161
Caribbean -Greater Antilles	2,367
Caribbean -Lesser Antilles and Bahamas	2,071
South America	30,428
Europe	8,895
Africa	3,319
Asia	2,697

https://www.fao.org/aquastat/en/.

According to the characterization of precipitation from the Nicaraguan Institute of Territorial Studies (Instituto Nicaragüense de Estudios Territoriales-INETER, 2012) with accumulate values from 1971 to 2012, the Pacific region of Nicaragua has a range of precipitation from 1,000 to 2,000 mm; the North and Central zone from 800 to 2,500 mm. The Caribbean zone called the autonomous region has the highest annual quantity with a range from 2,500 mm in the northern zone up to 5,000 mm in the extreme Southeast. The maximum precipitation is registered in July and August and the minimum between March and April.

Agricultural water withdrawal is at the highest level of total withdrawals for Central America in 76% but as percentage to total renewable water resources still relatively low with 0.7% [Food Agriculture Organization of the United Nations (FAO-AQUASTAT), 2022]. Water Stress Values (SDG 6.4.2) for Central America reflect the availability of water resources as they demonstrate how much freshwater is being withdrawn by all economic activities, compared to the total renewable freshwater resources available where Nicaragua has a value of 2.692 (Table 3). Nevertheless, Nicaragua has observed a progressive reduction in IWRW in the last 6 decades since 1960 of 60 720 m^3/capita/year due to population growth but also due to impacts on water quality (Vammen et al., 2019). The reduction in water quality has been caused by strong deforestation processes with increasing land use for agriculture and pasture lands for cattle herding, urbanization, contamination due to agrochemicals in agriculture, mining pollution and other industries including bad management of solid and liquid wastes. Important waterbodies such as crater lakes, Laguna de Masaya and Tiscapa and a tectonic lake in the capital, Lake Xolotlán (Managua) have completely lost the water quality required for human consumption due to improper use as a receiving body for deposition of solid and liquid wastes.

TABLE 2 Internal renewable water resources for countries of the Americas for 2018 [Food Agriculture Organization of the United Nations (FAO-AQUASTAT), 2022].

	Countries of the Americas	Total internal renewable water resources (IRWR) m^3/capita per year
1	Guyana	309,369
2	Surinam	171,878
3	Canada	76,892
4	Peru	51,298
5	Chile	47,253
6	Colombia	43,193
7	Belize	39,836
8	Panama	32,704
9	Venezuela	27,867
10	Brazil	27,025
11	Bolivia	26,733
12	Uruguay	26,730
13	Ecuador	25,895
14	Nicaragua	24,161
15	Costa Rica	22,603
16	Paraguay	16,820
17	Honduras	9,456
18	USA	8,622
19	Guatemala	6,680
20	Argentina	6,563
21	Mexico	3,241
22	El Salvador	2,434

https://www.fao.org/aquastat/en/.

Watersheds and precipitation seasons

The watershed system of Nicaragua is divided into six major level 4 basins according to the methodology of Pfaffstetter: the Autonomous Region of the South Caribbean Coast (RACCS)-9519, the Autonomous Region of the North Caribbean Coast (RACCN)-9517, the San Juan River Basin-952, the Rio Coco Basin-9516, the Rio Grande de Matagalpa Basin-9518 and the Pacific Basin-9533 (Figure 1 and Table 4). Surface waters of the majority of watersheds drain eventually to the Caribbean except from the Pacific Basin. Fifteen-one of the 80 principal rivers flow toward the Caribbean side, 4 into Lake Xolotán, 12 to Lake Cocibolca and the remaining 13 (longitude of 27–77km) short rivers to the Pacific Coast. The waters of the tributaries to Lake Xolotlán and to Lake Cocibolca, eventually flow into the Caribbean Sea *via* the San Juan River (Instituto Nacional de Información de Desarrollo-INIDE, 2020).

In spite of the abundancy of water resources annually, it is important to take into consideration for future use and climate change adaptation that precipitation is less, scarce or zero in the dry season from December to April in some basins and therefore surface runoff and infiltration are almost null except for the four watersheds, South Caribbean Coast (9,519), North Caribbean Coast (9,517), Río Grande de Matagalpa (9,518), and also in Río San Juan (952) in the southern area. The Pacific (9,533) and Río Coco (9,516) have well defined dry stations between December and April (Instituto Nacional de Información de Desarrollo-INIDE, 2020).

Groundwater

According to the Nicaraguan Institute of Territorial Studies (Instituto Nicaragüense de Estudios Territoriales-INETER, 2016), Nicaragua has 12 main aquifers located in the Pacific

TABLE 3 Average total renewable water resource per capita, long term annual precipitation, water stress and agricultural water withdrawal in 7 Central American countries [Food Agriculture Organization of the United Nations (FAO-AQUASTAT), 2022].

Country	Total renewable water resources per capita 2018 (IRWR- m^3/capita per year)	Long-term average annual precipitation in volume ($10^9 m^3$/year)	SDG 6.4.2 Water Stress	Agricultural water withdrawal as % of total water withdrawal (%)	Agricultural water withdrawal as % of total renewable water resources (%)
Belize	39,836	39.16	1.26	67.72	0.31
Panama	32,704	220.5	0.9011	36.83	0.32
Nicaragua	24,161	297.2	2.692	76.72	0.72
Costa Rica	22,603	149.5	5.211	72.03	2.04
Honduras	9,456	222.3	4.621	73.3	1.28
Guatemala	6,331	217.3	5.742	56.74	1.47
El Salvador	2,434	37.54	13.21	67.56	5.45

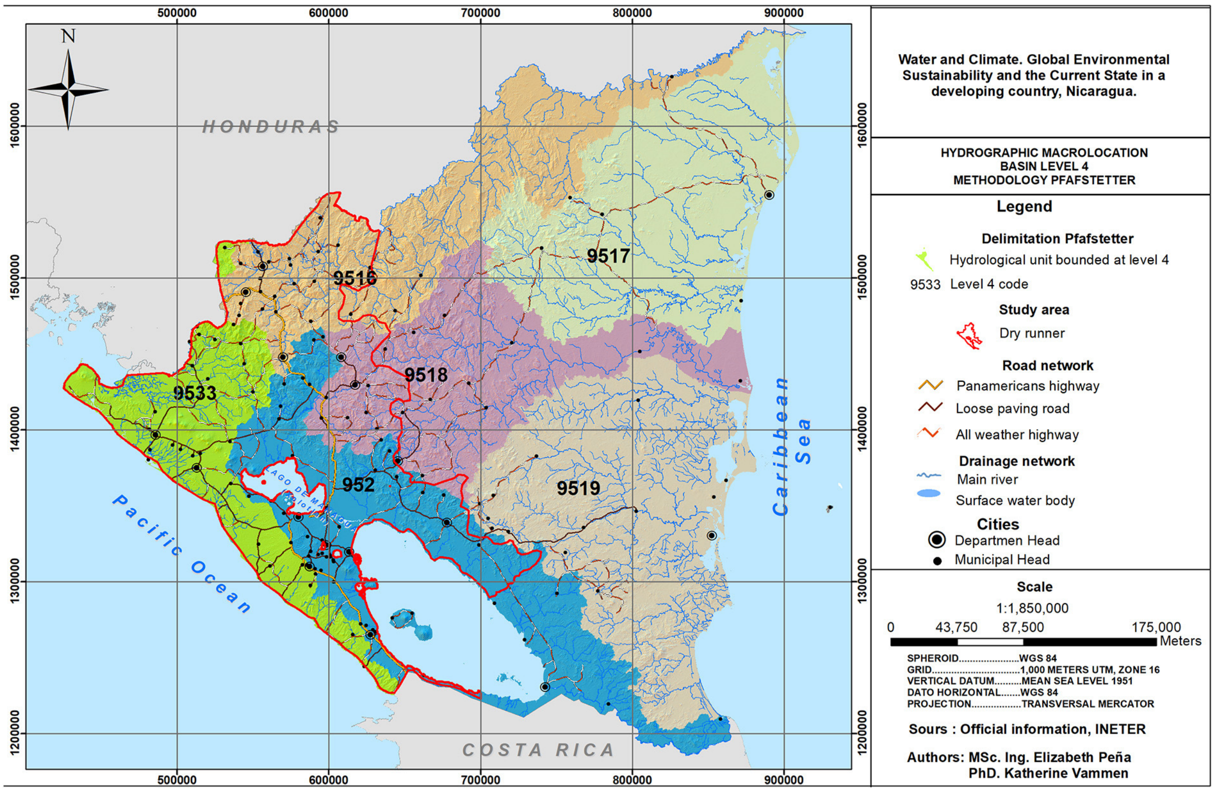

FIGURE 1
Hydrographic watersheds of Nicaragua (methodology Pfaffstetter). Prepared by authors with official information of INETER.

TABLE 4 Hydrographic watersheds of Nicaragua (prepared from Autoridad Nacional de Agua (ANA), Instituto Nicaragüense de Estudios Territoriales (INETER), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Programa de Asistencia Técnica en Agua y Saneamiento (PROATAS) y Universidad Nacional de Ingeniería (UNI), 2014), area and percentage of territory.

Hydrographic watersheds	Watershed code	Area in km^2	% National territory
Autonomous Region of the South Caribbean Coast (RACCS)	9,519	25 672.62	21.55
Autonomous Region of the North Caribbean Coast (RACCN)	9,517	23 879.21	20.05
Río San Juan	952	19 533.46	16.40
Río Coco	9,516	18 972.17	15.93
Río Grande de Matagalpa	9,518	18 856.55	15.83
Pacific	9,533	12 191.67	10.24
Total		119,105.68	

area, ~70% of which are shallow and prone to contamination due to the characteristics of the landscape. Smaller aquifers can be found in valleys located in the Central and Caribbean regions. Figure 2 shows the location of the aquifers designated in yellow. Eighty percent of the Nicaraguan population was supplied by groundwater used for irrigation, industry and drinking water in 2010 (Instituto Nicaragüense de Estudios Territoriales-INETER, 2010). In the last decade there has been a gradual change to diversification of the sources toward surface waters especially in the central and Caribbean side of the country corresponding better to the natural geographic distribution of surface and groundwater sources. The western aquifer located in the municipalities of León and Chinandega has the most potential in volume and the soils are very fertile in this area. This aquifer is used for irrigation of sugarcane and other perennial crops in the dry season. Further important aquifers for irrigation

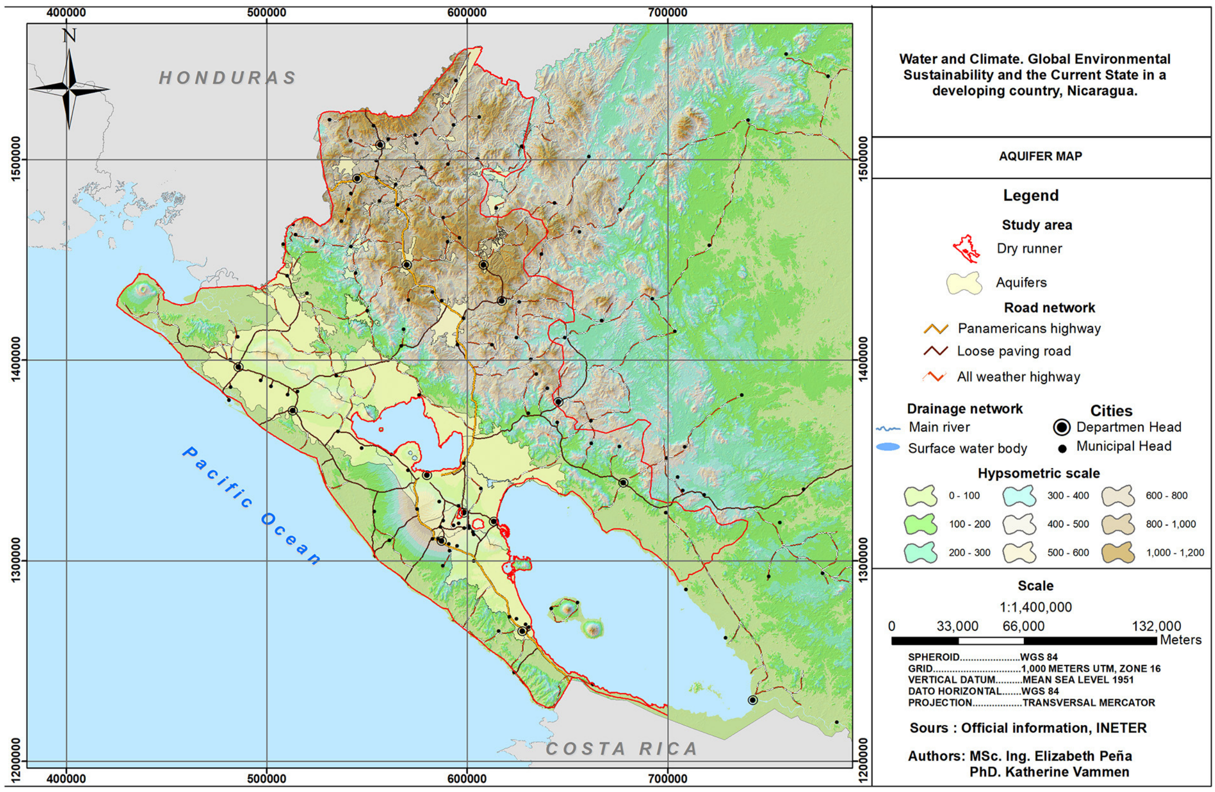

FIGURE 2
Map of location of aquifers. Prepared by authors with official information of INETER.

are: Sébaco, Nandaime Rivas, Malpaisillo, Tipitapa Malacatoya, Somotillo, Estelí for crops in the Pacific and Central zone. The aquifer of the Sierras is key for the supply of water for domestic and potable consumption in the largest city of Managua.

Surface waters

The great *lakes* of Nicaragua (Lago Cocibolca-8,144 km^2 y Lago Xololán-1,016 km^2) are the two largest lakes in area of Central America. Lago Cocibolca is the largest tropical lake of the Americas and number 20 globally (Schwoerbel, 1987) with a watershed of 23,844 km^2 and volume of $\sim$104,000 hm^3. The latter still has water quality adequate for human consumption and is therefore a potential reservoir for drinking water supply for the country and possibly other Central American neighbor countries in the future. At this time 5 urban centers have water treatment centers to guarantee human consumption of the lake water. Two additional cities this year will also be ready as a source forconsumption from the lake water. The watershed of Lago Cocibolca has been submitted to a massive deforestation and now has been converted to 70% pasture land (Vammen et al., 2006). This is a high threat for its water quality. It is urgent to increase efforts to expand and improve integral watershed management in order to preserve its quality.

The country has 80 major rivers; 51 of which flow into the Caribbean Sea. The impact on water quality of the majority of the rivers can be characterized with high environmental degradation mainly due to an increase in sedimentation from eroded areas of their watersheds due to the change in land use, "particularly deforestation, contamination by domestic waters due to the lack of sanitation systems in cities and rural areas, indiscriminate use of their waters for irrigation in agriculture, which affects the ecological flow of the river and contamination by fertilizers and pesticides used in agriculture" (Inter-American Network of Academies of Sciences-IANAS, 2019).

One example is Río Viejo which is uniquely important for the hydrological system as it is located in the highest upstream area of the San Juan River Basin (Basin 952, Figure 1), in other words, upstream to the sub-basin of the Lake Xololtán The river has a length of 157 km, and its sub basin an area of 1,553 km^2. A diagnosis of its water quality and quantity was performed in a study in 2010 and 2011 (Vammen, 2012) to produce multidisciplinary information to develop a strategy of watershed management in benefit of the population. The most important conclusions of the study included: (1) water production in the upper part of the sub-basin of the Río Viejo is high to medium, showing the importance to introduce measure of protection and reforestation, (2) deforestation processes were found in all its micro basins and, since the land has inclined slopes, runoff predominates over recharge and causes base flows which were not maintained in the dry season, (3) microbiological contamination due to fecalism (human and livestock) in the river and surrounding groundwater deposits, which represents a risk factor for consumption and recreational use by the population, and (4) overexploitation of surface water for irrigation. Some components of the strategic plan were achieved, for example the construction of a water treatment plant and sewage net in the municipality of Trinidad which caused heavy fecal and organic contamination of river waters. The most important recommendations to protect the upper part of the river basin as a forest reserve have not yet been accomplished.

Nicaragua has a unique chain of volcanoes and 16 volcanic lakes, Maar geological formations known locally as *Crater Lakes*, that run along a chain of volcanoes from the north to the south on the Pacific side of the country (Figure 3).

Distribution of the population and water resources

Related to the demand of water from the population, the distribution of natural water resources especially surface waters nationwide do not correspond to the abundance and density of inhabitants. As mentioned above the large majority (89.76%) of surface waters drain to the Caribbean coast where there only 15% of the population live. On the other hand, 85% of the Nicaraguan population live in the Pacific and Central zones where there is less surface water but access to more supplies of groundwater. In the last decade there have been some steps taken to begin to use more surface water for consumption through efforts in the PISASH project; recently the Caribbean population has better access to drinking water using surface waters, mainly rivers, close to urban centers with purification and waste water treatment plants.

Present state and environmental deterioration of other resources

Forests and biodiversity

Nicaragua has a large variety of tropical land ecosystems such as tropical dry forests mainly in the Pacific and Central territories and tropical humid forests in the Caribbean. In the last decades, there has been an accelerated deforestation process in both; Global Forest Watch (2020) has observed a reduction of 1.4 million hectares of tree coverage. The Ministry of Natural

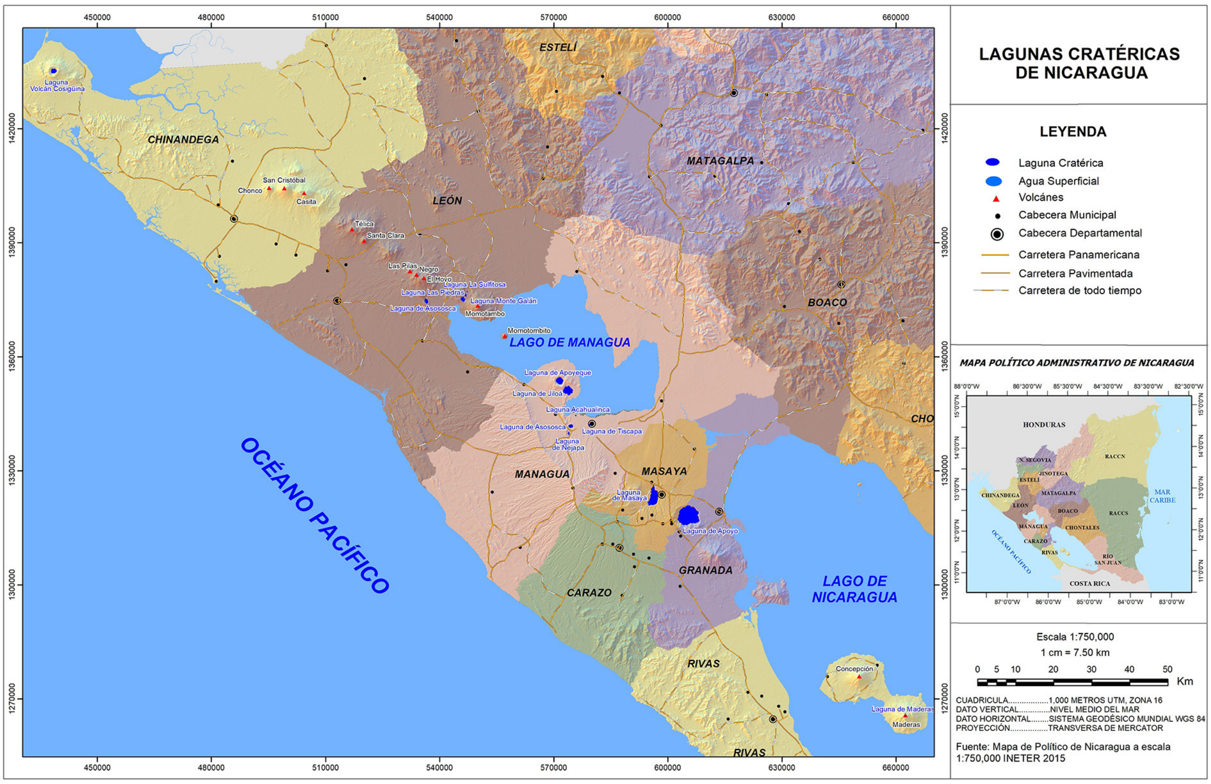

FIGURE 3
Map of crater lakes and volcanic chain. Prepared by authors with official information of INETER.

Resources and Environment (Ministerio del Ambiente y los Recursos Naturales., 2019) reports a loss of 1.5 million hectares of forests in the period from 2000 to 2015. This has also caused violent social conflicts especially due to the invasion of lands of indigenous communities in the Caribbean area. Large forest reserves such as *Bosawas* and *Indio Maiz,* inhabited mainly by indigenous communities, are under constant social threats and frequently hit by extreme climate events such as tropical storms and hurricanes and large forest fires. The tropical dry forests in the Pacific and northern central areas (Figure 4) have suffered an alarming reduction of forest cover in 90% from 2000 to 2011 [Data from Ministerio Agropecuario y Forestal (MAGFOR), 2000; Alliance for the Conservation of Dry Forests, 2011].

This loss of forests has affected the biodiversity and the quality of inland and coastal waters due to the increase in runoff that promotes erosion and as a consequence growing sedimentation in these waterbodies. These constant land use changes impact the biodiversity in aquatic and terrestrial ecosystems (Mantika-Pringle et al., 2015).

Both the Pacific and Caribbean coasts have vast wetlands the majority of which have been declared Ramsar sites and in the same way are losing their rich biodiversity due to these processes of erosion that bring heavy runoff that also contain agrochemicals from surrounding agricultural lands (Inter-American Network of Academies of Sciences-IANAS, 2019).

Energy

Nicaragua is a country with a large potential for conversion to renewable sources to reduce the use of petroleum. At this time energy resources depend on 43.1% from thermoelectrical plants, 19% from biomass use, mainly from sugar plantations, 16.9% from geothermal, 15.9% wind energy, and only 0.6% photovoltaic, sun energy (Ministerio de Energía y Minas, 2020) (Table 5).

The majority of greenhouse gases are generated by public and individual transport, all derived from petroleum and is the main source of air pollution.

Climate change impacts

As mentioned above, a constant increase in temperature trends has been observed in the "Central American region and this brings a higher demand for water from the atmosphere, drier soils and higher aridity impacting agriculture, ecosystems and increasing the potential for forest fires" (Hidalgo, 2021). The agricultural water withdrawal to total water withdrawal in Nicaragua is high even for Central America in 76.72% (Table 3). In the last decade changes have occurred also in certain periods of the year that historically have been more humid. Changes in precipitation regime patterns have been observed as events are growing in intensity, synchronization, and duration (Feng and Fu, 2013; Hidalgo et al., 2019).

Also. in the last years tropical storms have made land fall further south in the region (Huracanes Otto in 2016, Iota and Eta in 2021 and Bonnie in 2022).

Along with human activity such as changes in land use and deforestation, climate changes have caused diminution in forest zones especially in the tropical dry forests in the Pacific region and in the tropical humid forests in the Caribbean and southern regions of Nicaragua transboundary to Costa Rica (Huracanes Otto in 2016).

Evaluations and studies on the impact of climate change in Nicaragua are especially important due to their influence on the management of the agriculture cycle especially for subsistence small farmers and its effects on food security. The management of water resources is even more urgent due to the increasing probability of extreme events such as droughts in Central America (Hidalgo, 2021). Especially ecosystems are under the influence from climate change. "Other projected impacts of climate change include an increase in the frequency of heatwaves, rainforest biomass changes, and ocean acidification, which will impact mangrove forest, corals, and cause disruption in the trophic chain" (Durán-Quesada et al., 2020) in all of Central America.

Dry Corridor of Central America and Nicaragua

Central America has a very pronounced *Dry Corridor* which extends from Northwest (Guanacaste) in Costa Rica, through the Pacific area of Nicaragua especially in the north and in El Salvador, Honduras and Guatemala where the corridor widens into the central territory (Figure 5). The delimitation of the Central American Dry Corridor (CADC) varies from year to year (Hidalgo, 2021). The area of the Dry Corridor in Nicaragua (Figure 6) covers 21% of the national territory (Graterol Matute et al., 2019) which means ∼66% of the national population (estimation calculated from the corresponding municipal populations—Instituto Nacional de Información de Desarrollo-INIDE, 2020).

This Dry Corridor is known especially for higher aridity "Compared to the rest of the isthmus and for being strongly correlated to ENSO and to the strength of the trade winds from the Caribbean" (Hidalgo, 2021). Precipitations in the northern part of the Dry Corridor of Nicaragua range from 600 to 1,200 mm yearly (Bendaña, 2012). Temperatures oscillate between 17 and 34°C and altitudes vary from averages of 300 to 700 meters above sea level with individual elevations reaching up to 1,700 meters.

The Dry Corridor has been characterized by its high vulnerability to natural climate variability and anthropogenic climate change, and a strong socioeconomic susceptibility marked by poverty with food insecurity partly due to failure

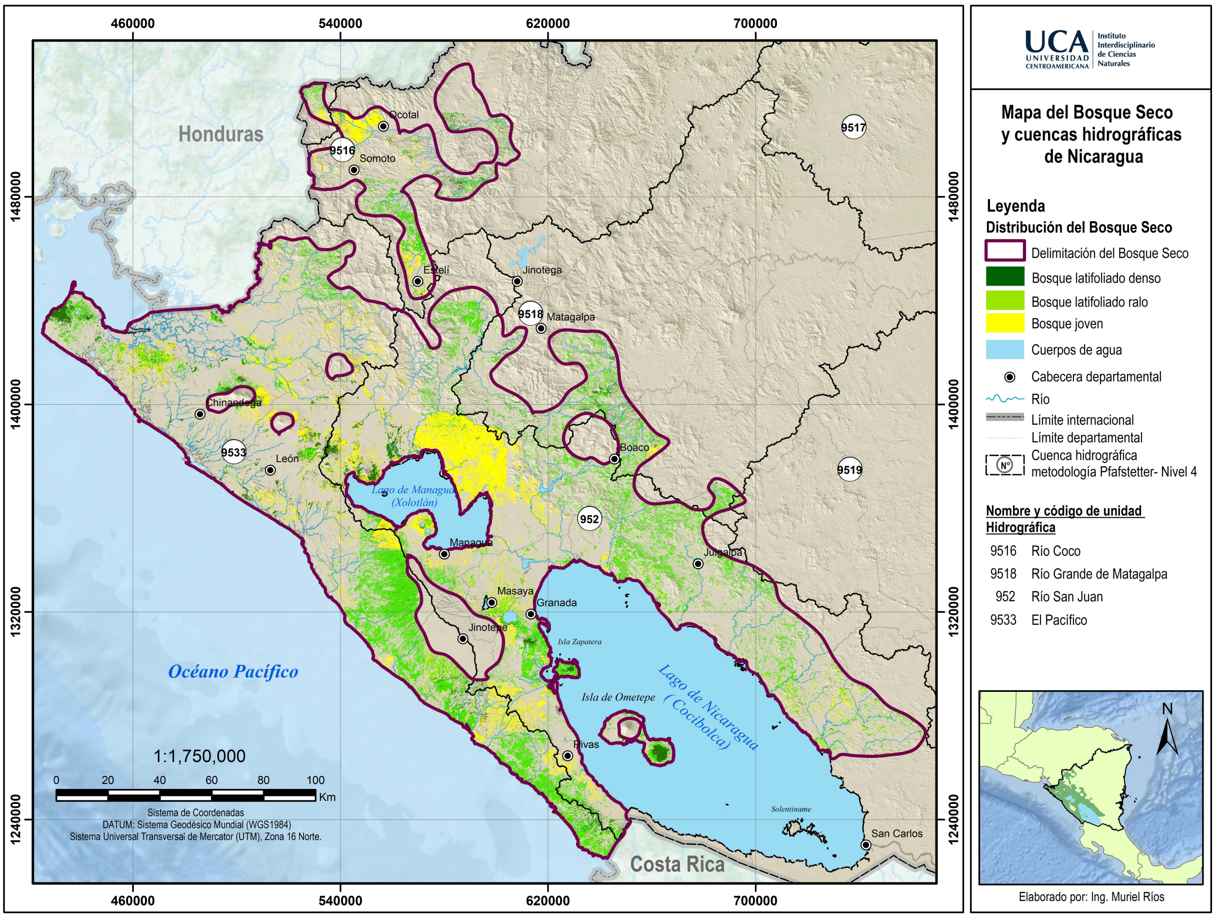

FIGURE 4
Map of dry tropical forests in Pacific of Nicaragua, elaborated by Ing. Muriel Rios.

TABLE 5 Prepared by authors from the report of National Energy Balance (Ministerio de Energía y Minas, 2020).

Forms of energy	Portion of national energy production (contribution in %)	Observation
Convencional thermal power central plants térmicas	43.1	Petroleum (Gasoline, Fuel Oil and Diesel)
Self-production from Biomass and hydroelectric plants.	19.0	Includes energy injected into National Interconnected System (Energía inyectada al Sistema Interconectado Nacional: SIM) and for self-consumption such as self-production of biomass from large sugar plantations and central hydroelectric plants.
Geothermal plants	16.9	
Central eolic plants	15.9	
Central solar photovoltaic	0.6	

in agriculture harvests which have caused frequent human migration waves. Agriculture has been considered as a high risk due to the effects of these droughts. Climate variability and change has led to an increase in frequency of drought periods strongly affecting farmers totally dependent on family agriculture. According to the World Food Program (2019),

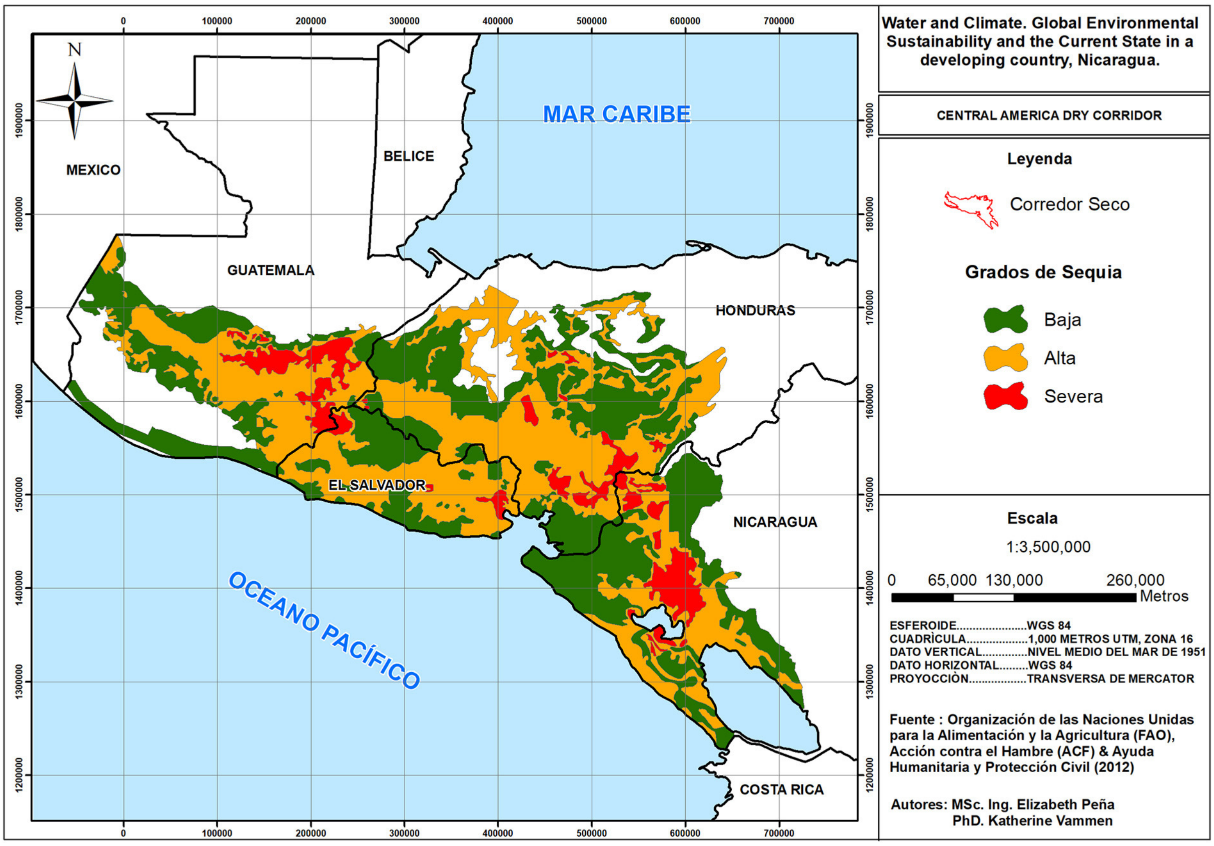

FIGURE 5
Dry Corridor of central America and degree of drought (Prepared by the authors on the basis of data supplied by Food Agriculture organization of the United Nations-FAO, 2012).

200,000 people are in potential risk of food insecurity as their means of living depend directly on income generated by small-scale subsistence agriculture which is under pressure due to changes in the agriculture cycle induced by climate change impacts on seasonal regime patterns.

The dry tropical forests in the Corridor are extremely fragmented and under risk of disappearance due to changes in land use, conversion to agriculture lands and cattle breeding pastures. Some droughts in particular are related to the anomalous distribution of precipitation during the rainy season specifically longer dry periods known as "canícula or veranillo." These longer dry periods during the rainy season are influenced by the higher ocean surface temperatures in the Pacific and reduced temperatures in Atlantic resulting in drier soils and more frequent dry periods. It has been predicted that this will cause an increase in aridity in a hotter climate in the future and prediction models of the Dry Corridor have shown significant tendencies in warmer temperature and less significative changes in total volume of precipitation (Hidalgo et al., 2019).

Several small studies of micro watersheds in the Dry Corridor from different institutions have shown a reduction in waterbodies resulting in a deficit in their water balances (Reyes Rodríguez, 2022).

All these factors have led to a number of project activities of different institutions such as Tropical Agriculture Center of Research and Teaching (CATIE-Centro Agronómico Tropical de Investigación y Enseñanza) who have contributed to food security and sustainable production especially in Las Segovias, northern department of Nicaragua, through the introduction of a variety of water harvesting systems.

Present land use in the Dry Corridor of Nicaragua

In the last two decades, there has been considerable changes in land use in all of Nicaragua. According to information of the Nicaraguan Institute of Territorial Studies (Instituto Nicaragüense de Estudios Territoriales-INETER, 2021) the present land use in the Dry Corridor has the following principal components: 31% is pasture, 21.9% is open and closed broadleaf forests, 19.7% is shrub and herbaceous vegetation

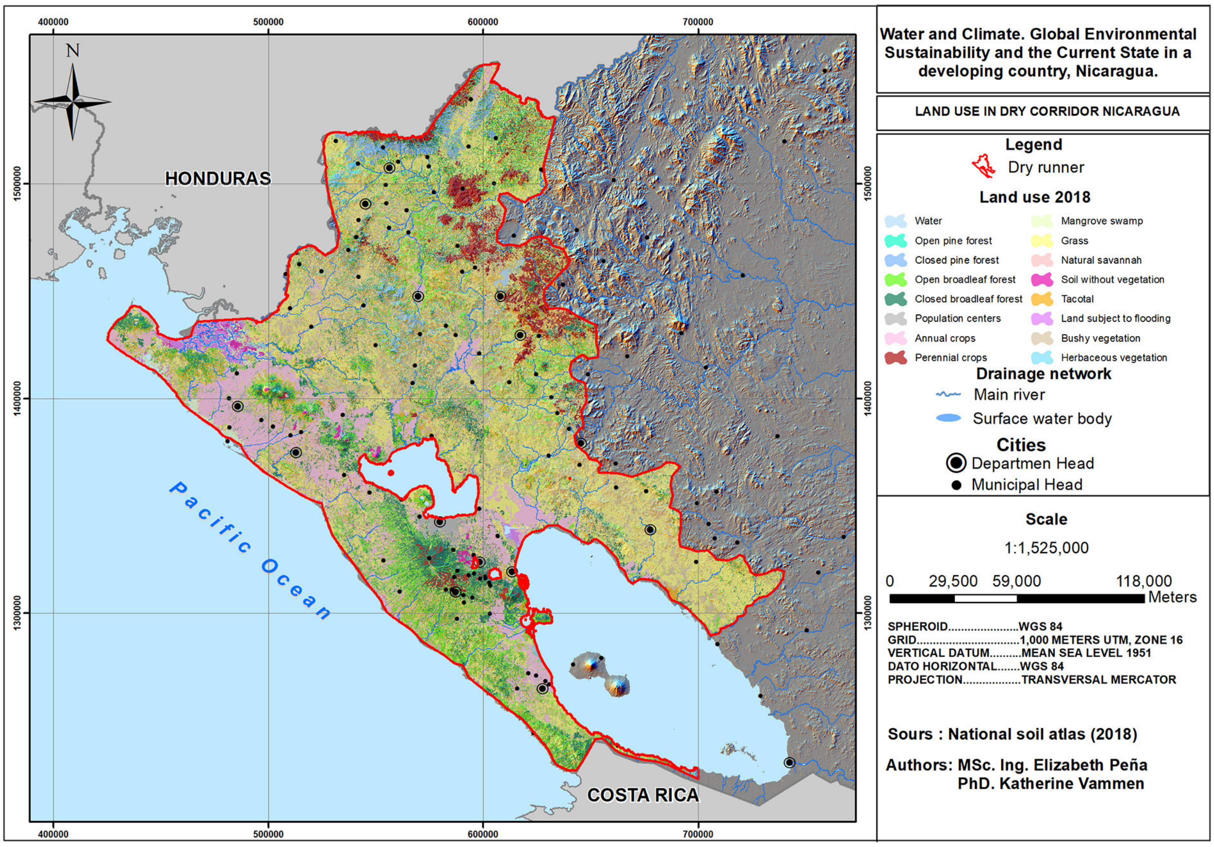

FIGURE 6
Present land use of the Dry Corridor of Nicaragua (Prepared by the authors. Source: National Atlas of Soils of the Republic of Nicaragua, 2018-2021, Instituto Nicaraguense de Estudios Territoriales (INETER), 2018).

and 14.6% is agricultural use of annual and perennial crops. Urban or populated rural centers cover 2.2%. This makes up a total of 95% and the rest are smaller components <1% (Figure 6).

According to the data base of land use in the Dry Corridor in different years, there have been significant changes in land use to pasture and agriculture in comparison to earlier years due to increasing food demand and especially under pressure from climate variability and change which has brought more extended drought years in the last decade (Pascale et al., 2021).

Groundwater under climate change

Water scarcity has also been observed due to over-exploitation of groundwater for agriculture in the *Pacific* zone of Nicaragua. For example, the most intense agriculture area of Nicaragua is located in the Pacific Area of Leon-Chinandega where the most extensive and fertile soils adequate for agricultural can be found and the most productive aquifers. Groundwater is the main source of irrigation in 74.4% (Ministerio del Ambiente y Recursos Naturales-MARENA, 2008). There are also indications that sources have also been contaminated by the intensive application of pesticides in the past and present (Delgado, 2003; Montenegro and Jiménez, 2009).

It is always important to have in mind that climate change could bring a reduction in average long-term precipitation which would cause a decrease in groundwater storage and therefore increasing pressure on water resources for all uses.

National and regional institutional support for water resources and climate

In Nicaragua specific institutions for the management of water resources have recently been working in cooperation in the context of the Sustainable Development Goals especially

SDG 6 ensuring Water and Sanitation for all. In 2021 a special Interinstitutional and Sectorial Commission of Water, Sanitation and Hygiene (COMISASH-Comisión Interinstitucional y Sectorial de Agua, Saneamiento e Higiene) was formed to work toward the Target 6.5.1 in order to implement integrated water resources management at all levels. The special Commission has recently developed a *Plan of Action for the Integrated Water Resource Management* (IWRM) for 2022-2026 (Ministerio del Ambiente y los Recursos Naturales, 2022).

The Plan of Action will be executed by the Ministry of Environment and Natural Resources (MARENA), the National Authority of Water (ANA) with cooperation of the Global Water Partnership-GWP. The aim is to promote priority actions in response to the needed integral management of water resources in Nicaragua supporting a sustainable development and protection of national natural resources, specifically related to the environmental necessities of Nicaragua.

There are also regional efforts of Central American Institutions such as the Central American Commission for Environment and Development (CCAD-Comisión Centroamericana de Ambiente y Desarrollo) part of the System of Integration of Central America (SICA-Sistema de la Integración Centroamericana). At this time there are special actions for the Integral Management of Watersheds specifically in the sub watershed of the river and delta system "el Estero Real" located in the northwestern corner of Nicaragua and which drains into the Golf of Fonseca and is shared between three Central American countries, Honduras, El Salvador and Nicaragua. This is part of the framework of the Regional Environmental Strategy known as ERAM (Estrategía Regional Ambiental Marco) for 2021 to 2025. SICA also supports regional efforts on climate change in a yearly forum on Central America Climate Applications Forum (https://www.sica.int/san/) which strengthens collaboration between countries in interchanging climate change information to develop adaptation and strategies to confront climate change.

National efforts such as plans for the Integrated Management of Watersheds have been developed in a tributary of Lago Cocibolca in the sub watershed of River Mayales by PROATAS (Program for Technical Assistance of Water and Sanitation, https://www.proatas.org.ni/) in 2014. Recently a plan of integral watershed management for the sub watershed of Río Dipilto has been elaborated and is in the process of implementation in the north central part of Nicaragua where a watershed committee has been formed and is active in executing certain activities of the plan. The latter is an interinstitutional cooperation between the Ministry of Environment (MARENA), the National Company of Aqueducts and Sewers (ENACAL), the Municipalities of Ocotal and Dipilto and the Emergency Social Investment Fund (FISE) with support from Swiss Cooperation in Central America (COSUDE).

Discussion: Strategy for protection of resources with emphasis in water and adaptation to climate change

In order to define the future orientation to sustainable development of Nicaragua, it is key to take better and more efficient advantage of the still favorable situation of natural resources and apply this strategy to build resilience to future climate change impacts. As has been stated, water resources could be an important motor for the sustainable development of the country. As this resource is a fundamental human right for the wellbeing of the population and there is no substitute, it is imperative to develop a strategy to secure its protection and conservation, adequate use, and it is an urgent priority to introduce measures of adaptation to meet the challenges of climate change based on information of water resources in all watersheds of the country.

We mention one important example which would involve the more effective use of the waters of Lake Cocibolca which has been designated in Article 97 of the General Law of National Waters-Law 620 (La Gaceta, 2007) as the natural reserve for human consumption. Also, a study of the The World Bank (2013) emphasized the importance of the lake as a source for supply of water for Nicaragua and a "hotspot of global biodiversity." The protection of its watershed is therefore key to promote the future consumption of its waters and as a possible source of irrigation based on a balanced plan of usage grounded on reliable information. As mentioned above, presently there has been some progress in the use of its waters as a source for human consumption with the introduction of purification plants in some of the surrounding urban centers and municipalities with the parallel construction of waste water treatment plants to prevent the continuing point source contamination promoted by Project PISASH [Programa Integral Sectorial de Agua y Saneamiento Humano (PISASH y Cocibolca), 2017, 2021]. This is not sufficient as globally it is known through many studies of lakes (Thornton et al., 1999) that eliminating only point sources of contamination is not sufficient to conserve the quality of water in waterbodies for human use. Diffuse contamination from the watershed is one of the main sources of contamination of lakes and rivers resulting from erosion which brings increased sedimentation into the lake, nutrients from agriculture and cattle grazing, other contaminants bound to the sediments such as pesticides and fertilizers used in agriculture and also solid and liquid wastes in runoff from urban centers (Vammen et al., 2019). For this reason, it is key to identify sources of diffuse contamination from human activities in the watershed considering the natural conditions of soils and geology, natural drainage due to specific topography, changes in land use and demographic factors. Studies of land use (Instituto Nicaragüense de Estudios Territoriales-INETER, 2015) in the watershed of Lake Cocibolca, show that most of its sub-basins have been transformed into land for the use as pastures, as a result of progressive deforestation over time where 71% is dedicated to the use of different types of pastures, 4% to agriculture and 19.8% are remaining forests. The last monitoring study of the lake's quality was carried out in 2014 to 2016 (Chang et al., 2017) by the Research Center for Aquatic Resources (CIRA/UNAN) with the cooperation of Center for Space and Remote Sensing Research (CSRSR) of the National Central University ofTaiwán. Results indicate a trophic level of mesotrophic to eutrophic "with zones of high eutrophication located at the entrance of the Tipitapa River that connects with Lake Xolotlán" (Vammen et al., 2019) and around urban centers which now in part have treatment plants installed. In the meantime, the vulnerability of the lake is growing as "deforestation continues due to non-sustainable agriculture and extensive cattle breeding advances relentlessly over the national geography" (Vammen and Montenegro, 2020) and particularly in the watershed of this unique waterbody and potential resource for the future of Nicaragua. At this time, the integral management of the watershed of Lake Cocibolca has not been developed nor implemented to prevent the continuation of diffuse contamination from its watershed; this would involve creating watershed committees as stipulated in Chapter IV of the Law 620 (La Gaceta, 2007) per subwatershed under the direction of state institutions that have the needed capacity to lead this process. As mentioned above, there are initiatives underway in some of the 16 subwatersheds to develop plans but their implementation is still to be resolved.

The *General Law of National Waters-Law 620* (La Gaceta, 2007) has clearly defined integral management of watersheds and the necessary actions needed such as generating knowledge of the country's water resources with the establishment of a National System of Information of Water Resources and water planning taking into account the necessary criteria to "guarantee the sustainable beneficial use and the integral use of the water resources of the hydrographical watersheds and aquifers as management units" (Article 16, La Gaceta, 2007). This would involve the National Authority of Water (ANA) in cooperation with corresponding municipalities with community participation, academia, civil society and all actors and active users. These goals and actions are still pending. It is now urgent to promote the elaboration of an integra management watershed program which should include action plans for each subwatershed of the lake with the objective to assure the quality of water and the corresponding definition and regulation of its uses for the future and includes "goals of social, economic and environmental utility in a sustainable manner: water for all uses and for all users." (Vammen and Montenegro, 2020).

This example is to demonstrate that Nicaragua has the "legal tools and framework and technical previsions necessary to implement useful plans in the use and protection of its watersheds for many years" (Vammen and Montenegro, 2020).

As mentioned above one of the fundamental conditions to define an adequate strategy for water resources is the production of scientific information about the conditions and particularities of surface and groundwater resources. This information organized in the National System of Information of Water Resources stipulated in the *General Law of National Waters* (Articles 14g and 27e) should include transparent data over the quantities extracted by all users, the problems of contamination from all sources, agriculture, domestic waste and others. This means also the establishment of a monitoring system for water quality in these waterbodies and the improvement of a national hydrological monitoring system in all watersheds also stipulated in Law 620 in Article 101 as responsibility of the Ministry of Environment and Natural Resources (MARENA). All these steps depend on the efficiency, economical and professional capacity of state institutions responsible for water resources supported by universities with experts in this area. This requires improvement in the formation and coordination of its professionals in interdisciplinary fields associated with *water and climate* and interinstitutional cooperation in the formation, use and maintenance of the system of information.

As part of the plan of integral management, it is now high priority due to progressing climate change to include a component of special management and protection of the existing forests and their gradual restauration by first reestablishing connections of fragments especially in areas where the principal aquifers of the country are present and along riparian zones associated with waterbodies suffering from processes of sedimentation; especially significant and urgent are the highly fragmented dry tropical forests of the Pacific and central region and the tropical humid forests in Caribbean territories where the majority of the indigenous and Afro-descendant communities are located. It is not enough to just reforest but it is key to develop integral plans according to the conditions of each watershed unit (Vammen and Montenegro, 2020). To achieve these strategies and plans, it is imperative to have improved institutional capacity with professionals in water, forest, natural and social sciences who cooperate with experts in the universities.

In all these, measures of adaptation to climate change, particular to the natural resources of the specific areas under concern, should be introduced with innovative methods. The environmental instability observed in the reduction of biodiversity and the accelerated extinction of species (Tórrez and Gutiérrez, 2020) is closely interlinked with measures to protect the water and forest resources. Currently there is clearly not enough information available concerning the biodiversity of terrestrial and aquatic species in Nicaragua and their corresponding ecosystem services.

In 2017, the World Bank in cooperation with the Government of Nicaragua developed a diagnosis and proposal of strategic lines with a team of interdisciplinary experts from state institutions and external experts related to the management of water in order to serve as the base for the elaboration of a National Plan for Water Resources of Nicaragua. This document was not published and the National Plan was put on hold to the present day due to the present profound political crisis creating a large national environmental, social and economic vulnerability.

Although in Nicaragua there exists a richness in natural resources especially water, the process of resource management has not been considered as a main factor in *national development*. This has been limited by failure to promote better management and prioritizing the necessary economic resources to secure a sustainable management. Gaps in institutional capacity to manage the state of resources, the organization of needed information of these resources, harmonic interinstitutional and international cooperation and the lack of regulatory aspects has played a roll.

An integral management of all resources should introduce measures to control the strong changes in land use, overexploitation of resources and environmental destruction through contamination due to agriculture, mining, and other industries that Nicaragua has suffered in the last decades and has made all territories more vulnerable to the effects of climate variability and change. This goes hand in hand with strategies to convert the generation of energy and transport systems to renewable resources which again needs the formation of professionals and technicians dedicated to this task.

Conclusions

Nicaragua is immersed in similar environmental problematic and climate change vulnerability as observed in the global context but as a developing country it also has deep educational, economic, institutional, political, and social factors which impede progress in achieving a sustainable development path. The fact that there is a richness in natural resources such as water, biodiversity, and also resources with good perspectives for conversion to renewable energy could open doors to overcome these limitations. Special emphasis on adaptation to climate change is urgent to find a strategy destined to overcome impacts on these natural resources along with measures to stop the effects of human intervention through drastic land use changes ignoring the importance of these so important strategic resources. The current environmental imbalance described above can only be met with a sustainable resource management orientated to meet the challenge.

These changes in environmental management requires a combination of urgent transformations in Nicaragua in the following:

A) Development of improved formation of national professionals with scientific, technological, and innovative knowledge directed to the better *comprehension of multiple dimensions of environmental and climate problematics* with improved institutional capacity and academic quality in universities, technical and educational institutions on all levels.
B) Establishment of improved institutional capacity of *governance directed to adequate environmental management* which requires a redesign and planning focused on integral management more coherent with the problems and necessary transformations of Nicaragua.
C) Reestablish the respect and importance of science, technology, and innovation toward the scientific community in Nicaragua which implies the formation of national research centers with qualified professionals better orientated to interdisciplinary studies necessary for the solution of environmental problems. In all this, it is necessary to promote international relations to stimulate exchange, the constant updating of scientific knowledge and the creation of strategic alliances especially on a *regional Central American* level.
D) It is an important condition to eliminate *clientelism and political intervention* in order to proceed with these transformations. More attention should be directed to include the participation of different sectors of the society in research, as science should serve all of society and take into consideration social justice and the establishment of equitable conditions.

Deterioration of natural resources through human activities, impacts of climate change, and biodiversity loss are clearly linked and integrally cause effects on human and ecosystem health. It is key to turn attention to the criteria of sustainability and reduce the extraction of resources for short term gains. As a planetary threat they require a combined response on a global level. For example, a rapid transition to wind and solar energy away from all fossil fuels reduce air contamination and slow down climate change, double benefits for planetary health (Fuller et al., 2022).

In all, it is imperative to promote an urgent change in the attitude or philosophical vision toward nature in the sense that humans are part of nature and all the degradation processes affect the population and nature, its resources and their potential to contributing in achieving a sustainable development. Corresponding to this it is urgent to introduce transformations in reducing activities of environmental impact, changes in lifestyle of the society with more attention to ecological problems especially in light of coming impacts of climate change.

Author's note

Both authors are women scientists and specialists in water sciences and interdisciplinary environmental studies. Both contributed to the analysis and projection of the specific environmental situation of Nicaragua in the context of the problematic of global environmental sustainability and the need for integral management of natural resources. This is a contribution dealing with the contradiction of a developing country rich in natural resources and its urgent need for better integral management especially of water under the impacts of climate change in Nicaragua.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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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.

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