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Department of Environment and Development

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Application of HydroBID and InVEST hydrologic models in tributaries of Lake Yojoa watershed

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Abstract

The relationship established by different natural and social variables make up the ecology of lakes and become a component for the communities that surround it. Hydrologic models are used to represent the relationship between abiotic elements in watersheds and provide a complete view on the dynamics that take place in a given territory. The Hydro-BID model is a process-based hydrologic model that was calibrated for the Yure and Varsovia River basins to perform the watershed-scale simulations. This study adresses the effect of climate change as a variable with potential impactsin the montly and annual flow into Lake Yojoa, Honduras. The InVEST® Nutrient Delivery ratio (NDR) was used to estimate nitrogen (N) and phosphorus (P) loads spactially distributed in the basin. As a result, this study presents the HydroBID model as an effective tool for estimating monthly streamflow in the Yure and Varsovia river basins with a Nash-Sutcliffe effciency index (NSE) of 0.85. Moreover, climate change scenarios modeled, indicate an increase in outflow under the SSP2-4.5 scenario by 2040, while the SSP3-7.0 scenario predicts a decrease in monthly outflow, primarily influenced by changes in precipitation. Finally, the InVEST® NDR model is suitable for estimating nutrient exports from non-point sources in the Yure and Varsovia basins and can be calibrated for validation of the nutrient loads input into Lake Yojoa.

Key words: Calibration, climate change, hydrology, modelling, spatial analysis

Resumen

La relación establecida por diferentes variables conforma la ecología de los lagos y se convierte en un componente social para las comunidades que lo rodean. Los modelos hidrológicos se utilizan para representar la relación entre elementos abióticos en las cuencas hidrográficas y proporcionar una visión completa de las dinámicas que tienen lugar en un territorio determinado. El modelo hidrológico “HydroBID” es un modelo hidrológico basado en procesos que fue calibrado para las cuencas de los ríos Yure y Varsovia para realizar simulaciones a escala de cuenca. Este estudio aborda el efecto del cambio climático como una variable que impacta el flujo mensual y anual en el Lago de Yojoa, Honduras. El modelo “InVEST® Nutrient Delivery Ratio” (NDR) se utilizó para estimar las cargas de nitrógeno (N) y fósforo (P) distribuidas espacialmente en la cuenca. Como resultado, este estudio presenta el modelo “HydroBID” como una herramienta efectiva para estimar el caudal mensual en las cuencas de los ríos Yure y Varsovia, con un índice de “Nash-Sutcliffe” (NSE) de 0.85. Además, los escenarios de cambio climático modelados indican un aumento en el flujo de salida bajo el escenario SSP2-4.5 para 2040, mientras que el escenario SSP3-7.0 predice una disminución en el flujo mensual, influenciado principalmente por cambios en la precipitación. Por último, el modelo “InVEST®” NDR es adecuado para estimar las exportaciones de nutrientes de fuentes difusas en las cuencas de los ríos Yure y Varsovia y puede ser calibrado para la validación de las cargas de nutrientes que ingresan al Lago de Yojoa.

Palabras clave: Análisis espacial, calibración, cambio climático, hidrología modelación

Introduction

Lake ecosystems are influenced directly by their watersheds, the biological and hydrological processes that take place on the land and rivers that lie uphill (Hairston & Fussmann, 2001). These water bodies operate as ecosystems with complex interactions including food-web dynamics, ecosystem metabolism, biogeochemistry, and community organization. Community organization plays an important role in the management of watersheds since human activities may alter hydrological processes and nutrient input. Due to the variables that encompass the ecology of lakes, many researchers have studied the dynamics of land use, temperature, slope and precipitation to analyze the resilience of freshwater bodies (Garg & Garg, 2002; Hernández et al., 2005; Li et al., 2011).

Human activities, such as land use change, have a significant influence on climate change by altering the distribution of ecosystems and are associated with energy fluctuations and mass exchanges (Dale, 1997). Land use and land cover are characteristics that determine the vulnerability of places and people to climatic, economic, and socio-political disturbances. When observed on a global scale, land use and land cover changes are significant and affect aspects of land functioning (Lambin et al., 2003). When large tracts of forest are deforested, evapotranspiration is reduced, resulting in less cloud formation and less precipitation (Dale, 1997).

Nutrient load inputs are dependent on the characteristics of the land use. Many researchers have studied the relationships between these characteristics to create management strategies (Malagó et al., 2017; Otiang'a-Owiti & Oswe, 2007). For instance, Hecky et al. (2003) revealed how sediment, nutrient concentrations, and loads are responsive to the degree of agricultural land use in the territory. Consequently, the lowest sediment concentrations originated from basins that had a high proportion of intact forest (Hecky et al., 2003). Similarly, Fraterrigo and Downing (2008) studied the effect of landscape composition to assess the factors that drive the variation between a lake's chemistry across watersheds. They found that watersheds with low transport capacities move water and nutrients more slowly. Nutrients such as phosphorus (P) for example, can be occluded by clay soils and have a lower incidence over the loads input in the water.

Hydrologic models are used to represent the relationship between abiotic elements in watersheds. Geographic Information Systems (GIS) have become a vital element in modern hydrologic studies; any hydrologic model is an abstract image of a component of a natural process (Vieux, 2001). GIS can process complex mathematical algorithms, therefore its outbreak as a commonplace approach to hydrology. Technology has enabled the transformation of modeling to operate, using radar and satellite imagery, high performing computing and storage, serving as physics-based models (Vieux, 2001; Yuqiong & Hoshin, 2007). The selection of a model is based on its competence for the hypothesis of the research, equivalently, landscape and spatial scales should be considered (Addor & Melsen, 2019; Mendoza et al., 2015).

The Inter-American Development Bank (IDB) has positioned itself as a leader in the water and sanitation sector, leading international projects for the development, conservation, and analysis of water resources in the continent. After learning about the needs of the region, the IDB created a simulation tool to support the Latin American and Caribbean (LAC) region in water resource management and planning. Hydro-BID was designed in collaboration with regional and local water utilities to gain a better understanding of water management challenges and provide a response. Hydro-BID has been established at the regional level as a database and modeling tool capable of estimating water availability at a watershed and sub-basin scale (IDB, 2022). Among the scientific outreach efforts, a series of training courses for hydrology experts have been produced for each beneficiary country of the bank, with the purpose of achieving appropriate planning in the LAC basins. Hydro-BID has been successfully used to analyze water demand under climate change scenarios in the Gualí River and León River Basin in Colombia (Mena et al., 2021). Similarly, it has been applied to study the impact of El Niño Events on sediment loading in Peru (Escurra et al., 2016).

Despite the extension of the model is increasing, Hydro-BID is yet to be used to analyze the impacts of climate change and other factors for watersheds in Honduras. Lake Yojoa is the only freshwater lake in the country, with a surface area of 79 km^2. Lake Yojoa is of great importance for Hondurans, since it encompasses touristic activities, aquaculture practices and a strong sense of belonging to the community. This investigation seeks to validate a hydrological model for Lake Yojoa's sub watershed. Additionally, it is intended to use this model to predict different climate change scenarios, alternatively creating a tool that aids community organization and helps perform regulations that protect the lake. The specific objectives of this study are: i) To calibrate the HydroBID model for stream flow for the Yure and Varsovia river basin, ii) To predict future flows based on climate change scenarios for the Yure and Varsovia tributaries of the Yojoa subwatershed and iii) To evaluate the InVEST® Nutrient Delivery Ratio model for nutrient load estimation.

Materials and Methods

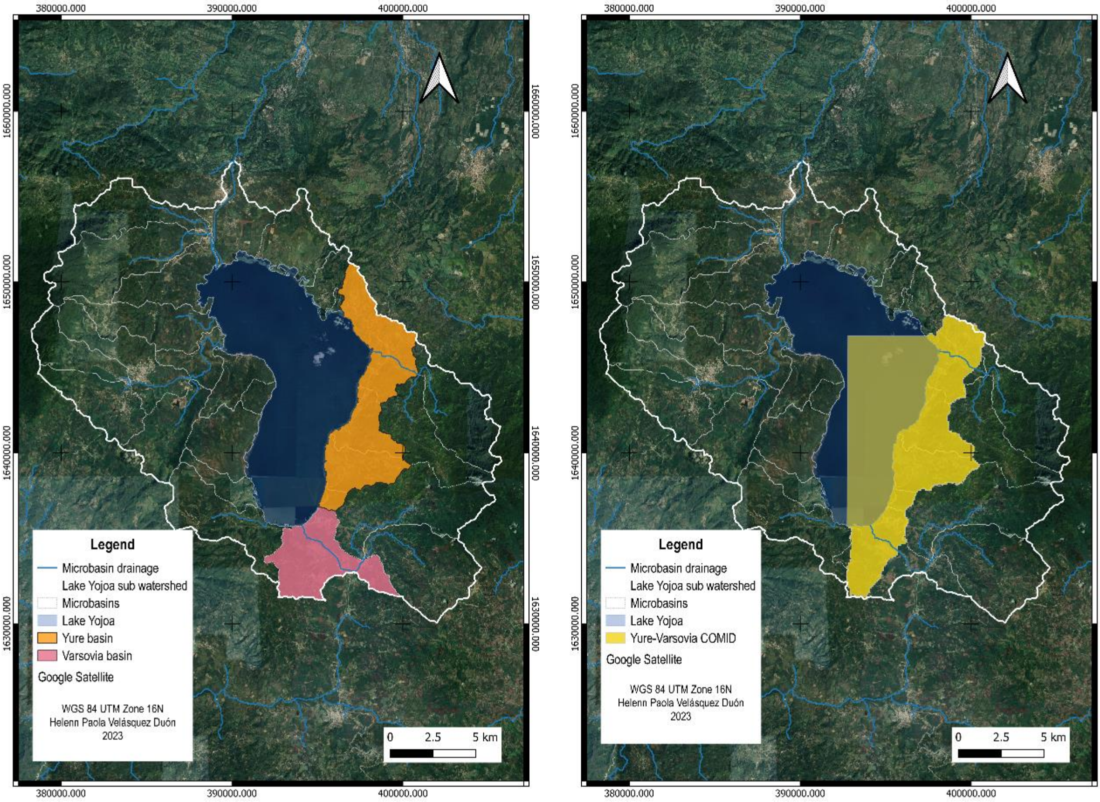
Site of Study

Lake Yojoa is the only freshwater lake in Honduras, it's recognized as a site with great biodiversity and attractive landscapes. Lake Yojoa sub watershed belongs to the Ulua watershed and is located among the departments of Cortés, Comayagua, and Santa Bárbara. The watershed has a hydrological code of 0521 and has a total area of 43,475.77 ha. Moreover, the subwatershed is divided into 28 basins. The main tributaries of the lake are the Yure, and Varsovia rivers and the Balas and Raíces streams. The tropical rain forest climate of Lake Yojoa dictates the environmental condition of the study area. Lake Yojoa is located at 632 masl, has a tropical monsoon climate, an average temperature of 24 °C and rainfall of 2,300 to 3,000 mm/year. Lake Yojoa has a length of 16.2 km, a width of 6 km and an area of 79 km^2.

The basins were identified through the hydrographic delimitation of Agua de Honduras platform and the LAC-AHD database of HydroBID. It is important to note that these delimitations differ from each other, and this is due to their respective resolutions. Therefore, for this study, both delimitations were considered depending on the specific objective to be addressed. The delimitation by Agua de Honduras is the officially recognized one in the country and provides a more accurate representation of the flow dynamics in the territory. However, it cannot be directly input into the HydroBID platform. In Figure 1, selected basins represent the desired analysis zone with the highest possible accuracy. The Yure-Varsovia basin is identified with the COMID 211547300.

Figure 1

Hydrographic delimitation by Agua de Honduras (left)and LAC-AHD (right) for study site.



This study is quantitative since the simulation modelling process requires quantitative data to produce quantitative results; it is nonexperimental, and transversal. It is nonexperimental and transversal since the variables will not be manipulated, the data will be collected once and will not be compared to past data. Moreover, to determine the prevalence and relationship between the variables used to forecast climate change scenarios, this research will have a correlational scope.

Hydro-BID Hydrological Model

The Hydro-BID model was used to simulate the hydrologic processes and estimate streamflow under current land use and under climate change scenarios. A key aspect for the model is the need of constant historical records of the watershed such as rainfall, temperature and flow for a minimal period of five years (Gómez, 2020). IDB created a database to aid the simulation process for the LAC region. The Analytical Hydrography Dataset for Latin America and Caribbean (LAC-AHD) contains

330,000 sub-basins represented as shapefiles. This information was obtained from Shuttle Radar Topography Mission (STRM) satellite images, considering a resolution of 90 × 90 m.

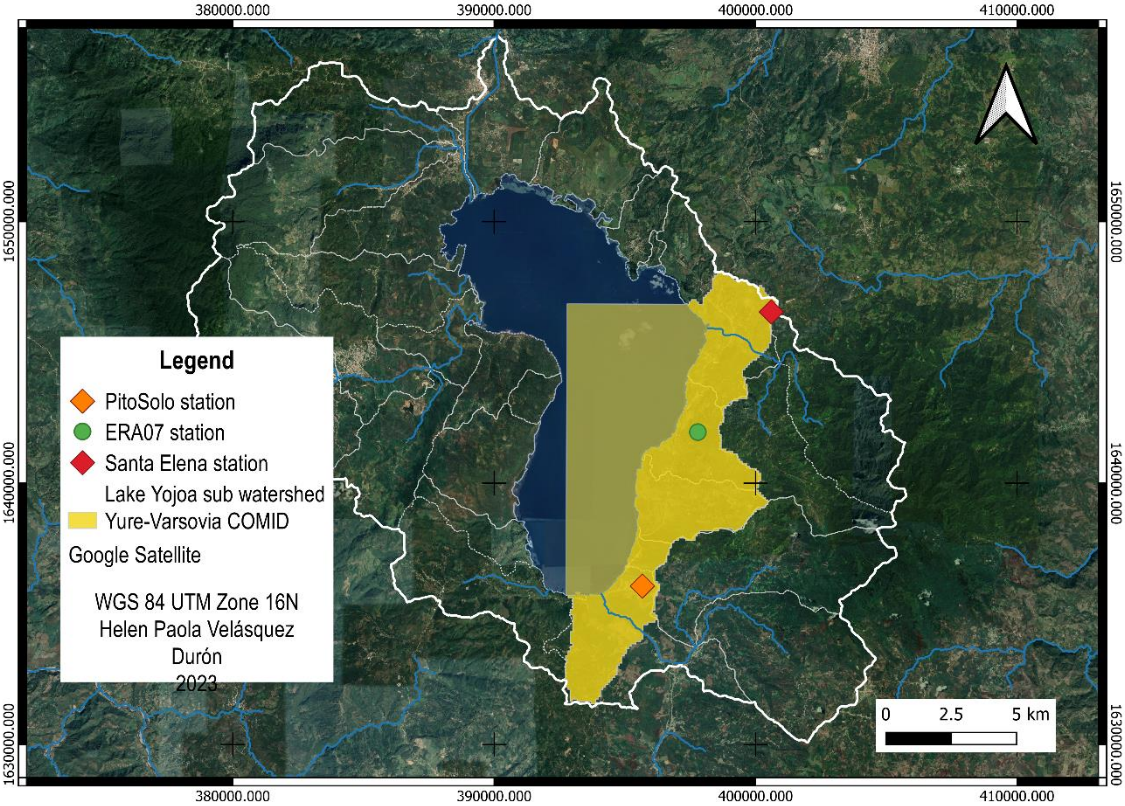
Furthermore, Hydro-BID uses SQLITE, a free model that allows organizing and formulating a database, SQLITE is related to the AHD database, by means of a unique identifier (COMID) of the sub-basins where both data are identified with the same code. Additionally, the model is aided by rainfall-runoff models which are used for generating daily and monthly flows for the basins designed in the AHD.

The HydroBID model requires daily input data of precipitation and mean temperature for each sub-basin. These series are calculated from measured series obtained at specific stations. The hydrological analysis requires continuous time series with the longest possible time interval. There is hydro-meteorological information available from various sources in the area. For this study, historical observed data from three selected stations were used, considering their geographical location and the length of the records.

Weather data, including daily precipitation and temperature were obtained from the IDB database. The hydroclimatic stations available for the study site are Pito Solo, Santa Elena and ERA07 stations from ENEE (Empresa Nacional de Energía Eléctrica). Their geographical location is defined by the Latitudes -87.96949 and Longitudes 14.79667 and Latitudes -87.95 and Longitudes 14.75, respectively (Figure 2). It was identified that stations Pito Solo, Santa Elena and ERA07 have records available from 1984 to 2021. The model requires a minimum of 5 years of records (Moreda et al., 2016). Therefore, precipitation and temperature data from the year 2003 to 2012 were entered to match availability of stream flow data. Once the stations were defined and the study period was selected, the files were generated according to the specifications established for the model and added to the Structured Query Language (SQL) database file.

Figure 2

Identified hydroclimatic stations for study site



Land Use

Land use input was based on the Forest and Land Cover Map of Honduras for 2018, designed as an essential tool for planning and decision making in economic development and management of the forestry sector in the country. The ICF ("Instituto Nacional de Conservación y Desarrollo Forestal, Áreas Protegidas y Vida Silvestre" of Honduras), through the Forest Monitoring Unit and with the financial and technical support of the UN-REDD Program of the Food and Agriculture Organization of the United Nations developed these maps with detailed and updated land uses with a resolution of 10 × 10 m (Annex A). This data was input for the HydroBID model within the land use factors (Table 1). Land use data was also used to create the biophysical tables required for nutrient load estimation.

Table 1

HydroBID catchment land use/land cover input table for Yure-Varsovia basins

Land use	Code	Area (ha)	CN	HSG	K factor
Humid Broadleaf Forest	1	2,451.68	70	C	0.21
Deciduous Broadleaf Forest	2	68.45	76	C	0.21
Mixed Forest	3	231.92	76	C	0.21
Humid Flooded Broadleaf Forest	4	13.64	72	C	0.21
Dense Conifer Forest	5	21.27	70	C	0.21
Scattered Trees	11	23.54	73	C	0.25
Coffee Plantations	12	14	74	C	0.42
Humid Secondary Vegetation	14	65.58	72	C	0.35
Deciduous Secondary Vegetation	15	3.14	72	C	0.31
Savannas	16	28.9	81	C	0.29
African Oil Palm	17	3.81	70	C	0.41
Pineapple	21	71.88	76	C	0.45
Grasslands/Crops	24	846.61	79	C	0.31
Discontinuous Urban Area	26	89.88	98	C	0.78
Continental Bare Soil	29	40.79	91	C	0.7
Continental Wet Area	30	254.53	98	C	0
Natural Lakes and Lagoons	32	3,943.09	100	C	0

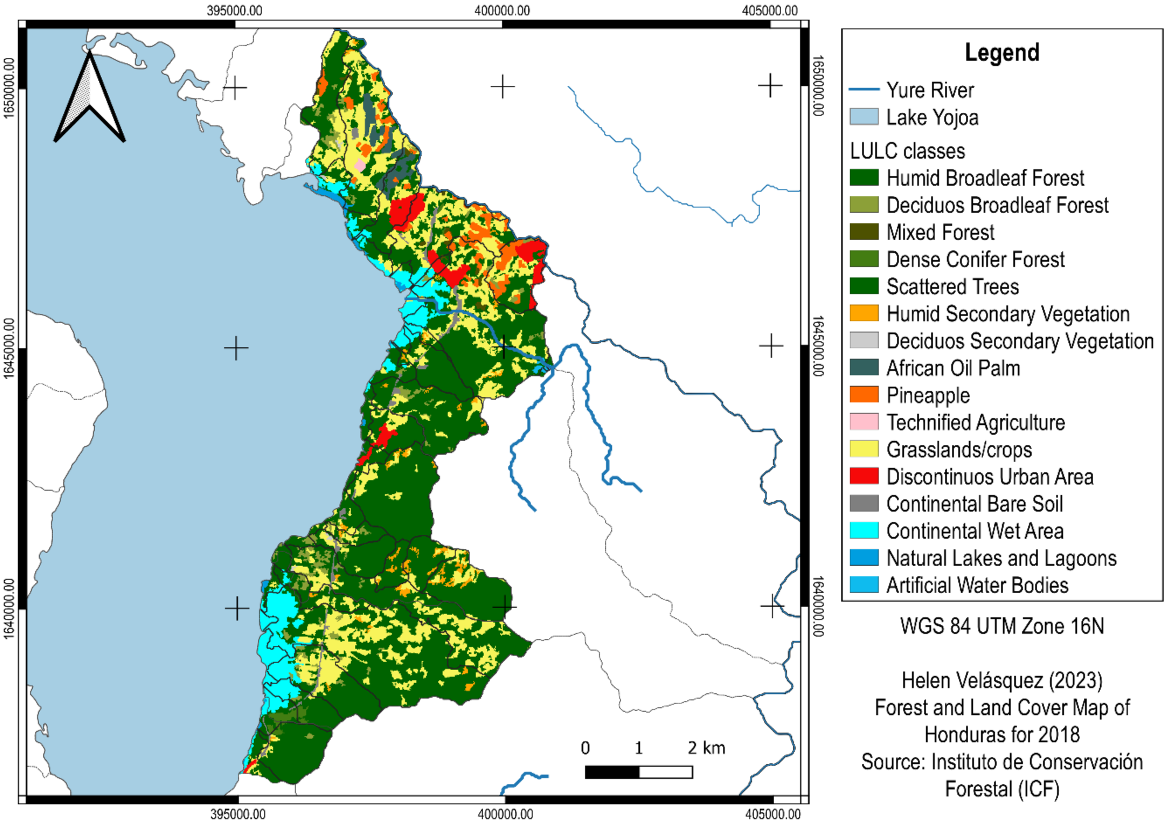
Since detailed field surveys of soils in the area were not possible, a generalized soil map was used for preparation of K factor and curve number input. Agua de Honduras developed digital soil property maps for center and west of Honduras with a 30 m resolution to serve as input for water-related analysis for the platform. This catalog contains raster images of soil texture class, organic matter content (%), silt (%), sand (%), clay (%), and water holding capacity.

To estimate erodibility (K) factor the United States Department of Agriculture (USDA) nomograph was applied. Soil characteristics affect its susceptibility to erosion (Annex B). The nomograph estimates erodibility based on texture (%silt, %sand, %organic matter), soil structure and permeability (Neitsch et al., 2002; Organización de las Naciones Unidas para la Agricultura y la Alimentación [FAO], 1969). Since the map provides very little detail of the soil characteristics at the site, the values for K are very similar, differing on sites with bare soils or urban areas. Similarly, CN values were adapted from the Soil and Water Assessment Tool (SWAT) User Manual which provides average curve numbers for general land uses (Neitsch et al., 2002). Soil was classified into a hydrologic soil group (HSG) and further identified according to hydrologic condition and treatment or practice (Prasannakumar et al., 2012; United States Department of Agriculture [USDA], 2004).

To estimate nutrient exports using InVEST®, the model was applied using the values of the biophysical table giving nutrient loads by land use (Figures 3 and 4). The Varsovia and Yure basins were modelled individually using the hydrographic delimitation of “Agua de Honduras”.

Figure 3

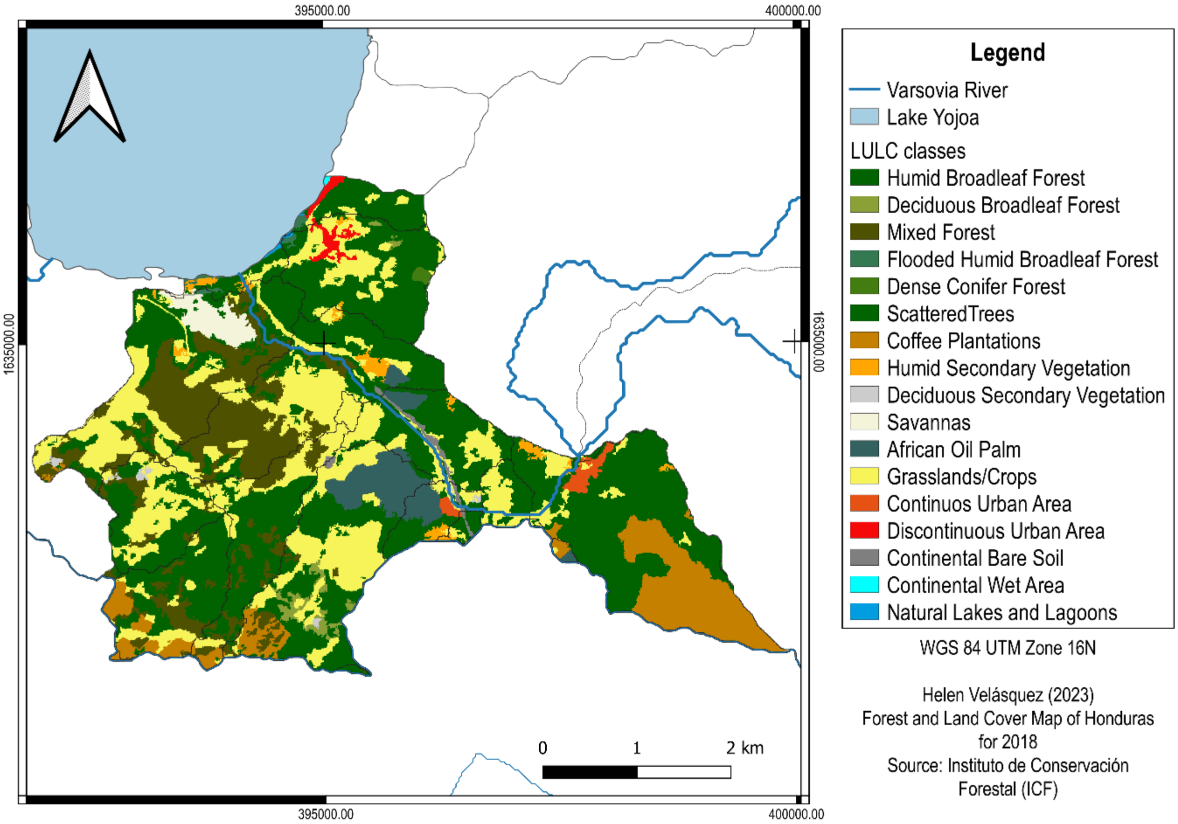
Land use and land cover map for the Yure River basin



Helen Velásquez (2023)
Forest and Land Cover Map of Honduras for 2018
Source: Instituto de Conservación Forestal (ICF)

Figure 4

Land use and land cover map for the Varsovia River basin



Helen Velásquez (2023)
Forest and Land Cover Map of Honduras
for 2018
Source: Instituto de Conservación
Forestal (ICF)

Stream Flow 2003-2012

For stream flow calibration for the Yure and Varsovia river basins, the observed flows measured by ENEE and provided by the IDB were used. Daily flow presented in m^3/s had a ten-year extension from January 2003 to December 2012, thus, this period was selected for model calibration.

Climate Change Scenarios

The Intergovernmental Panel on Climate Change (IPCC) has established a range of scenarios based on Shared Socio-economic Pathways (SSPs) used in the Coupled Model Intercomparison Project Phase 6 (CMIP6), which recognize that global radiative forcing levels can be achieved by different pathways of emissions and land use. SSP scenarios identify four priority scenarios that modelling groups are asked to perform (Table 2), where the first number refers to the assumed shared socio-economic pathway, and the second refers to the approximate global effective radiative forcing (ERF) in 2100. These scenarios present higher climate sensitivity in comparison to CMIP5, SSP2-4.5 and SSP3-7.0 were selected as the scenarios for the model. It should be noted that these scenarios have been applied to Honduras by the World Bank's Climate Change Knowledge Portal (CCKP) where essential climate variables can be projected.

Table 2

SMIP6 scenarios assessed in Sixth Assessment Report

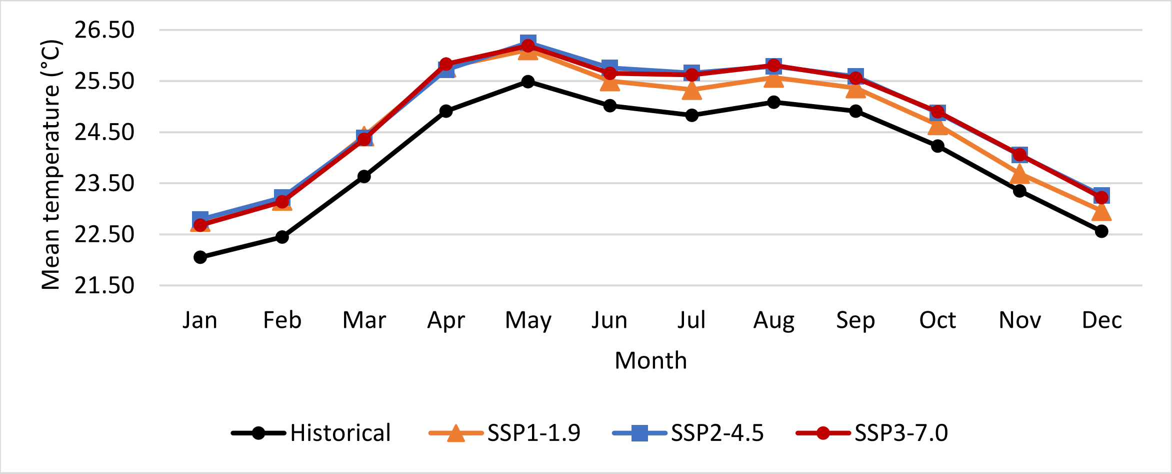
Shared-Socio-economic Pathways	Performed Scenario
SSP1-2.6	Sustainable pathways
SSP2-4.5	Middle-of-the-road
SSP3-7.0	Regional rivalry
SSP5-8.5	Fossil fuel-rich development
SSP1-1.9	Assessment of the Paris Agreement goal

Note. SSP1-2.6 is preferred over SSP1-1.9 because the latest has fewer simulations available.

The mean projected climate data aids in-depth analysis into future climate scenarios and potential risks due to changing climates (World Bank, 2023). Shared Socioeconomic Pathways were analyzed as a multi-model ensemble, which represents the range and distribution of the most plausible projected outcomes. Figure 5 shows this projected data for near term conditions.

Figure 5

Projected climatology of mean-temperature for 2020-2039 Honduras, Multi-Model Ensemble

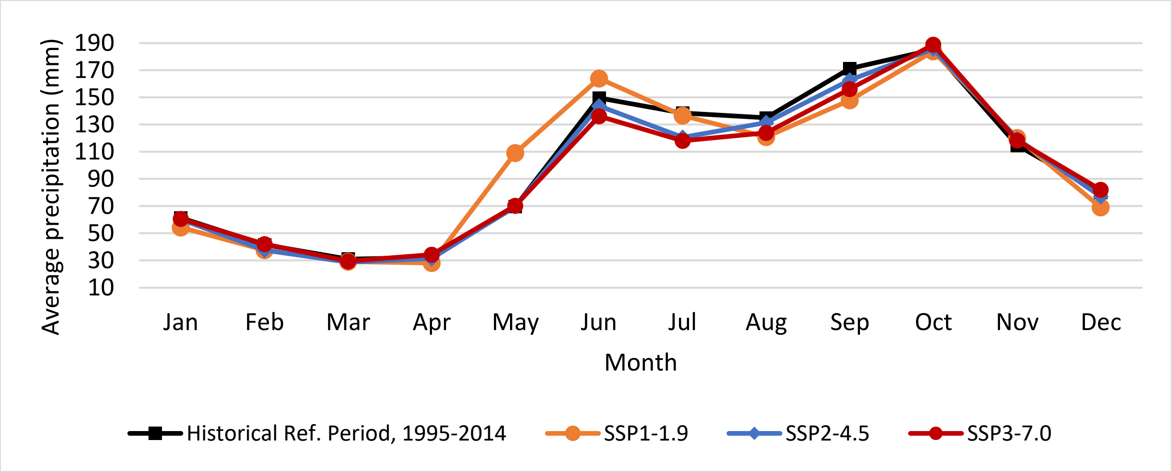


Note. Adapted from World Bank Climate Change Portal

Similarly, precipitation variables were analyzed. It is important to note that the projected change in seasonal precipitation is presented as a percentage, which serves as a usefull indicator reviweing projected anomalies, it is recommended to compare this values to undestand absolute values of precipitation in and gain a complete preception of projected changes in precipitation dynamics as delivered by the HydroBID Climate Scenario Model. Monthly values were entered in percentages to estimate precipitation increase and decrease (Annexes D and E). Figure 6 shows the mean precipitation for each of the modeled scenarios.

Figure 6

Projected climatology for mean precipitation for 2020-2039 Honduras Multi-Model Ensemble



Note. Adapted from World Bank Climate Change Portal

InVEST® Nutrient Delivery Ratio

The Nutrient Delivery Ratio (NDR) model is an integrated module of the InVEST® software package. It was selected to spatiotemporally quantify nutrient retention capacity for nitrogen and phosphorus. The model used a mass balance approach, representing steady-state flow of nutrients though empirical relationships. The model does not account for details of the nutrient cycle. Sources of nutrients are determined based on a land use/land cover (LULC) map and associated loading rates. The calculation of pixel-level export relies on the export at the watershed level and is determined by adding the nutrient export of each individual pixel. Nutrient delivery is based on delivery ratios, nutrients transported by surface flow and subsurface flow (model calculates surface component for nitrogen only). The model requires spatial units in projected coordinate system, raster inputs are resampled to match the cell size of the DEM.

Digital Elevation Map (DEM)

A Digital Elevation Model (DEM) is required as the main input for the NDR module. The hydrological aspects of the DEM used in the model should be correct. The DEM from ALOS PALSAR satellite was used. This DEM provides a high-quality corrected resolution of 12.5 × 12.5 m. It was derived from a single complex Synthetic Aperture Radar (SAR) image. Additionally, it was provided in Universal Transverse Mercator (UTM) coordinates in zone 16 N, projected according to the WGS 84 spatial reference system.

Once the DEM was downloaded, the process of filling sinks and null spaces present in the data was carried out. This step aims to correct irregularities and ensure that the digital elevation model accurately represents the terrain relief. Subsequently, the DEM was cropped to limit it to the Lake Yojoa sub-watershed. Next, a search for micro-catchments was conducted based on the delineations provided by Agua de Honduras. This search allowed for the identification of specific areas within the basin that form the micro-basins relevant to the study.

An analysis of the basin was then performed using the r.watershed tool in GRASS 7.8.5®. This analysis provided information such as the number of cells draining through each cell, drainage direction, and sub-basins. These data are essential for understanding water flow and hydrological dynamics in the study basin. To obtain territorial units for analysis after the simulation, the basin was divided into micro-catchments and polygonised.

Biophysical Table

The biophysical table assists the biophysical properties related to nutrient load and retention. This table is linked to the Land Use Land Cover (LULC) raster where each land is assigned to a unique integer code. The NDR model employs a mass-balance approach to simulate N and P as affected by vegetation and other constraining and stimulating factors (Rají et al., 2020). Each entry on the biophysical table must be accompanied by nutrient load (kg/ha yr^{-1}), nutrient retention efficiency (ratio), critical length (m), root depth, and Universal Soil Loss Ecuation (USLE) factors C and P (Annex K). For this data a thorough literature review was carried out (Tables 3 and 4).

Table 3

Biophysical table input for the Yure basin

Land use/Land cover description	Load		Efficiency		Critical length		Proportion Subsurface	Source
	(N)	(P)	(N)	(P)	(N)	(P)	(N)	
Humid Broadleaf Forest	3	0.4	0.8	0.67	200	20	0.47	(Lötjönen et al., 2021)
Deciduous Broadleaf Forest	3	0.1	0.8	0.67	200	20	0.47	(Trate, 2005)
Mixed Forest	4	0.1	0.7	0.6	200	20	0.47	(Trate, 2005)
Dense Conifer Forest	3	0.4	0.8	0.6	150	20	0.47	(Johnson, 1992; Trate, 2005)
Scattered Trees	2.5	0.45	0.7	0.6	150	20	0.47	(Racit et al., 2008)
Humid Secondary Vegetation	2	0.3	0.65	0.6	150	15	0.47	(Racit et al., 2008)
Deciduous Secondary Vegetation	3	0.3	0.65	0.6	150	15	0.47	(Tucker et al., 2007)
African Oil Palm	150	166	0.8	1.3	500	50	0.45	(Uexkull, 1980)
Pineapple	200	70	0.4	0.5	300	30	0.25	(Millward & Mersey, 1999)
Technified Agriculture	300	150	0.65	0.6	150	30	0.3	(Mendoza et al., 2011)
Grasslands/Crops	89	0.5	0.5	0.4	25	15	0.3	(Mendoza et al., 2011)
Discontinuous Urban Area	5	1	0.1	0.3	10	15	0.1	(Mendoza et al., 2011)
Continental Bare Soil	3	0	0.1	0.4	0	15	0.55	(Mikhailova et al., 1997)
Continental Wet Area	0	0	0.05	0.4	0	15	0.66	(Trate, 2005)
Natural Lakes and Lagoons	0	0	0.05	0.4	0	15	0.66	(Trate, 2005)

Land use/Land cover description	Load		Efficiency		Critical length		Proportion Subsurface	Source
Artificial Water Bodies	0	0	0.05	0.4	0	15	0.66	(Mendoza et al., 2011; Soranno et al., 1996)

Table 4

Biophysical table input for the Varsovia basin.

Land use/Land cover description	Load		Efficiency		Critical length		Proportion subsurface	Source
	(N)	(P)	(N)	(P)	(N)	(P)	(N)	
Humid Broadleaf Forest	3	0.4	0.8	0.67	200	20	0.47	(Lötjönen et al., 2021)
Deciduous Broadleaf Forest	3	0.1	0.8	0.67	200	20	0.47	(Trate, 2005)
Mixed Forest	4	0.4	0.7	0.6	200	20	0.47	(Trate, 2005)
Flooded Humid Broadleaf Forest	2	0.1	0.7	0.6	200	20	0.47	(Trate, 2005)
Dense Conifer Forest	3	0.4	0.8	0.6	150	20	0.47	(Johnson, 1992; Trate, 2005)
Scattered Trees	2.5	0.45	0.7	0.6	150	20	0.47	(Mikhailova et al., 1997)
Coffee Plantations	231	60.1	0.6	0.48	50	15	0.25	(Haggar et al., 2011; Salamanca-Jimenez et al., 2017)
Humid Secondary Vegetation	2	0.3	0.65	0.6	150	15	0.47	(Racit et al., 2008)
Deciduous Secondary Vegetation	3	0.3	0.65	0.6	150	15	0.47	(Stewart et al., 2012)
Savannas	10	0.2	0.1	0.2	50	5	0.45	(Stewart et al., 2012)
African Oil Palm	150	166	0.8	1.3	500	50	0.45	(Uexkull, 1980)
Grasslands/Crops	89	0.5	0.5	0.4	25	15	0.3	(Mendoza et al., 2011)
Continuous Urban Area	89	0.5	0.5	0.4	25	15	0.1	(Mendoza et al., 2011)
Discontinuous Urban Area	5	1	0.1	0.26	10	15	0.1	(Racit et al., 2008)
Continental Bare Soil	3	0	0.1	0.4	0	15	0.66	(Racit et al., 2008)
Continental Wet Area	0	0	0.05	0.4	0	15	0.55	(Racit et al., 2008)
Natural Lakes and Lagoons	0	0	0.05	0.4	0	15	0.66	(Mendoza et al., 2011; Soranno et al., 1996)

The InVEST® model provides results that may be compared with observations, however, the time series of nutrient concentration used for model validation should span over 10 years due to inter-annual variability. Since nutrient fluxes have been measured for one year only, calibration of the model cannot be achieved.

Threshold Flow Accumulation (TFA) value was selected after analyzing the r.watershed tool in GRASS 7.8.5®. The drainage network, length of flow segments and delineation of micro-catchments were assessed for values of 500, 1,000, 2,000 and 5,000 to select the value that was consistent with the characteristics of the study area. The value selected for TFA was 1,000. Moreover, for Nutrient Runoff Proxy, the average precipitation raster provided by the IDB was input. The Borselli K Factor selected was the default value of 2 for calibration between hydrologic and connectivity and the nutrient delivery ratio.

Nutrient Fluxes 2023

Nutrient load data was gathered for the four main tributaries of the lake. Yure and Varsovia rivers, have been studied for total phosphorus (TP) and total nitrogen (TN), which were analyzed according to the US Environmental Protection Agency (EPA) methods (1982). Laboratory triplicate samples were applicable and averaged for final single values. This data was recollected for a total of 5 months from January to May of 2023. Nutrient loading was analyzed at the Zamorano Water Quality Laboratory of the department of Environment and Development. This data offers a general reference of nutrient concentrations in the tributaries and availability for a comparison between modeled values.

Calibration of the Model

The calibration of the model consists of achieving a fit between measured and simulated values by adjusting the most influential parameters. The validation of the model consists of measuring its predictive capability by comparing the observed flows with those simulated with the parameters determined in the calibration phase, but in a different time. Good model calibration is important in hydrologic simulation studies to reduce uncertainty in simulation models. The calibration process will primarily be done by trial-and-error simulations.

Statistical Analyses

The variables used to determine statistically the errors in the Hydro-BID model are: the percentage error between the simulated values with the observed values, standard deviation of the time series of simulated and observed flows using a relationship between minimum and maximum values and the Nash-Sutcliffe efficiency index (NSE) (Gómez, 2020). The NSE metric minimizes the root mean square error between streamflow.

Results and Discussion

Yure-Varsovia Stream Flow Calibration

For the Yure-Varsovia basin, the parameters of curve number (CN), available water content (AWC), recession coefficient (r), and percolation coefficient (s) were calibrated (Table 5). Changes in the parameters were made based on the flow duration curve and hydrographs before calibration (Annex C). Since the recession coefficient indicates a channel's ability to return to its natural state after a flood, it was necessary to decrease its value to increase runoff and bring the discharge closer to the observed values, as well as reduce the frequency of peak flows. Similarly, the value of available water content was decreased to represent low infiltration and obtain a higher proportion of runoff. Regarding the sensitivity of the calibration parameters in HydroBID, it was discovered that AWC followed by the r coefficient exhibit the highest sensitivity. Mena et al. (2021) associates this to the AWC’s determining factor of the volume of water capable of being absorbed before saturation and its consequent conversion into flow. Furthermore, the CN (0.73) was also decreased from the starting value suggested by Moreda et al. (2014), based on the general land and soil data of the site, to obtain better modeling indicators.

Table 5

Calibrated model parameters for Yure-Varsovia basin

Model parameter	Value
Curve Number (CN)	0.565
Available Water Content (AWC)	0.78
Recession Coefficient (r)	0.0031
Seepage Coefficient (s)	0.0125
Grow season ET factor	1
Dormant season ET factor	1
Temperature Threshold	1

Statistics were used as a guide to determine the accuracy of the simulated values. As the calibration of the parameters progressed, the statistics for monthly values were reviewed to achieve the closest match to the desired results. After 54 simulations, the values presented in Table 6 were obtained. The Nash-Sutcliffe coefficient was used as the main indicator, followed by ensuring that the correlation coefficients were close to 1, and finally reaching the lowest percentage of error. Moreover, the percentage of error was the most sensitive to parameter changes, making it useful in achieving precise values, such as a CN of 0.565. Consequently, the presented statistics fall within the appropriate range and serve as indicators of an excellent simulation.

Table 6

Statistical indicators for calibration

Statistics	Appropriate calibration range	Value
Overall volume error (%)	±20 - 30 or 30 - 40	2.21
Correlation (r)	> 70	0.93
Modified Correlation (Rmod)	> 70	0.88
Nash-Sutcliffe Efficiency (NSE)	0.40 - 0.60	0.85

In Figure 7, the percentage of time in which the discharge is equaled or exceeded is depicted through the flow duration curve. In this case, the model is overestimating the likelihood of encountering a discharge equal to or greater than the observed value for outflow peaks and presents a more accurate adjustment to lower outflow events (Gómez, 2020). This is further supported by observations from the monthly result hydrograph, which shows simulated peak discharges in m^3/s surpassing the observed ones for the period of 2003 to 2012 on three events (2005, 2006, 2010) and lower flow rates aligned more accurately to observed values (Figure 8).

Figure 7

Flow duration curve for observed and modeled discharges in the calibration of Yure-Varsovia watershed

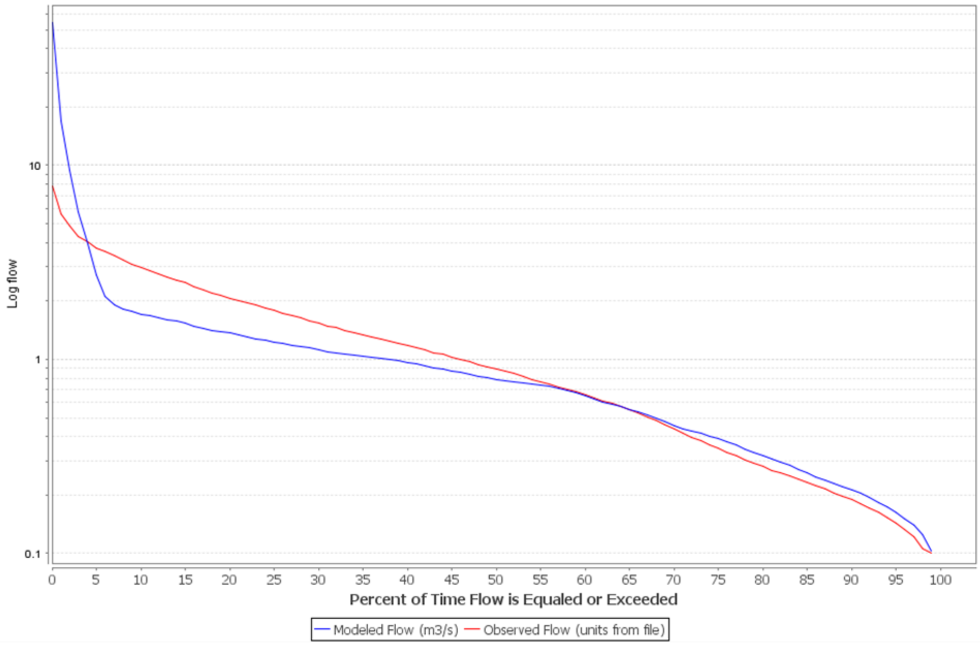
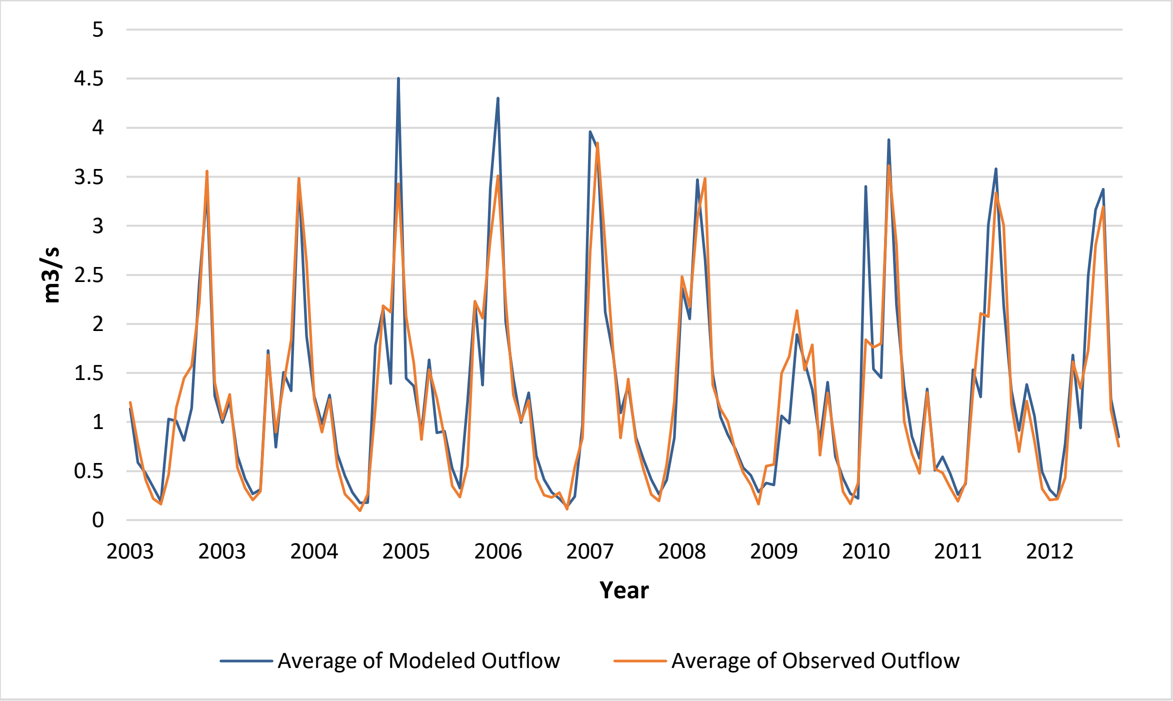


Figure 8

Hydrograph of observed and modeled monthly discharges (m³/s)



It was noticeable that the model did not respond accurately to daily outflow modeled values for the basins. Berestovoy (2022) noticed that the model did not consider the percentage of the Yukyry basin classified as wetlands accurately, which affected the simulation due to the retained flow in these areas. Considering, the LAC-AHD included a 48% of the lake as part of the basin, this might be a cause for inaccurate modeled daily outflow.

The model demonstrates an overestimation of the probability of outflow peaks occurrences (Figure 8), while simultaneously, underestimating the likelihood of surpassing the given flow with greater discharge than the specified threshold in Figure 7. Furthermore, Mena et al. (2021) highlight that HydroBID is designed to capture average flow characteristics. Thus, the preservation of flow volumes in Figure 7 and 8 confirms the model’s suitability for evaluating hydrological regimes within the study and presents this difference as negligible.

Climate Change Scenarios

By analyzing climate change scenarios (high emissions) for the years 2020 and 2040, it is possible to address the short-term vulnerability of the basin to changes in temperature and precipitation and to understand how they can adversely affect the water supply for the community that depends on the lake. This simulation also represents a validation for the model as it presents the hydrological context of the basin accurately. Arsenault et al. (2018) argue that the validation of a model should not be considered inseparable from the calibration. However, they discuss that to reduce model uncertainties, the optimal validation should include all available years, having the same length of the calibration period. This insight provides a guide to assess hydrological changes under future climate change scenarios.

Figure 9 shows the average discharge simulated by the model for each scenario. For SSP2-4.5 there is an increase in stream flow from May through October, this aligns with the precipitation projections for this scenario that present higher rates of precipitation. On the other hand, the average discharge for SSP3-7.0 presents a decrease in outflow, showing a slight reduction in water supply for the near future under a negative high emission scenario. Gómez (2020) evidences that evapotranspiration was significantly increased when developing higher emission scenarios which accounts for a decrease in outflow.

Figure 9

Average monthly outflow for climate change scenarios for 2040 (SSP2-4-5 and SSP3-7.0)

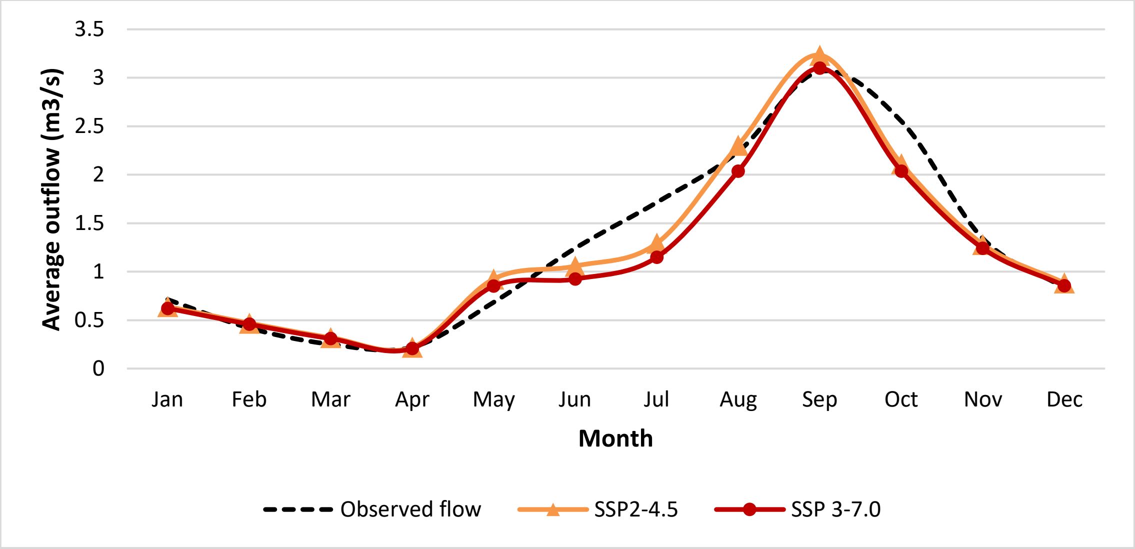
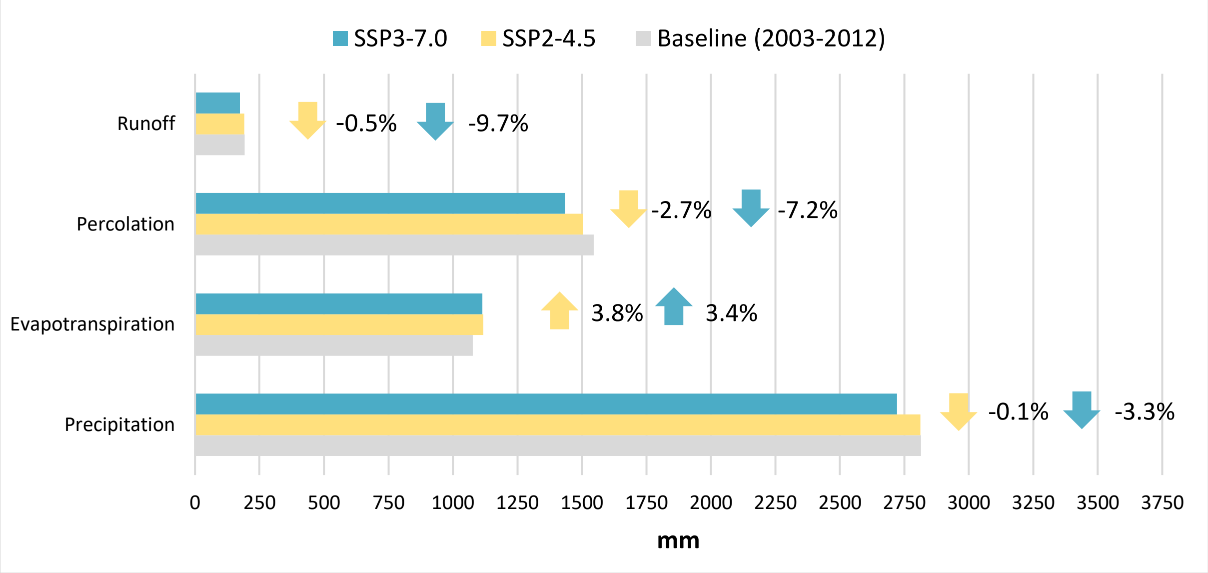


Figure 10 presents the water balance modeled for SSP2-4.5 and SSP3-7.0 with the percentual change for each component (Annex G and H). For both scenarios, modeled and observed flows presented an NSE of 0.85, which suggests modeled conditions similar to current climate conditions. Figure 10 shows that the increased temperature impacts evapotranspiration rates for both scenarios. It is observed that SSP2-4.5 has a higher evapotranspiration percentual change (3.8%), compared to SSP3-7.0 (3.4%), yet precipitation will be reduced in a higher rate (-3.3%).

Consequently, the projected increased temperatures and higher evapotranspiration rates will eventually lead to a decrease in runoff. This has been documented by Sun et al. (2023) who investigate the impacts of climate change on the water quality and quantity for the Yellow River Basin in China, were modeled and higher temperatures reduced runoff, particularly during the dry season.

Figure 10

Average water balance percentage change for SSP2-4.5 and SSP3-7.0 for 2040



A Pearson correlation analysis was carried out between temperature, precipitation, and outflow under both SSP scenarios which showed that the correlation coefficient of precipitation with outflow was higher than that with temperature, with a value of 0.88 (p-value <0.01). Precipitation is the most influential climate change variable for the basin. It is projected that direct flow will be greater than base flow. In a study by Kumar and Marcy (2017), the authors analyzed the hydrological dynamics of a lake basin and found that precipitation was the dominant factor controlling both inflows and outflows. They demonstrated that changes in precipitation patterns directly influenced the water balance of the lake, affecting its water levels and overall hydrological regime. The IPCC report assessed with high confidence that the near-term predications exhibit positive surface temperature information, for up to ten years, which provides evidence of the certainty of the results (IPCC AR6 Working Group I, 2022).

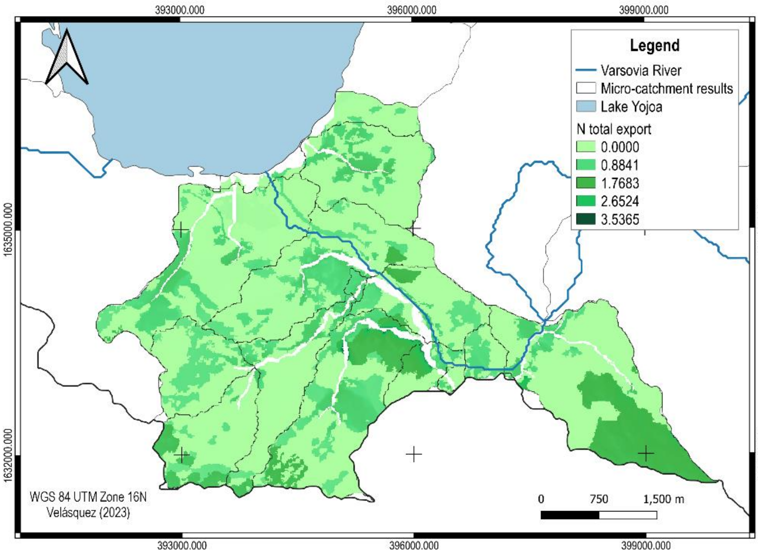
Nutrient Estimation

To estimate nutrient exports using InVEST®, the model was applied using the values of the biophysical table giving nutrient loads by land use. The model estimates N and P exports based on non-point sources. Domestic and industrial waste are point sources of pollution often part of the nutrient budget that should be accounted as a sum to modeled nutrient exports. However, the Yure and Varsovia basins have an average population density of > 50 inhabitants/km^2, with small population centers and dispersed settlements (Ministerio del Ambiente y los Recursos Naturales [MARENA], 2004). The communities lack comprehensive sewerage systems, and there is no significant industrial activity in the watershed that can be considered as a point source of pollution. Therefore, point sources were disregarded as they are not significant in the tributaries.

The Varsovia basin presented a TN export range from 0-3.536 kg/pixel and a total of 51.41 ton TN/year accounting for non-point sources. As expected, Figure 11 presents a higher concentration of TN on agricultural land uses such as coffee plantations, african oil palm and grasslands/crops. The TN average annual load estimated on the laboratory was 30.637 ton TN/year. Similarly, Acosta (2018) estimated 11.85 ton TN/year for the Varsovia River using export coefficients of nutrients bases on land use. Acosta's estimation differs both modeled and measured values, despite this, it is fair to consider nitrogen loading parameters for calibration to account for apparent overestimation. This data serves as a general indicator of the model parameters to be adjusted.

Figure 11

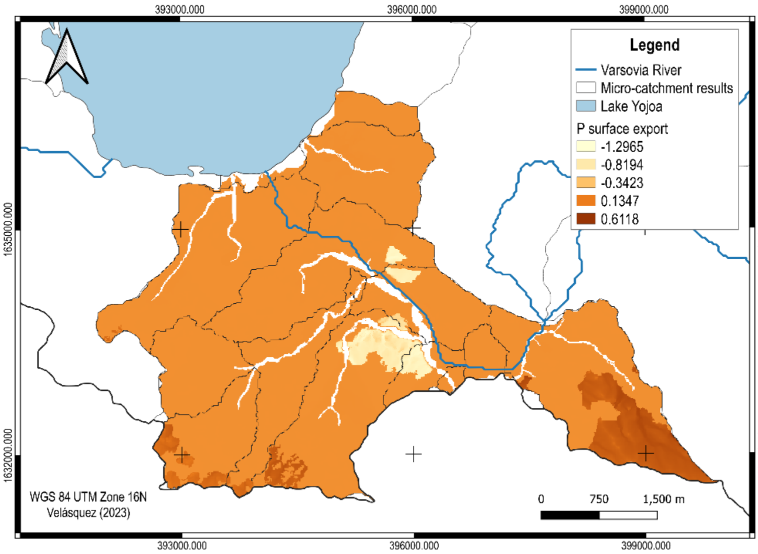
TN estimation for the Varsovia basin



For TP, the raster values for P superficial exports range from -1.30 -0.61 kg/pixel and the model estimates total of 0.003 ton TP/year (Figure 12). Similarly, measured values for the tributary are estimated to be 8.185 ton TP/year. Acosta´s (2018) estimation for the basin is total of 5.9 ton TP/year. In this case, the model underestimates phosphorus exports in the basin.

Figure 12

TP estimation for the Varsovia basin

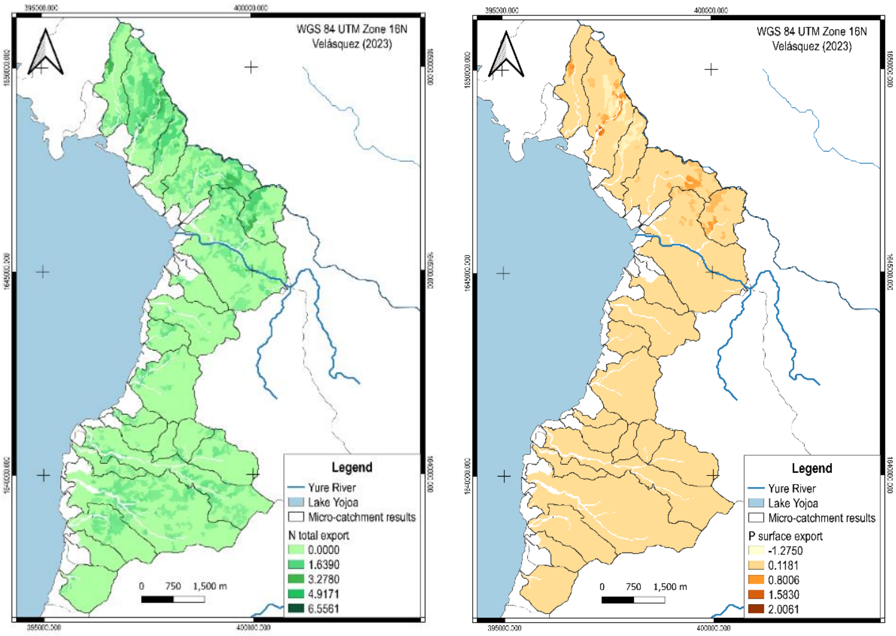


TP estimation for the Varsovia basin presents negative values, this is due to the DEM and LULC map resolution of the input. InVEST® is mainly designed for landscape analysis, the recommended spatial resolution is 30 m, since the model should capture the heterogeneity within the landscape accurately. Benez-Secanho and Dwivedi (2019) studied the joint effects of spatial resolution of input spatial data and spatial extent on the outputs under common assumptions. Their results provide insight on how DEM and land cover data sets affect nutrient export. Models using higher resolution DEMs predicted overall lower exports and lower resolutions predicted higher export compared to the baseline, due to the aggregation of land use classes.

The Yure river basin TN and TP estimation ranges from 0 - 6.556 kg TN/pixel and -1.275 - 2.00 kg TP/pixel, respectively; it presents a total of 64.87 ton TN/year and 1.02 ton TP/year (Figure 13). Likewise, measured values for the tributary are estimated to be 26.52 ton TN/year and 6.22 ton TP/year. Acosta´s (2018) estimation for the basin is total of 22.18 ton TN/year and 4.6-ton TP/year. The model continues to overestimate N exports and underestimate P superficial exports.

Figure 13

TN and TP estimation for the Yure basin



In order to further analyze micro-catchment retention and nutrient concentration Annex I and J present the values modeled for each nutrient.

InVEST® suggests that for model validation, the time series of nutrient concentration should cover a sufficiently long period (ideally at least 10 years) to mitigate the impact of inter-annual variability. Additionally, it is important for the time series to have relatively complete data throughout the year, without significant seasonal gaps, to enable accurate comparisons with total annual loads. Modeling the dynamics of nutrient transport at the watershed scale is a challenging task, as acknowledged by studies such as Bruer et al. (2008) and Scanlon et al. (2007). Due to these challenges, calibration of models is difficult and not advised unless accompanied by thorough analyses that establish confidence in the accurate representation of underlying processes. Hence, it is important to highlight that the following comparison is not intended as a calibration measure for the model. Nevertheless, it serves as a tool to assess the differences within an initial simulation using the available observed parameters form the tributaries.

Conclusions

The HydroBID model proves to be a valuable tool for predicting monthly streamflow in the Yure and Varsovia river basins. The model demonstrates adequate calibration parameters. While it tends to overestimate the probability of outflow peaks, adjustments can be made to align the flow duration curves.

Incorporation of climate change scenarios within HydroBID model provides insights into the basin's response under near-term conditions, considering changes in precipitation and temperature. The SSP2-4.5 scenario indicates an increase in outflow by the year 2040, while the SSP3-7.0 scenario predicts a decrease in monthly outflow for the site. The hydrologic response of the basin to high emission scenarios is primarily influenced by changes in precipitation and evapotranspiration, which impacts water supply.

The InVEST® Nutrient Delivery Ratio model offers a viable approach for estimating nutrient exports from non-point sources in the Yure and Varsovia basins. To improve accuracy, adjustments should be made to the nutrient loads and critical length parameters, enabling a more comprehensive assessment of the differences between measured and modeled values over extended time periods. Similarly, the model presents limitation in nutrient export estimation depending on the resolution of the DEM input, therefore, a lower resolution (30 m) could reduce estimation uncertainties, as seen with TP exports for the basin.

Recommendations

Lake Yojoa presents an interesting study site due to the rising concern for mitigating its trophic state and the economic activities that depend on it. Therefore, it is necessary to calibrate and validate nutrient load estimation models to facilitate its management and the creation of watershed-level regulations. The InVEST® model requires an extensive dataset for model calibration, which may hinder its use in the Honduran context, due to the lack of records of water quality for the main tributaries of the lake. Future investigations should focus on measuring nutrient loads to ensure accurate load estimations and ease calibration that may provide information for scenario assessments.

The HydroBID model provides a tool that facilitates calibration by presenting statistics alongside the outputs of each simulation. On the other hand, InVEST® is a model that requires prior knowledge of geographic information systems (GIS) for input data entry and output interpretation. Similarly, it requires individual statistical analysis for calibration, which can result in a longer and more tedious manual calibration process. Hence, future modelers must consider the characteristics and parameters of the model to be used, as well as its calibration requirements, in order to successfully carry out the modeling for each specific purpose.

The availability of data required for the use of both models can hinder its application in the national context. Input parameters corresponding to soil characteristics are usually found at very coarse scales in Honduras, which can make it difficult to accurately represent these variables at the sub-basin level. Similarly, the estimation of nutrients requires highly precise parameters that demand field data collection to ensure the proper functioning of a model. Moreover, the time extension of these parameters presents a limitation for further validation of the model. These input data are directly linked to land uses and land cover maps, so the specificity of the used map will determine the quality of the simulations performed.

The HydroBID and InVEST® hydrological models encompass a range of modules that can be effectively applied to diverse areas within the country. Notably, these models offer features such as calculation of the hydropower potential of a dam, estimating sediment levels, and generating scenarios for flood risk management. However, more training and technical assistance is needed for a wider application and expansion of the community of practice.

Model developers can increase the community of practice through a communication system and the creation of expert communities that serve as support for addressing doubts. Models require adjustments for various study sites, so facilitating communication between modelers and developers can allow for real-time model improvement and encourage their use.

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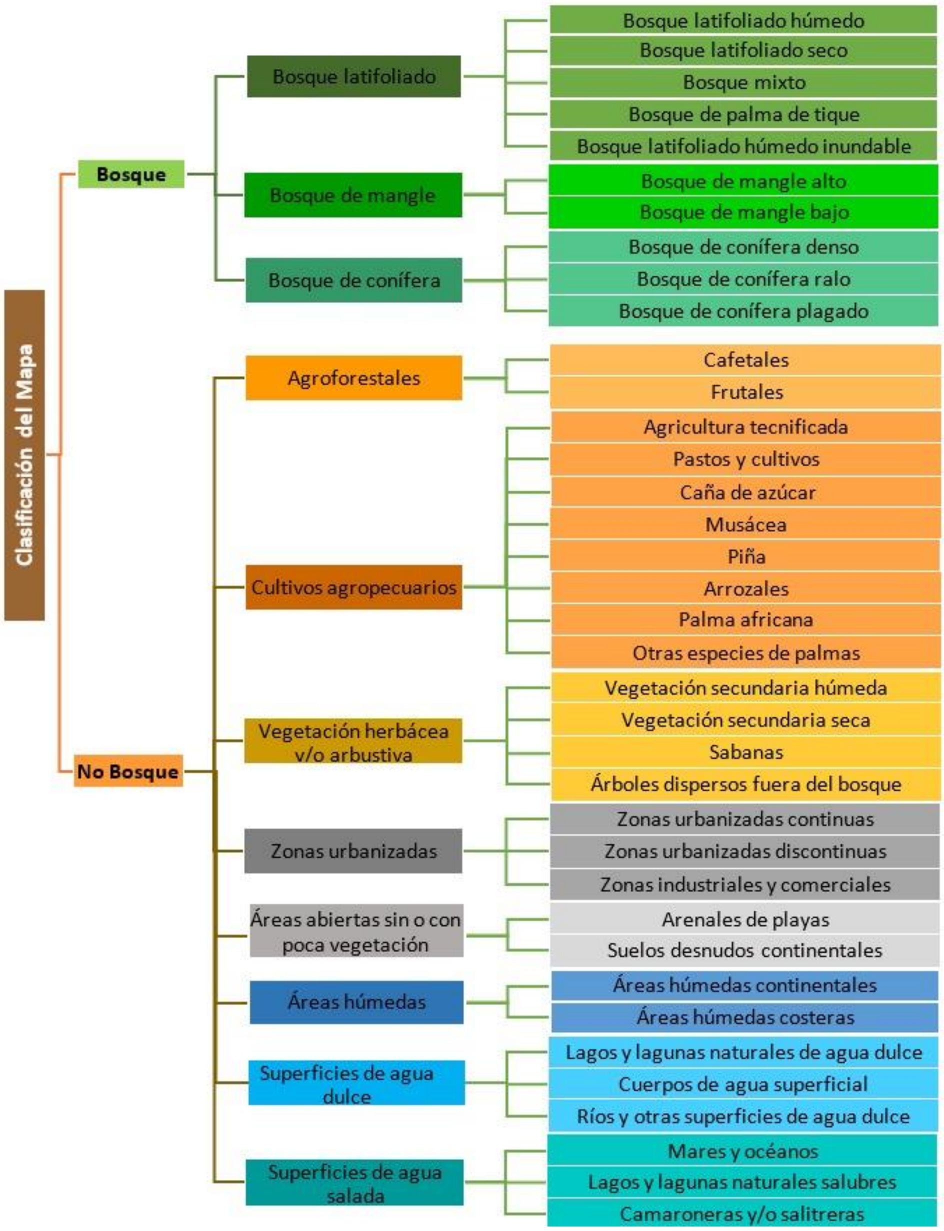
Annexes

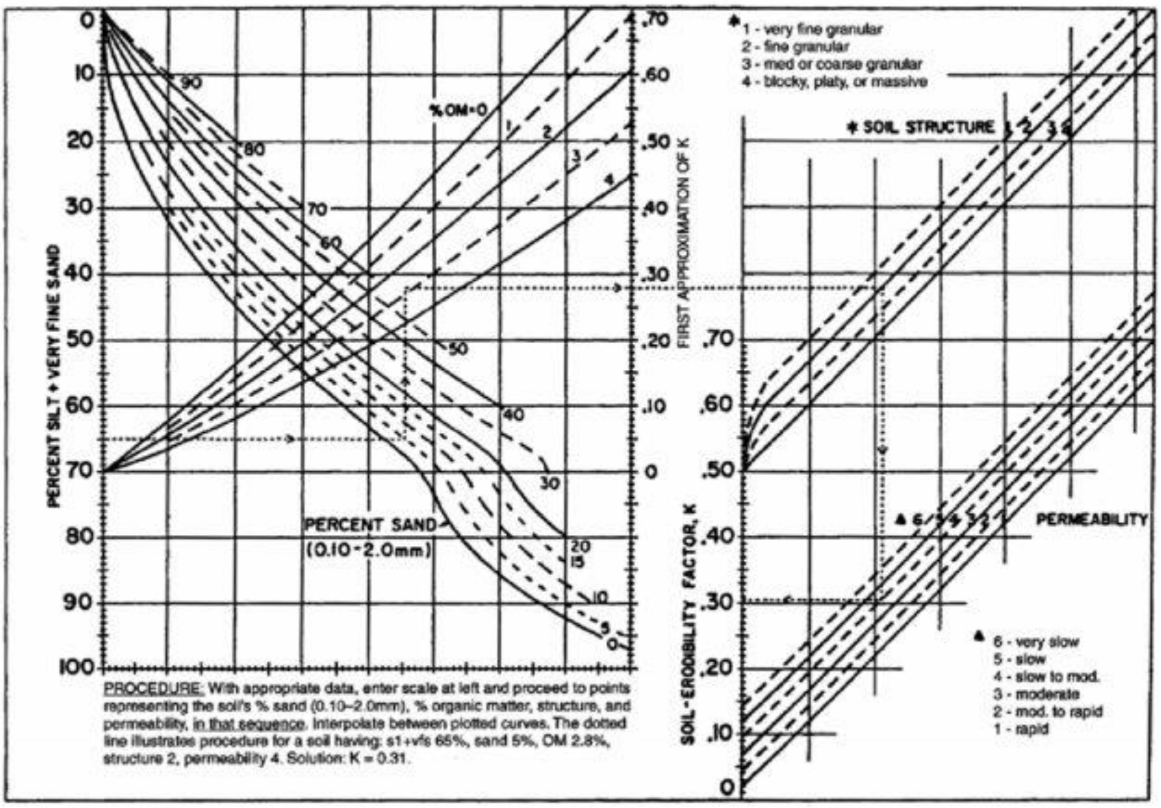
Annex A

Classification levels of the 2018 forest map



Annex B

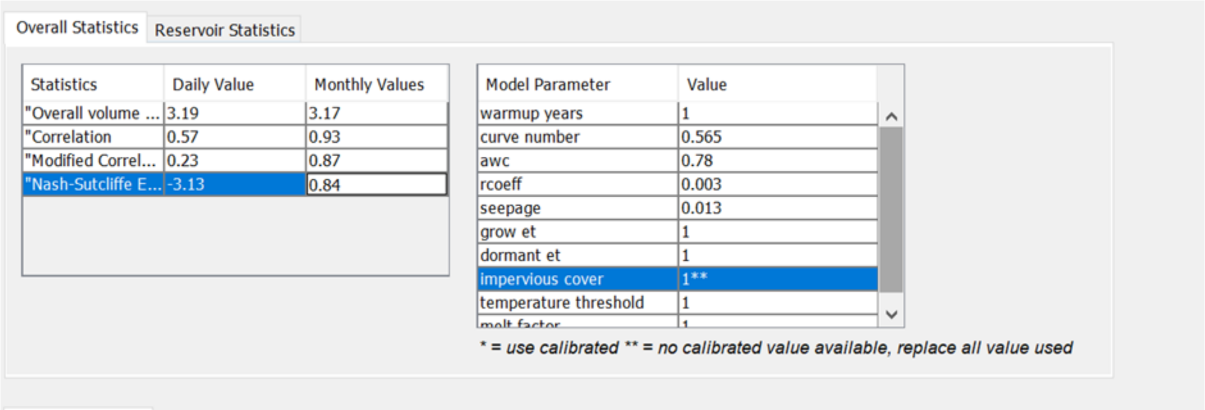
USDA nomograph used for K factor calculation



PROCEDURE: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10–2.0mm), % organic matter, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: s1+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Annex C

Output overall statistics of calibration for streamflow from the HydroBID platform



Statistics	Daily Value	Monthly Values
"Overall volume ...	3.19	3.17
"Correlation	0.57	0.93
"Modified Correl...	0.23	0.87
"Nash-Sutcliffe E...	-3.13	0.84

Model Parameter	Value
warmup years	1
curve number	0.565
awc	0.78
rcoeff	0.003
seepage	0.013
grow et	1
dormant et	1
impervious cover	1**
temperature threshold	1
melt factor	1

** = use calibrated ** = no calibrated value available, replace all value used*

Annex D

Climate change projected SSPs for temperature for 2040 HydroBID input

Month	Site 1981-2021	Change in T° (1)	Change in T° (2)	Change in T° (3)	SSP1-1.9 revised	SSP2-4.5 revised	SSP3-7.0 revised
Jan	20.16501	0.7	0.74	0.63	20.86501	20.90501	20.79501
Feb	21.1782	0.71	0.77	0.69	21.8882	21.9482	21.8682
Mar	22.44529	0.79	0.76	0.73	23.23529	23.20529	23.17529
Apr	24.08783	0.86	0.81	0.92	24.94783	24.89783	25.00783
May	24.60718	0.62	0.76	0.7	25.22718	25.36718	25.30718
Jun	24.09776	0.48	0.74	0.63	24.57776	24.83776	24.72776
Jul	23.34464	0.5	0.83	0.79	23.84464	24.17464	24.13464
Aug	23.51649	0.48	0.7	0.72	23.99649	24.21649	24.23649
Sep	23.70767	0.45	0.68	0.65	24.15767	24.38767	24.35767
Oct	22.68164	0.41	0.65	0.67	23.09164	23.33164	23.35164
Nov	21.01289	0.34	0.7	0.71	21.35289	21.71289	21.72289
Dec	20.35465	0.4	0.7	0.66	20.75465	21.05465	21.01465

Annex E

Climate change projected SSPs for precipitation for 2040 HydroBID input

Month	(%) SSP2	(%) SSP3
January	0.9928	0.985
February	0.9928	0.985
March	1.0316	0.9973
April	1.0316	0.9973
May	1.0316	0.9973
June	0.9846	0.9297
July	0.9846	0.9297
August	0.9846	0.9297
September	1.0025	0.9903
October	1.0025	0.9903
November	1.0025	0.9903
December	0.9928	0.985
Average	0.736667	0.708333

Annex F

SSP2-4.5 water balance for 2040 based on 2003-2013 baseline

Year	Modeled Outflow (m^3/s)	Observed Flow (m^3/s)	Precipitation (mm)	ET (mm)	Percolation (mm)	Runoff (mm)
1	1.126	1.206	2,675.985	1,063.187	1,464.362	158.056
2	1.200	1.286	2,852.33	1,124.22	1,558.13	150.93
3	1.244	1.232	2,581.89	1,057.21	1,324.83	211.64
4	1.605	1.536	3,228.04	1,106.38	1,863.01	252.07
5	1.272	1.224	2,710.00	1,144.14	1,360.61	220.98
6	1.344	1.444	3,030.72	1,142.19	1,681.18	185.07
7	0.848	1.011	2,385.44	1,135.42	1,177.05	75.91
8	1.404	1.306	2,872.46	1,124.21	1,523.82	228.87
9	1.306	1.307	2,963.10	1,157.92	1,615.86	196.34
10	1.365	1.214	2,819.37	1,123.69	1,462.72	233.90

Annex G

SSP3-7.0 water balance for 2040 based on 2003-2013 baseline

Year	Modeled Outflow (m^3/s)	Observed Flow (m^3/s)	Precipitation (mm)	ET (mm)	Percolation (mm)	Runoff (mm)
1	1.066	1.206	2,598.81	1,057.40	1,403.56	147.09
2	1.127	1.286	2,767.35	1,122.50	1,489.55	136.29
3	1.167	1.232	2,496.34	1,052.55	1,260.66	194.91
4	1.506	1.536	3,122.00	1,099.67	1,787.13	228.72
5	1.187	1.224	2,624.36	1,139.71	1,299.80	200.46
6	1.262	1.444	2,934.73	1,140.41	1,603.78	168.26
7	0.797	1.011	2,312.08	1,131.86	1,114.46	68.80
8	1.295	1.306	2,765.74	1,121.87	1,445.72	202.48
9	1.215	1.307	2,865.67	1,155.68	1,540.90	176.19
10	1.279	1.214	2,729.35	1,116.09	1,400.79	213.35

Annex H

Micro-catchment nutrient export estimation results for the Yure river basin

Micro-catchment	N total export (kg/year)	P surface export (kg/year)
1	2,983.781	38.105
2	2,587.616	-428.076
3	5,305.597	55.787
4	0.042	0.000
5	113.155	1.312
6	2,140.255	17.783
7	13,830.053	2531.223
8	2,970.374	354.776
9	10,846.309	-1687.289
10	385.536	1.648
11	2,398.772	89.766
12	4,640.154	-253.225
13	1,879.530	-706.785
14	116.392	1.315
15	290.634	9.230
16	1.486	0.005
17	926.465	5.338
Total	51,416.151	30.914

Annex I

Micro-catchment nutrient export estimation results for the Varsovia river basin

Micro-cathment value	N total export (kg/year)	P surface export (kg/year)
1	3,431.967	233.357
2	3,818.579	-906.191
3	850.860	16.727
4	414.101	4.649
5	504.741	10.188
6	166.055	6.057
7	605.161	5.652
8	1,229.056	23.113
9	120.591	5.722
10	469.354	17.898
11	2,419.767	19.411
12	266.737	8.490
13	5,052.700	49.342
14	1,229.644	25.475
15	14,090.020	-482.794
16	1,616.691	39.590
17	4,480.137	697.053
18	8,083.931	817.458
19	8,017.273	345.209
20	353.448	7.987
21	7,652.116	74.175
Total	64,872.928	1,018.568

Annex J

NDR data requirements: adapted from InVEST® User Manual

Input	Description	File details
Workspace	Folder where all the model's output files will be written.	Folder
File suffix	Will be appended to all output file names. Useful to differentiate between model runs.	text
Digital elevation model	Map	Raster, meters
LULC	Map with unique integer, all values must have corresponding entries in biophysical table.	Raster
Nutrient runoff Proxy	Map of runoff potential, the capacity to transport nutrient downslope.	Easter, unitless Quick flow index or annual precipitation.
Watersheds	Map of boundaries	Vector, polygon/multipolygon
Calculate nitrogen	True/false	Statement
Calculate phosphorus	True/false	Statement
Biophysical table	Replace '[NUTRIENT]' in the column names with 'n' or 'p' for nitrogen or phosphorus respectively. Nitrogen data must be provided if Calculate Nitrogen is selected. Phosphorus data must be provided if Calculate Phosphorus is selected. All LULC codes in the LULC raster must have corresponding entries in this table.	.csv Lucode Load_n Load_p (kg/ha*year)
Threshold Flow Accumulation	Number of pixels that must flow into a pixel before it is classified as a stream. 50000	Number, number of pixels Appendix 1 for more information on choosing this value.
Borselli K Parameter	DEFAULT is 2. Calibration parameter that determines the shape of the relationship between hydrologic connectivity and the nutrient delivery ratio.	Number, unitless SITE SPECIFIC
Subsurface critical length (nitrogen)	The distance traveled after which it is assumed soil retains nitrogen at its maximum capacity.	Number, m
Subsurface maximum retention efficiency (nitrogen)	The maximum nitrogen retention efficiency that can be reached through subsurface flow. This characterizes the retention due to biochemical degradation in soils.	Ratio