The Greenhouse Gas Emissions Estimates of Hydropower Reservoirs in Vietnam Using G-res Tool: Bridging Climate Change Mitigation with Sustainability Frameworks

INITIATIVE ON
Low-Emission Food Systems

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December 2023

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Suggested citation

Ghosh, S.; De Sarkar, K.; Chowdhury, A.; Holmatov, B.; Rajakaruna, P. 2023. *The greenhouse gas emissions estimates of hydropower reservoirs in Vietnam using G-res Tool: bridging climate change mitigation with sustainability frameworks.* Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Initiative on Low-Emission Food Systems. 52p.

Acknowledgements

This work was carried out with support from the CGIAR Initiative on Low-Emission Food Systems. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund.

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Summary

Quantifying greenhouse gas (GHG) emissions in hydropower reservoirs is linked with national and international sustainability objectives. Deploying scalable and effective cloud-based technologies improves the accessibility, reproducibility, and timeliness of the quantification process. This novel strategy promotes global sustainability in the hydropower industry while making it easier to comply with environmental regulations. It can promote informed decision-making, increase transparency, and expedite the transition to clean energy sources. Considering the use of cloud computing in GHG quantification can support global efforts to mitigate climate change and advance the development of hydropower systems into more sustainable global infrastructure. Earth Observation (EO) data with cloud computing facilities such as Google Earth Engine (GEE) and G-res (an online tool by the International Hydropower Association) can help fill in the missing data gaps and calculate GHG emissions from hydropower reservoirs in Vietnam following IPCC recommendations for estimating GHG emissions. Seven hydropower reservoirs (Ban Ve, Binh Dien, Ho Ham Thuan, Ho Hoa Binh, Ho Song Hinh, Thac Ba and Yali) from different parts of Vietnam were selected as test cases for calculating GHG emissions using the G-res tool. The initial results from the analysis show that the Binh Dien reservoir reports the highest GHG aerial emission rate per year, while the lowest has been observed for the Thac Ba reservoir. Similarly, the highest emission rate has been observed for the Ban Ve reservoir, while the lowest has been recorded for the Thac Ba reservoir. The initial results reported here provide an understanding of GHG emissions from the hydropower reservoirs (test cases) and are needed to be verified with the respective reservoir authorities for actual emissions.

Contents

1 Introduction

Natural and artificial water reservoirs can act as sources of greenhouse gas (GHG) emissions, contributing to climate change. Understanding and mitigating GHG emissions from large hydropower reservoirs can play a crucial role in achieving sustainable and low-carbon power generation. The multipurpose reservoirs serve various purposes, such as water storage, flood management, irrigation, along with power generation. However, the decomposition of organic matter in these reservoirs leads to the release of GHGs, primarily carbon dioxide (CO_2) and methane (CH_4), which are potent to escalate global warming (Yang et al., 2014). The GHG reduction potential of global hydropower is estimated to be around 8% of total anthropogenic emissions (Scherer and Pfister, 2016).

Several pathways contribute to their generation, including diffusion from the reservoir surface, bubble formation, and degassing in the downstream flow (Figure 1). Emissions from a growing number of artificial reservoirs are considered anthropogenic sources of emissions. More than 60 thousand large dams exist in the world (Adamo et al., 2020). Hydropower generation is a typical application of large artificial reservoirs, with power plants requiring substantial reservoirs for efficient operation. The International Hydropower Association (IHA) reports that East Asia and the Pacific have the highest installed capacity and power generation, closely followed by North and Central America, driven by the region's focus on clean and sustainable energy in response to climate change and increased energy demands. In contrast, Africa lags in terms of large-scale installations and power generation capacity (IHA, 2021).

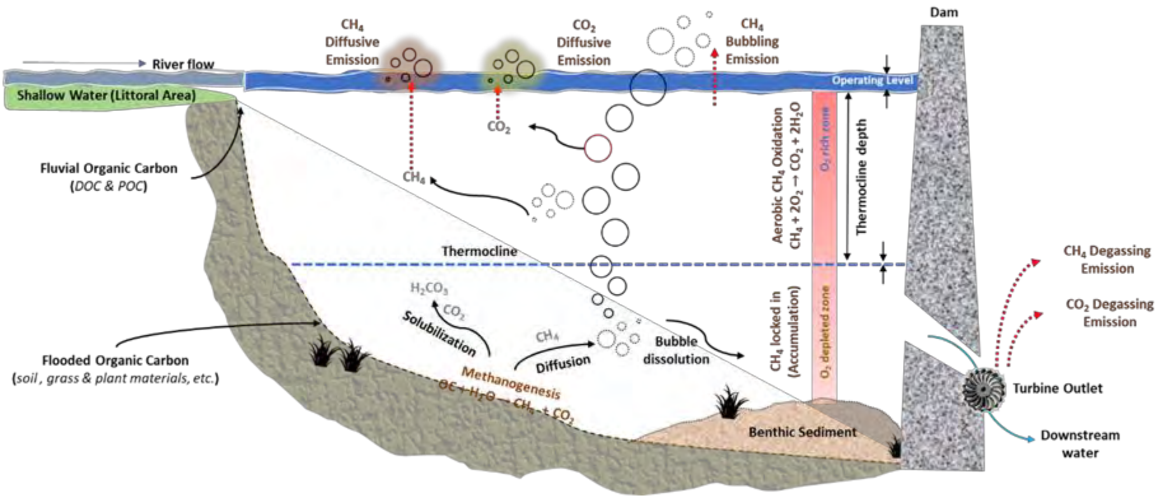

Figure 1. Schematics of large hydropower reservoirs and pathways leading to GHG emissions (CO_2 & CH_4)

While hydropower is considered a clean, renewable energy source, it often requires building a dam (physical structure) that helps to collect water in a reservoir (behind the structure). The process of constructing dams leads to emissions due to various construction activities, but water reservoirs forming behind dams are often overlooked sources of continuous emissions. The movement of GHG emissions from hydropower reservoirs into the atmosphere is a complex process influenced by a combination of several factors. Mapping and understanding the impacts of these factors is crucial in mitigating GHG emissions during hydropower project development, especially in the context of climate change mitigation, low carbon development and energy transition goals. Factors that influence GHG emissions from hydropower reservoirs can be categorized into five main categories – (1) climatic drivers (temperature, wind speed, and precipitation), (2) water environmental factors (dissolved oxygen, organic matter, and nutrients), (3) reservoir and catchment characteristics (operating level, latitude, reservoir age, urbanization levels), (4) hydrological conditions (sedimentation), and (5) biological conditions (vegetation cover and microbial activity) (Rosa and Santos, 2000; Barros et al. 2011; Deemer et al., 2016). Thus, quantifying GHG emissions from large hydropower reservoirs involves considering various drivers, including the type and quantity of flooded vegetation, water temperature, duration of inundation, reservoir size and depth, location, land use changes, and other environmental conditions. However, quantifying GHG emissions is challenging given data availability constraints for reservoirs with limited biophysical and environmental inputs. Earth Observation (EO) data with cloud computing facilities such as Google Earth Engine (GEE) and G-res (an online tool by IHA) can help fill in the missing data gaps and calculate GHG emissions from hydropower reservoirs following IPCC recommendations.

Understanding the interplay of the driving factors and their effects on GHG emissions from large hydropower reservoirs is a prerequisite for developing effective mitigation strategies. By considering a combination of climate, water, reservoir, catchment, hydrological, and biological factors, it is possible to manage hydropower development for optimizing GHG emissions, supporting sustainable energy practices and implementing global climate action agenda at the sub-national level towards achieving Sustainable Developmental Goals (SDGs) 7, 12, 13, 16 and 17.

2 Overview of Global Hydropower Reservoirs

Hydropower is the largest renewable source of power generation, supplying more electricity than wind, solar thermal, solar photovoltaic, tide/wave/ocean and geothermal sources combined (2020 data; IEA, 2023). As such, sustainable hydropower projects can contribute to carbon reduction objectives while enhancing variable renewables with flexibility and storage. Hydropower, a pivotal source of electricity generation, has emerged as a prominent contributor to the global energy landscape. Accounting for approximately one-sixth of the world's electricity production, its significance surpasses that of nuclear energy and other renewable sources combined. This prevalence spans more than 150 nations, underscoring its widespread adoption and utilization globally. An additional testament to the extensive imprint of hydropower lies in the vast expanse of hydropower reservoirs, covering approximately 3.4 × 105 sq. km (Barros et al., 2011). This substantial coverage encapsulates nearly 20% of the total global reservoir area, a noteworthy indication of the scale and impact of hydropower initiatives worldwide (Barros et al., 2011).

In 2021, global installed hydropower capacity reached almost 1400 GW, the highest among all renewable energy technologies, a noteworthy indication of the scale and impact of hydropower initiatives worldwide (IEA, 2022). As per the World Hydropower Outlook 2023, the leading contributors to this hydroelectric dominance include China, Brazil, United States, Canada, Russia and India, collectively dominating the top ranks in hydropower generation (IHA, 2023). Furthermore, recent statistics (Figure 2) as of 2022 reveal Vietnam's ascent into this echelon, firmly positioning itself among the top twenty producers of hydropower, contributing 1.2% of the global hydropower share (IHA, 2023), consolidating its role among the global energy leaders.

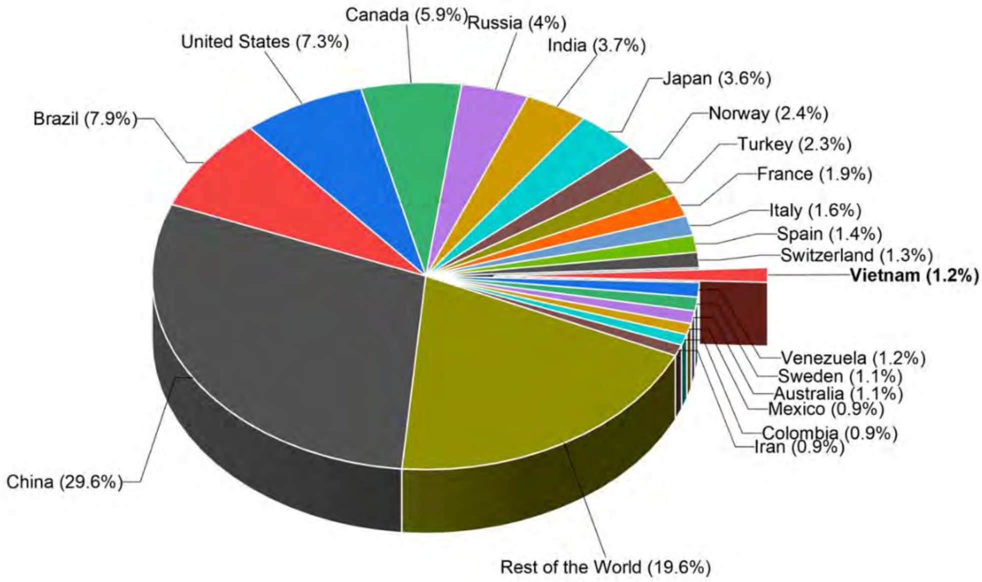

Figure 2. Hydropower installed capacity (GW; 2022) of the top 20 hydropower producers and the rest of the world, including pumped storage

(Data source: IHA 2023)

It is becoming increasingly evident that the future of renewable hydropower will experience a fundamental change. Hydropower will continue to be valued for its flexibility and ability to support the enormous rise in wind and solar energy required to reduce global warming by providing low-cost, base-load electricity in many markets (IHA, 2021).

3 Bibliometric Analysis

Bibliometrics is a field of study that uses publications' bibliographic data and citation relations to evaluate and reveal the structure of a research field (Mallik and Ghosh, 2018). This section of the report outlines a bibliometric study conducted to assess the research landscape of GHG emission in relation to hydropower reservoirs applications within advanced geospatial research. Utilizing the SCOPUS database and VOSviewer (Van and Waltman, 2013) for data visualization and analysis, publication trends and thematic clusters in this interdisciplinary field were identified. SCOPUS is one of the largest abstract and citation databases for academic literature, which makes it a good source for articles for bibliometric studies (Burnham, 2006; Chowdhury et al., 2023). Information was retrieved from the SCOPUS database using a structured query of keywords related to greenhouse gases and hydropower reservoirs (("GHG" OR "Greenhouse gas" OR "Green house gas") AND ("Hydropower" OR "Hydroelectric" OR "Hydro-power" OR "Hydro electric" OR "Hydropower" OR "Hydro-electric")). The search yielded a dataset that was then analyzed using VOSviewer to create network visualizations of co-authorship, co-citation, and keyword co-occurrence.

A reserved key for Scopus, TITLE-ABS-KEY, looks for a term in document titles, abstracts, and keywords. The information was taken from the "Scopus Preview database" for the years 1989–present (in December 2023). Several search strings have been created by combining crucial phrases legitimately connected to the 'reservoir' and 'greenhouse gas' used to find the publishing data on this subject. Initial findings indicate a robust increase in publications over the last decade, signalling growing interest in the field. The co-authorship analysis uncovered several key research clusters, while co-citation networks revealed foundational papers and emerging research fronts. Keyword analysis highlighted prevalent themes such as "greenhouse gases", "GHG emission" and "hydropower".

The analysis shows that researchers from 113 countries have contributed to the exploration of GHG emission and its twinging effects with hydropower over a span of more than 30 years (Figures 3 and 4). United States exhibits the highest number of scientific publications, accounting for 251 articles in the mentioned span. China shows the second highest number of publications (213), followed by Brazil (168), Canada (137) and India (117) in this research domain, securing a position among the top five countries in the world. 74 countries out of 113 countries have just published less than 10 articles over the studied period and in this domain of investigation. Vietnam, being in the top twenty hydropower producers globally, has contributed to only four research publications until the analysis period, providing a new avenue for forthcoming research to address climate action focusing on cleaner energy, sustainability, and a greener future.

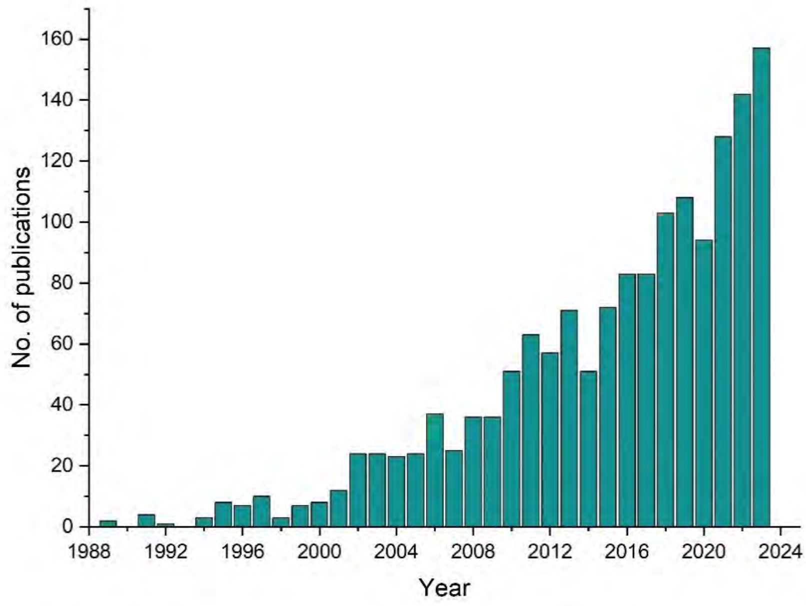

Figure 3. Number of publications during 1989-2023

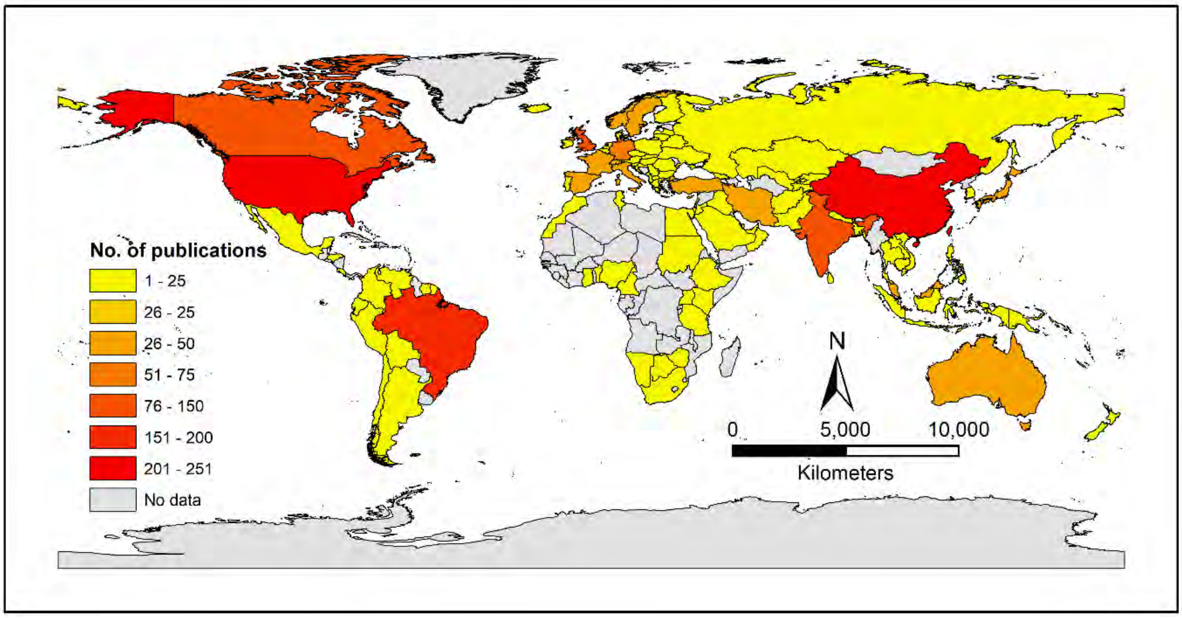

Figure 4. Number of publications globally during 1989-2023

The network visualization analysis (Figures 5 and 6) was created using the 1565 research articles downloaded from the Scopus database and VOSviewer software based on the co-occurrences and country-wise co-authorship analysis. The number of indexed keywords based on the articles obtained from the 1565 articles was 7358, out of which 88 keywords were utilized to create the network diagram based on 35 co-occurrences considering the top 2% of co-occurrence that occasioned 4 clusters and 3478 links. The keywords were then standardized using the standard nomenclature and generalization, such as *greenhouse gases* and *greenhouse gas* were considered as GHG.

Likewise hydroelectric, *hydro electric*, *hydro-electric*, *hydro power*, *hydro-power* were standardized to hydropower. A few more keywords were similarly standardized. The number of publications over the years (Figure 4) matched well with the countries of co-authorship, bringing out the top five co-authored countries as United States, China, Brazil, Canada, and India based on the size of circles in the network diagram (Figure 6).

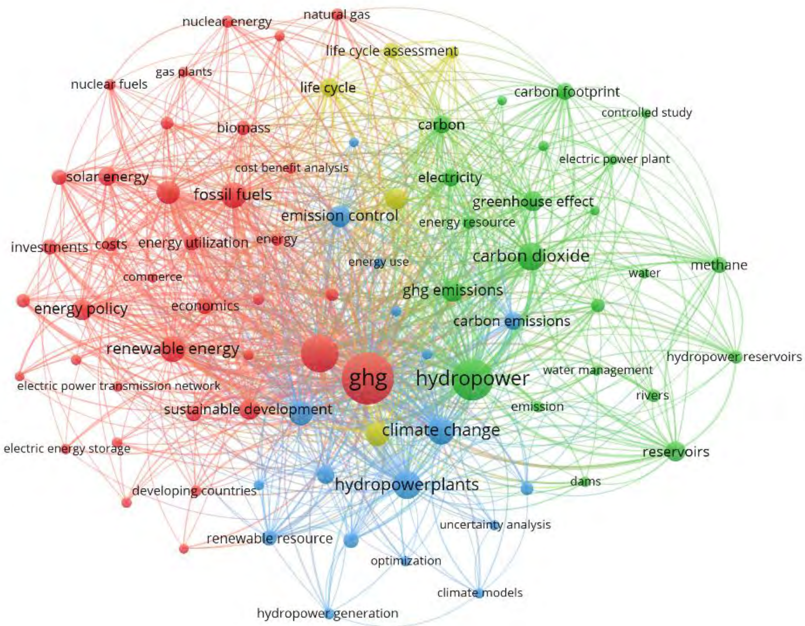

Figure 5. Network visualization diagram based on 35 co-occurrences of indexed keywords.

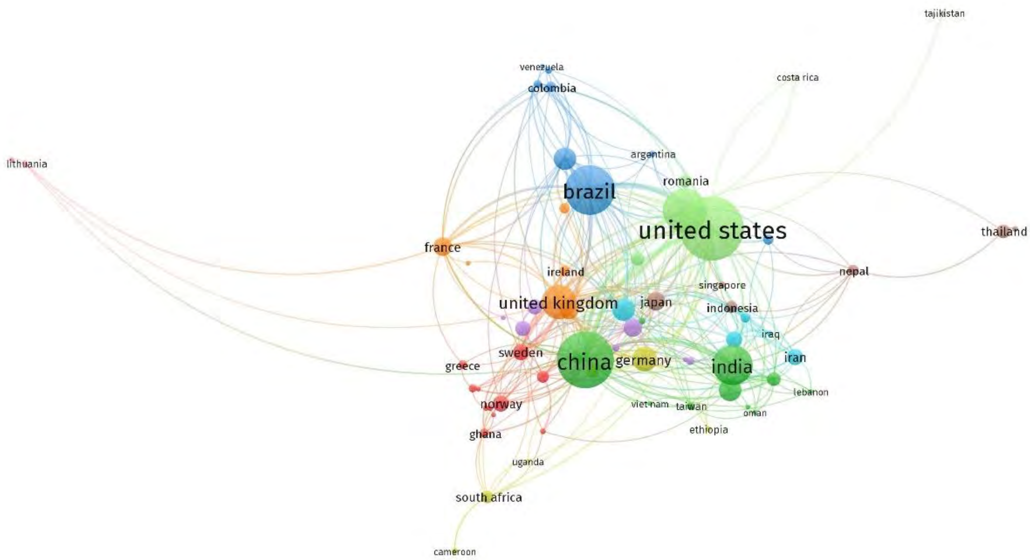

Figure 6. Network visualization diagram based on country-wise co-authorship.

In recent years, quantifying GHG emissions from hydropower projects has become an emerging point of research in Vietnam. Three pivotal studies that delve into the intricate relationship between hydropower development and GHG emissions in Vietnam have been highlighted in this section. Räsänen et al. (2018) evaluated GHG emissions from hydropower reservoirs in the Mekong Basin, including Vietnam. Amidst rapid hydropower expansion, this study quantified emissions from 141 existing and projected reservoirs using statistical models based on global data. Results showed a broad emission range (0.2–1994 $kgCO_2eMWh^{-1}$) over the reservoirs' 100-year lifespan, with a median of 26 $kgCO_2eMWh^{-1}$. Notably, irrigation-facilitating hydropower reservoirs exhibited significantly higher emissions, over 22,000 $kgCO_2eMWh^{-1}$. This study underscores the importance of considering climatic impacts alongside other effects of hydropower development. Nguyên et al. 2017 focused on the Son La hydropower reservoir in Vietnam, employing regression analysis to correlate water quality metrics with GHG emissions. The study identified key factors influencing CO_2 (temperature, dissolved oxygen, alkalinity, pH) and CH_4 emissions (temperature, chemical oxygen demand, pH). Regression models based on actual water quality measurements provided accurate CO_2 and CH_4 emissions predictions, with correlation coefficients of 0.93 and 0.92, respectively.

The World Bank (2017) provided a comprehensive overview of GHG emissions from reservoirs, discussing the CO_2 and CH_4 cycles, spatial variation, and atmospheric interactions. The report included guidelines for dam project preparation, from initial screening to post-impoundment monitoring. It highlighted the application of the G-res tool and EO data for demonstrating emission estimates of the Trung Son reservoir, and the G-res tool with EO data for demonstrating emission estimates of the Trung Son reservoir in Vietnam. The report also included detailed input data and quantified emissions, offering valuable resources for future research. These studies underscore the need for comprehensive evaluations of climatic impacts in hydropower development, which are imperative to align with emission reduction goals, SDGs, and climate justice imperatives through integrating advanced technological tools, ensuring a holistic approach, and fostering equitable benefits. This conscientious integration of environmental considerations will not only act as a stepping stone in the pressing debate of climate action but also align with international efforts, promoting responsible and inclusive energy solutions in the pursuit of a resilient, low-carbon future.

4 Hydropower Energy Odyssey in Vietnam

Vietnam's journey towards hydropower energy has been motivating, involving major advancements in energy production, irrigation, legislation, policy, and the execution of large multipurpose hydropower projects. The nation has built a large network of dams and power plants by deliberately using its river systems (Nguyen et al., 2018). Vietnam, a nation endowed with abundant water resources, saw the opportunity to use hydropower to meet its expanding energy needs while tackling energy demand. Vietnam's hydropower journey has come to be accompanied by multipurpose hydropower projects representing a holistic approach to resource utilization (Bao et al., 2017). The upward trajectory is best illustrated by the Srepok 3 and 4 projects, which combine flood management, irrigation, and energy production (Ty et al., 2012). The hydropower projects at Son La and Hoa Binh stand out among them as outstanding accomplishments that significantly improve the nation's energy grid (Gencer and Spencer, 2012). These initiatives offer a reliable supply of electricity and substantially lessen Vietnam's dependency on fossil fuels, in line with international efforts to combat climate change (Urban et al., 2018).

Vietnam's hydropower journey has prioritized irrigation, meeting agricultural supply–demand equilibrium and improving food security in parallel with energy generation. Vietnam's dedication to striking a balance between its energy needs and the sustainable management of its water resources is demonstrated by this dual-purpose strategy (Batra, 2023). Vietnam's hydropower journey (Figure 7) is projected to stay strong in the years ahead as the government leadership delves into cutting-edge technologies and global partnerships to strengthen and maximize energy production and water management (Ha-Duong, 2023). A change towards a diverse and sustainable energy portfolio is imminent with the addition of renewable energy sources, such as solar and wind, to the hydropower environment (Kunkel et al., 2012). Vietnam's hydropower story is a strategic development that includes legislation, hydropower multipurpose projects, irrigation, energy production, and policy (Middleton et al., 2012). The nation is steadfast in its commitment to a sustainable and inclusive energy future even as it negotiates the challenges of striking a balance between environmental stewardship and economic growth (Waibel, 2010). This is attributable to the insights acquired and the progress accomplished during this voyage, guaranteeing the prudent use of hydropower. The legislative structure encourages transparency and accountability within the sector, making environmental impact evaluations and community consultations integral to project procedures (Huu et al., 2013).

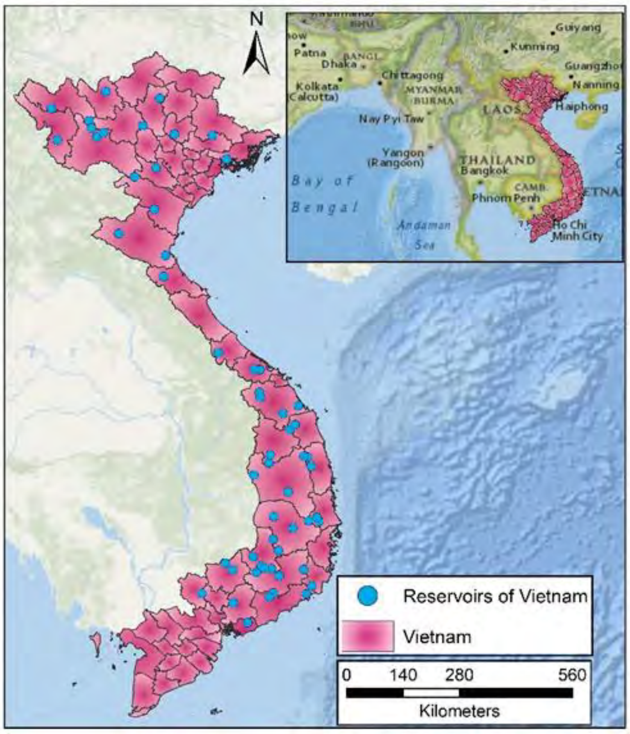

Figure 7. Location of Large Hydropower Dams in Vietnam (created by authors)

(Data source: GeoDAR Database on Dams version 11, 2022)

5 Quantification Techniques Using EO Data: GHG Emissions from Hydropower Reservoirs

Several physical methods are available for assessing GHG emissions, including bubbling traps, ultra-portable GHG analyzers, infrared gas analyzers, eddy covariance, Gas chromatography, and floating chambers (Rosa and Santos, 2000; Kumar et al., 2021). However, these physical methods for estimating GHG emissions face limitations. They often require significant labour, resources, and on-site measurements, which can be time-consuming and expensive. These methods may not capture emissions comprehensively over large areas or extended periods due to spatial and temporal constraints, potentially leading to inaccuracies. Additionally, their invasive nature, requiring direct access to the sites, can disrupt ecosystems or industrial processes. They also might lack the ability to capture emissions at fine scales or resolutions, posing challenges in obtaining detailed and accurate data.

In contrast, integrating earth observation data with remote sensing methods offers wider spatial coverage, frequent monitoring, and the ability to capture emissions from inaccessible or remote areas, presenting a more holistic view of emissions while overcoming some limitations of physical methods. Earth observation data and modelling techniques emerge as a powerful lens, enabling researchers to explore, comprehend, and map the intricate tapestry of greenhouse gas dynamics across diverse landscapes and ecosystems, fostering a more profound understanding essential for informed environmental stewardship and global sustainability efforts.

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for estimating GHG emissions from large reservoirs (Figures 8 and 9). These guidelines recommend various methods to measure and estimate emissions. Direct measurements involve collecting water samples from the reservoir and analyzing them for dissolved CO_2 and CH_4. Traditionally, GHG emissions from reservoirs are measured using sensors and bubble traps positioned at the water-air interface. These measurements need to consider spatiotemporal variations in emissions, which can vary significantly depending on the season and location (Räsänen et al., 2018).

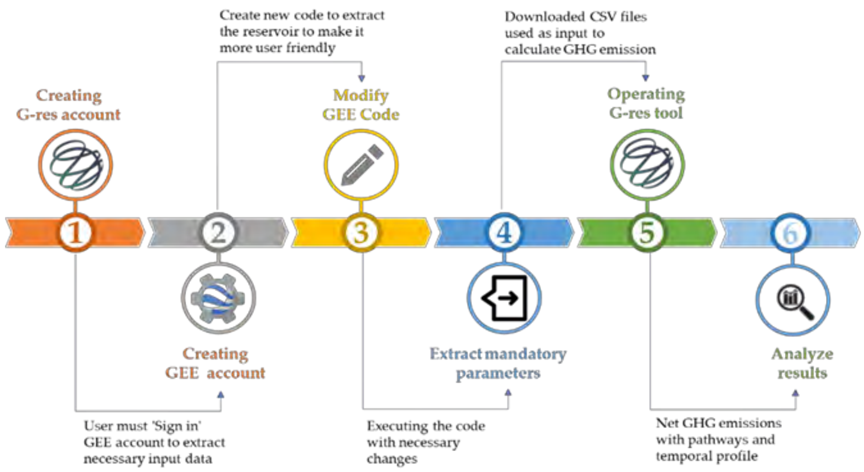

Figure 8. Methodology for estimating GHG emissions.

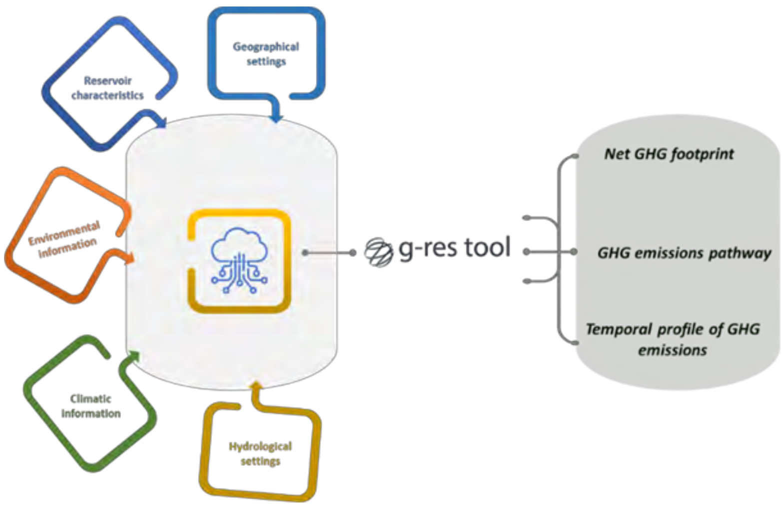

Figure 9. Approach to calculate GHG emissions using GEE and G-res tool.

In addition to direct measurements, statistical models are used to estimate GHG emissions from reservoirs (Abril et al., 2005). Such models consider factors such as flooded organic matter, water temperature, and environmental conditions to provide estimates of emissions. The complexities in measurement and modelling have hindered research efforts in this field. G-res tool has been developed to address these challenges (Prairie et al., 2021). G-res employs advanced modelling techniques that consider factors like hydrodynamics, sedimentation, and the carbon cycle to provide more robust estimations of GHG emissions from reservoirs using EO data via cloud platforms like GEE. EO data entails collecting data related to land cover, temperature, etc. These data types are then analyzed using algorithms and models to estimate the amount of flooded organic matter and assess the potential emissions of GHGs. Thus, integrating the G-res tool with the GEE platform enables better understanding and decision-making regarding reservoir management and mitigation strategies.

GEE, a cloud-based platform (Gorelick et al., 2017), contains valuable capabilities for environmental monitoring and modelling (Bhattacharya et al., 2022). It provides access to a large amount of remote sensing data, including satellite imagery, which can be used to analyze land cover changes and vegetation dynamics. Using GEE, researchers can estimate environmental and climatic drivers of potential CH_4 emissions resulting from its decomposition. The platform can also help to estimate the size and volume of water reservoirs, providing an assessment of how much water they can hold and the extent of their potential CO_2 emissions. Based on IPCC recommendations, the G-res tool is designed to estimate the net GHG footprint of reservoir creation (Prairie et al., 2021). It serves as a decision-making tool by facilitating the communication of potential impacts and identifying areas where mitigation measures may be necessary. The tool utilizes input data that does not require on-site measurements, leveraging parameters that can be accessed using specific codes in GEE. By combining the capabilities of the G-res tool and GEE (Figures 8 and 9), researchers and stakeholders can enhance their understanding of the environmental implications of reservoir development through informed decision-making and targeted interventions to support sustainable management practices.

Reliable estimation of GHG emissions from large reservoirs (World Bank, 2017) can provide new opportunities for developing effective climate change mitigation strategies through sustainable reservoir management. Utilizing tools like GEE and the G-res tool, stakeholders can understand linkages between factors such as vegetation cover, water temperature, reservoir characteristics and GHG emissions and make informed decisions to minimize the environmental impact of large reservoirs through evidence-based mitigation measures.

All the methods and data used in this study are based on IPCC-recommended guidelines (G-Res-Tool-User-Guide-v3.2)[1]. The data table that has been used in this study is provided in Table 1.

Table 1. Important input variables and their sources to estimate net emission using G-res (modified from Prairie et al., 2021)

	Variables	Units	Data Source
Reservoir Variables	**Climate zone**	--	Rubel and Kottek, 2010 (Köppen - Geiger climate classification)
	Dam coordinates	Degree Decimal	Field survey/Literature/GRanD Database
	Impoundment year	yr	Reservoir authority/Literature/ GRanD Database
	Reservoir area	km^2	Reservoir authority/Literature/ GRanD Database/Land use landcover map/Waterbodies boundary
	Maximum depth	m	Reservoir authority/Literature/ GRanD Database/ Hydrographic survey
	Mean depth	m	Reservoir authority/Literature/ GRanD Database/ Hydrographic survey
	Reservoir area	km^3	Reservoir authority/Literature or can be estimated in G-res
	Thermocline depth	m	Reservoir authority/Literature or can be estimated in G-res
	Littoral area	%	Reservoir authority/Literature or can be estimated in G-res
	Water residence time	yr	Reservoir authority/Literature or can be estimated in G-res
	Mean monthly and annual air temperature	°C	Hijmans et al., 2005 or another climate database
	Annual precipitation	mm yr^{-1}	Hijmans et al., 2005 or other climate database
	Mean monthly and annual wind speed	ms^{-1}	Hastings et al.,1999 or other wind-related database
	Reservoir mean global horizontal radiance	kWh m^{-2} d^{-1}	NASA, 2008
	Phosphorus concentration	µg L^{-1}	Reservoir authority/Literature or can be estimated in G-res
	Soil carbon content of the inundated reservoir area	$kgCm^{-2}$	SoilGrids - global gridded soil information (Hengl et al., 2017)
Catchment Variables	**Catchment area**	km^2	Reservoir authority/Literature/ GRanD Database/Land use landcover map/Waterbodies boundary
	Mean annual runoff	mm yr^{-1}	Fekete et al., 2000 or Reservoir authority/Literature
	Population density	person km^{-1}	CIESIN, 2005
	Annual discharge	m^3s^{-1}	Reservoir authority/Literature or can be estimated in G-res
	Land coverage	%	ESA – CCI, 2017

[1] https://g-res.hydropower.org/wp-content/uploads/2022/12/G-Res-Tool-User-Guide-v3.2.pdf (Accessed December 19, 2023)

6 Test Cases

In GRanD Database version 1.3,[2] a total of 7,321 reservoirs have been registered from all over the world. From Vietnam, 40 reservoirs are included in the GRanD Database, ranging from the year of impoundment between 1964 to 2016. Among them, a total of seven hydropower reservoirs (Table 2) were selected from different parts of Vietnam (Figure 10). GHG emissions from these reservoirs are calculated using the G-res tool, which is demonstrated in the following sub-sections.

Table 2. Hydropower Reservoirs of Vietnam

Reservoirs	Long.	Lat.	GRanD Database Reservoir ID	GRanD Database Catchment ID	Impoundment Year	Installed Capacity (MW)
Ban Ve	104.49	19.34	22425	4060015260	2010	320
Binh Dien	107.50	16.32	22426	4060015430	2005	44
Ho Ham Thuan	107.89	11.31	22442	4060016810	2001	300
Ho Hoa Binh	105.22	20.78	22443	4061023270	1994	1920
Ho Song Hinh	108.95	12.89	22462	4060016210	2001	70
Thac Ba	105.02	21.75	22467	4061015370	1971	120
Yali	107.83	14.23	23445	4061128130	1996	720

Figure 10: Location maps of the selected reservoir

[2] https://www.globaldamwatch.org/grand/ (accessed on December 19, 2023)

Table 3 provides information on the pre-impoundment GHG emissions for selected reservoirs. Pre-impoundment emission rates are negative for several reservoirs, indicating a sink of GHG. The reservoirs at Ban Ve (-63 $gCO_2e/m^2/yr$), Binh Dien (-455 $gCO_2e/m^2/yr$), and Ho Ham Thuan (-20 $gCO_2e/m^2/yr$) all exhibit negative emission rates, pointing to a sink of GHG. Positive emission rates for the reservoirs Ho Hoa Binh (4 $gCO_2e/m^2/yr$), Ho Song Hinh (33 $gCO_2e/m^2/yr$), Thac Ba (17 $gCO_2e/m^2/yr$) and Yali (23 $gCO_2e/m^2/yr$) are also not significantly high. The analysis of these values is crucial for understanding the carbon dynamics associated with reservoir formation.

Table 3. Pre-Impoundment GHG Emission

Name of Reservoir	**Emission Rate** ($gCO_2e/m^2/yr$)	**of which CO_2 Emission** ($gCO_2e/m^2/yr$)	**of which CH_4 Emission** ($gCO_2e/m^2/yr$)
Ban Ve	-63	-63	0
Binh Dien	-455	-455	0
Ho Ham Thuan	-20	-48	28
Ho Hoa Binh	4	-16	20
Ho Song hinh	33	-11	44
Thac Ba	17	0	18
Yali	23	-4	27

Table 4 presents the post-impoundment GHG emissions for various reservoirs. The post-impoundment emission rate of the Ban Ve reservoir is 606 $gCO_2e/m^2/yr$, of which 279 $gCO_2e/m^2/yr$ is contributed by CO_2 emissions and 327 $gCO_2e/m^2/yr$ by CH_4 emissions. Similarly, for the Ho Ham Thuan reservoir, the post-impoundment emission rate is 289 $gCO_2e/m^2/yr$, of which 88 $gCO_2e/m^2/yr$ is contributed by CO_2 emissions and 201 $gCO_2e/m^2/yr$ by CH_4 emissions. The largest post-impoundment emission rate is found in the Binh Dien reservoir, i.e., 999 $gCO_2e/m^2/yr$, of which 299 $gCO_2e/m^2/yr$ is contributed by CO_2 emissions and 700 $gCO_2e/m^2/yr$ by CH_4 emissions. While the lowest post-impoundment emission rate is observed in the Thac Ba reservoir (48 $gCO_2e/m^2/yr$) of which 17 $gCO_2e/m^2/yr$ is contributed by CO_2 emissions and 31 $gCO_2e/m^2/yr$ by CH_4 emissions.

Table 4. Post-Impoundment GHG Emission

Name of Reservoir	Emission Rate ($gCO_2e/m^2/yr$)	of which CO_2 Emission ($gCO_2e/m^2/yr$)	of which CH_4 Emission ($gCO_2e/m^2/yr$)
Ban Ve	606	279	327
Binh Dien	999	299	700
Ho Ham Thuan	289	88	201
Ho Hoa Binh	94	44	50
Ho Song hinh	296	43	254
Thac Ba	49	17	31
Yali	149	31	118

Table 5 offers a comprehensive analysis of the post-impoundment GHG emissions for different reservoirs based on different paths. CH_4 emission via diffusive, bubbling, and degassing processes and CO_2 emission via diffusive pathway only are measured in the study. The figures show how the reservoirs would affect the environment, especially in terms of GHG emissions. Significant emissions are found in all three categories for the Binh Dien reservoir; CH_4 degassing has especially significant emissions (603 $gCO_2e/m^2/yr$) when compared to other processes. In contrast, Thac Ba showed lower emissions (27 $gCO_2e/m^2/yr$) overall. Reservoirs such as Ban Ve and Binh Dien have comparatively large CO_2 diffusive emissions, indicating the release of CO_2 through the water surface contributes to the greenhouse effect and climate change.

Table 5. Detailed GHG Post-Impoundment Emission from Different Pathways

Name of Reservoir	CH_4 Diffusive ($gCO_2e/m^2/yr$)	CH_4 Bubbling ($gCO_2e/m^2/yr$)	CH_4 Degassing ($gCO_2e/m^2/yr$)	CO_2 Diffusive ($gCO_2e/m^2/yr$)
Ban Ve	73	9	244	279
Binh Dien	82	15	603	299
Ho Ham Thuan	49	27	125	88
Ho Hoa Binh	35	2	14	44
Ho Song hinh	86	25	142	43
Thac Ba	27	1	4	17
Yali	56	12	50	31

Subtracting the Pre-Impoundment emissions from the post-impoundment ones provides the Net GHG Footprint impression. A summary of the net GHG footprint connected to each of the seven test case hydropower reservoirs can be found in Table 6, which allows standardized comparison among the hydropower reservoirs. Out of all the reservoirs listed, Binh Dien reservoir has the highest net GHG footprint (1454 $gCO_2e/m^2/yr$) with specific emissions of CO_2 (754 $gCO_2e/m^2/yr$) and CH_4 (700 $gCO_2e/m^2/yr$). A net GHG footprint of 32 $gCO_2e/m^2/yr$, of which 18 $gCO_2e/m^2/yr$ contributed by CO_2 and 14 $gCO_2e/m^2/yr$ contributed by CH_4 emissions, lead the Thac Ba reservoir to be the lowest areal emitter of GHG. Net GHG footprint for the reservoirs Ho Ham Thuan (309 $gCO_2e/m^2/yr$), Ho Hoa Binh (90 $gCO_2e/m^2/yr$), Ho Song Hinh (263 $gCO_2e/m^2/yr$), Thac Ba (31 $gCO_2e/m^2/yr$) and Yali (126 $gCO_2e/m^2/yr$) provide a thorough understanding of their effects on the environment.

Table 6. Net GHG Footprint

Name of Reservoir	**Emission Rate** ($gCO_2e/m^2/yr$)	**of which CO_2 Emission** ($gCO_2e/m^2/yr$)	**of which CH_4 Emission** ($gCO_2e/m^2/yr$)
Ban Ve	669	342	327
Binh Dien	1454	754	700
Ho Ham Thuan	309	135	173
Ho Hoa Binh	90	61	30
Ho Song hinh	263	53	210
Thac Ba	31	18	14
Yali	126	35	91

Data Access

In the G-res tool, the input parameters can be saved or exported in *.mer* file format. These *.mer* files can be reused to optimize the input datasets to estimate the emissions for different scenarios. The initial results presented in Tables 3, 4, 5 and 6 in this report can be accessed through the G-res tool using the *.mer* files from Ghosh et al. (2024) (https://zenodo.org/records/10511354). The datasets can be modified with localized datasets for better accuracy. The initial results reported here provide gross estimations and are needed to be verified with the respective reservoir authorities for actual emissions.

7 Policies for Curbing GHG Emissions

Global policies have become essential to combat climate change by setting international standards for reducing GHG emissions and fostering global cooperation to address environmental crises. Such agreements are crucial for ensuring a sustainable and habitable world for succeeding generations. The principle of net zero or carbon neutrality necessitates that any activity releasing CO_2 be offset by another that eliminates an equal amount (Ahluwalia et al., 2021). For a nation to be considered carbon-negative, it must extract more CO_2 from the atmosphere than it emits. In the aftermath of the Kyoto Protocol, several developed nations, notably Britain, Canada, United States and Japan, are aiming to achieve "net zero" emissions by 2050.

Vietnam recently acknowledged the importance of addressing GHG emissions as part of its commitment to global climate action goals (Hoa and Matsuoka, 2017). Policy and legislation have been key factors forming Vietnam's hydropower environment (Can, 2002). Considering multiple government agencies and regulations involved, Vietnam has a complex institutional framework for reducing GHG emissions that aims to promote sustainable development and lessen the nation's carbon footprint (Lam, 2016). Policies about GHG emissions (Table 7) are primarily shaped and carried out by the Ministry of Natural Resources and Environment (MONRE). A significant policy framework managed by MONRE is the National Green Growth Strategy[3], which was introduced in 2012. By including climate change adaptation and mitigation in national planning, it seeks to advance sustainable development. The initiative lays forth goals for cutting GHG emissions and highlights the importance of moving towards a low-carbon, green economy.

[3] https://cidd2015.sciencesconf.org/file/BTC2015_GG_in_VN_Final_Summary.pdf (Accessed: December 22, 2023).

Vietnam's Nationally Determined Contributions (NDCs) demonstrate its adherence to international agreements, especially the Paris Agreement. The NDCs set forth precise goals for mitigating and reducing greenhouse gas emissions in several industries. Coordination between MONRE, Ministry of Industry and Trade (MOIT), and other pertinent ministries is part of the institutional responsibility for implementing the NDC. These cooperative initiatives demonstrate the all-encompassing strategy used to address GHG emissions in the nation. The Ministry of Planning and Investment (MPI) in Vietnam plays a role in the institutional framework by supervising the planning of socioeconomic growth. The five-year socioeconomic development plans include targets for reducing greenhouse gas emissions and combating climate change, which balance environmental sustainability with economic growth (Ninh, 2014). This integration ensures that Vietnam's development policies incorporate climate factors. One of the most important organizations in putting environmental protection and climate change policies into action is the Vietnam Environment Administration (VEA), which is an agency under MONRE[4]. The Environmental Protection Planning, which includes steps to reduce GHG emissions, is supervised by the VEA. For projects and industries, this planning framework contains evaluations of the environmental effects, including GHG emission considerations.

Renewable energy development is crucial to Vietnam's plan to reduce GHG emissions. The procedures for promoting the growth of solar power projects are delineated in the Prime Minister's Decision No. 11/2017/QD-TTg (USAID, 2018). MOIT is in charge of coordinating these initiatives and creating rules and regulations for the energy industry. Vietnam wants to boost the proportion of renewable energy in its overall energy mix to lessen its dependency on fossil fuels and reduce greenhouse gas emissions. Vietnam's provinces and cities have created their climate action plans and programs to address local sources of greenhouse gas emissions in addition to the country's efforts. To effectively execute ambitious GHG reduction initiatives, there are still obstacles to overcome, such as the need for improved capacity building, knowledge transfer, and financial resources. Vietnam's carbon reduction goals depend on the corporate sector, civic society, and government agencies continuing to work together. In conclusion, Vietnam's institutional structure for reducing GHG emissions reflects a thorough and cooperative strategy encompassing numerous ministries and agencies. Vietnam has demonstrated its commitment to tackling the intricate issues of climate change and supporting worldwide efforts to reduce greenhouse gas emissions through incorporating climate considerations into development planning, adherence to international agreements, and prioritization of renewable energy sources.

[4] https://www.trade.gov/country-commercial-guides/vietnam-environmental-technology (Accessed: December 22, 2023).

Table 7. List of Legislations for Environmental Protection related to the Hydropower sector in Vietnam.

Legislation/Regulation	Ministries	Description/How it Relates
Environmental Protection Law (2014) No. 55/2014/QH13	Ministry of Natural Resources and Environment (MONRE)	Provides a comprehensive legal framework for environmental protection, including principles and regulations for environmental impact assessment (EIA), planning, and natural resource management[5].
Law on Water Resources Law (2012) No: 17/2012/QH13	MONRE	Governs the management and protection of water resources, applying to hydropower projects. It aims to ensure sustainable water use while minimizing adverse environmental impacts[6].
Decree No. 120/2017/ND-CP	MONRE	Focusing on sustainable and climate-adaptive development of the Mekong Delta, which is researching and applying agro-economic models as well as new agricultural technologies to develop sustainable and climate-adaptive production systems and high-value good sectors[7].
Circular No. 27/2012/TT-BTNMT	MONRE	Offers guidance on the environmental impact assessment (EIA) process, specifying the required contents of an EIA report and procedures for approval with relevance to hydropower projects[8].
Decree No. 83/2014/ND-CP	MONRE	Specifies penalties for administrative violations in environmental protection, establishing fines and sanctions for non-compliance of conventional petroleum engine fuels and biofuels businesses[9].
Renewable Energy Development Strategy and Planning (2068/QD-TTg)	Ministry of Industry and Trade (MOIT)	Focus on renewable energy such as hydropower, wind power, solar power, biomass energy and biogas. Development is built upon resources and socioeconomic development needs and tied in with national and local resources and energy needs[10].

[5] https://faolex.fao.org/docs/pdf/vie168513.pdf (Accessed: December 22, 2023).
[6] https://waterpartnership.org.au/wp-content/uploads/2020/12/Vietnam-Law-on-Water-Resources-2012.pdf (Accessed: December 22, 2023).
[7] https://english.luatvietnam.vn/resolution-no120-nq-cp-dated-november-17-2017-of-the-government-on-sustainable-and-climate-resilient-development-of-the-mekong-river-delta-118378-doc1.html#:~:text=120%2FNQ%2DCP%20dated%20November%2017%2C%202017%20on%20sustainable,coverage%20will%20reach%20over%209%25 (Accessed: December 22, 2023).
[8] https://faolex.fao.org/docs/pdf/vie206254.pdf (Accessed: December 22, 2023).
[9] https://www.global-regulation.com/translation/vietnam/2954301/decree-83-2014-nd-cp%253a-about-petroleum-trading.html (Accessed: December 22, 2023).
[10] https://policy.asiapacificenergy.org/sites/default/files/Decision%20No.%202068-QD-TTG%20on%20Development%20Strategy%20of%20Renewable%20Energy%20of%20Vietnam%20by%202030%20with%20a%20vision%20to%202050_EN.pdf (Accessed: December 22, 2023).

8 Conclusion and Way Forward

The findings from the seven test cases hydropower reservoirs, demonstrated notable variation in GHG emissions, highlighting the necessity of tailored mitigation plans specific to their geographic and environmental settings. The results emphasized upon the critical need to consider phenomena such as land use and land cover patterns, climatic conditions, local hydrological features, and environmental settings while crafting and implementing mitigation strategies for reducing GHG emissions from hydropower reservoirs.

Vietnam can gain invaluable insights by conducting thorough scientific investigations into GHG emissions from hydropower reservoirs leveraging EO data, G-res and empirical models. Contiguous spatiotemporal datasets, including satellite imagery and other EO data, are helpful for building robust GHG emissions monitoring systems. Standardized approaches for GHG quantification from hydropower reservoirs need to be developed to enable the establishment of benchmark data. This practice enables researchers to overcome data unavailability and formulate precise mitigation strategies, which is crucial for optimizing hydropower's potential while minimizing its environmental impact.

The present report paves the way for informed decision-making and sustainable development, contributing to a commitment to reducing its carbon footprint and fostering a greener and more environmentally responsible energy sector through mitigation strategies. Collaboratively, researchers, policymakers, and local communities can devise and execute mitigation solutions congruent with climate change's aims and sustainable development. This entails ensuring the long-term viability of mitigation measures by taking the socioeconomic repercussions and embracing community input into account.

Furthermore, the creation of creative ways to lower GHG emissions from the hydropower reservoirs depends heavily on investments in research and technology. Reforestation and other sustainable land management techniques are examples of nature-based solutions that can be integrated to reduce emissions and improve ecosystem health. Advancing renewable energy sources and creating low-carbon energy substitutes can also support reservoir management's overall sustainability. This research yields policy insights that emphasize the need for strengthening the policies pertaining to cleaners’ renewable energy, emission standards, and environmental protection initiatives to achieve the SDGs.

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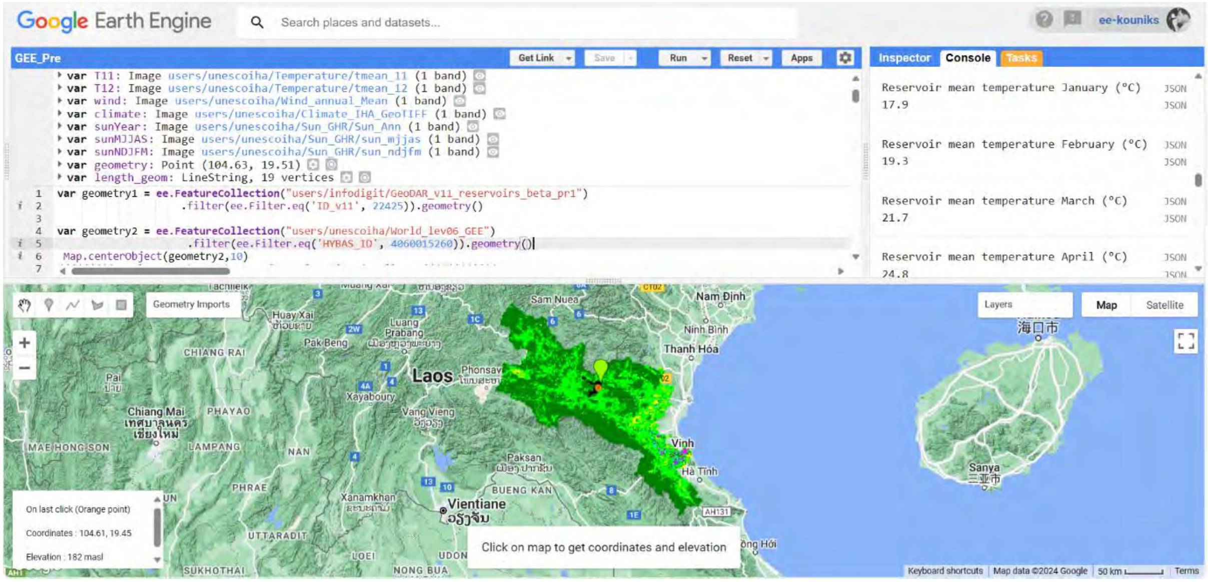
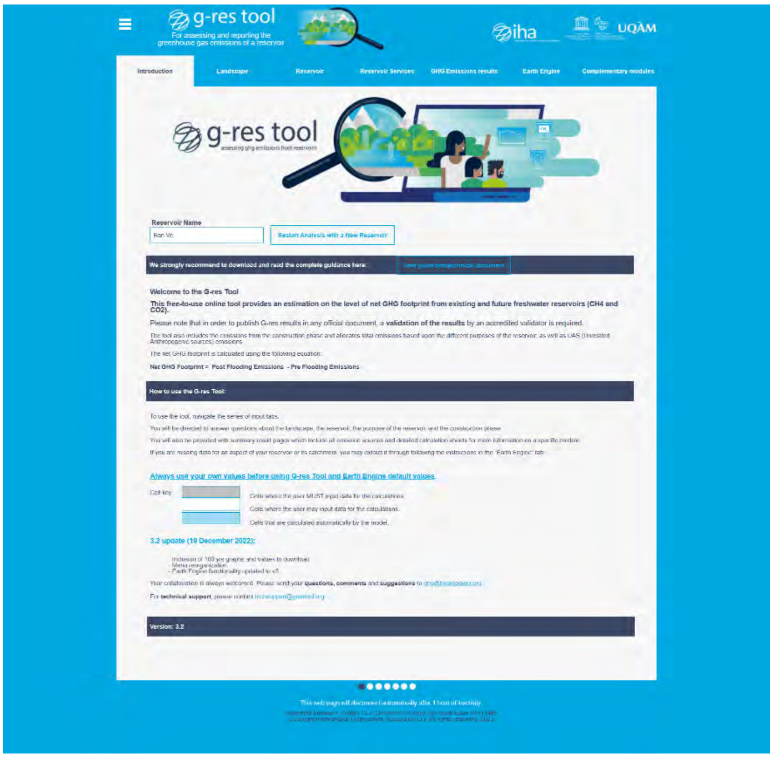
Annex 1

AI.1. Ban Ve

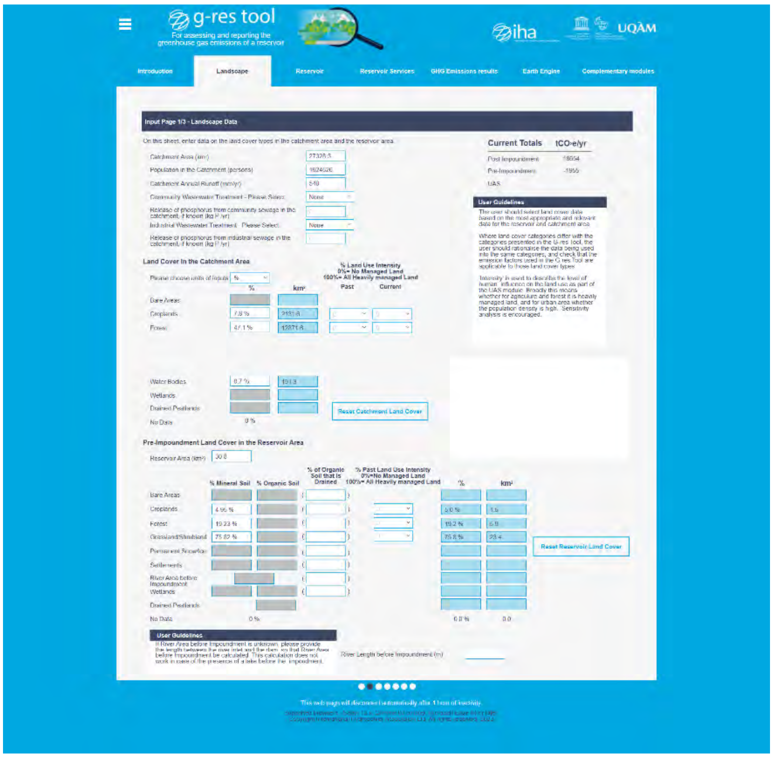
GEE Code for extracting mandatory input parameters.



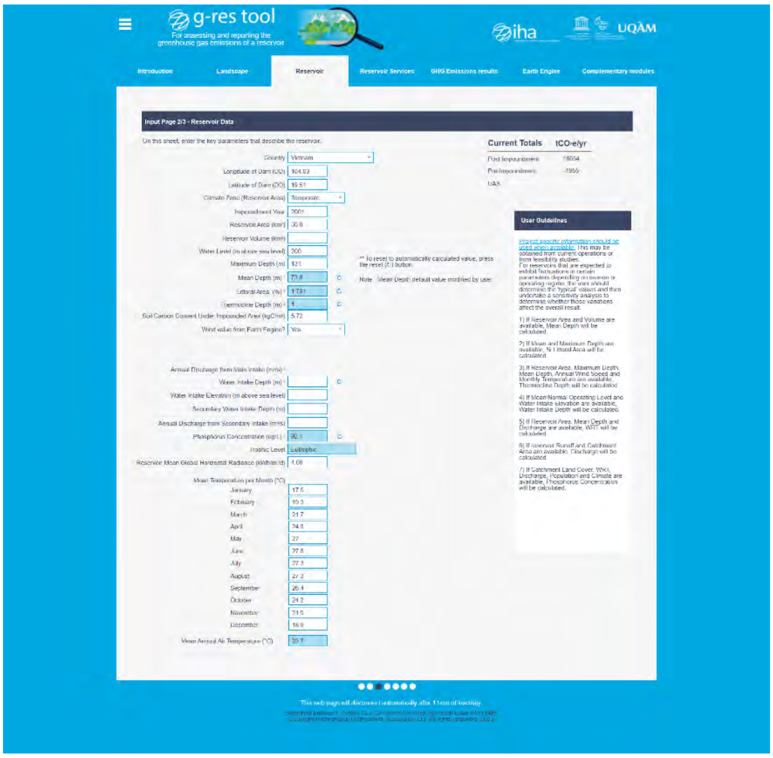
G-res Interface



Reservoir Details



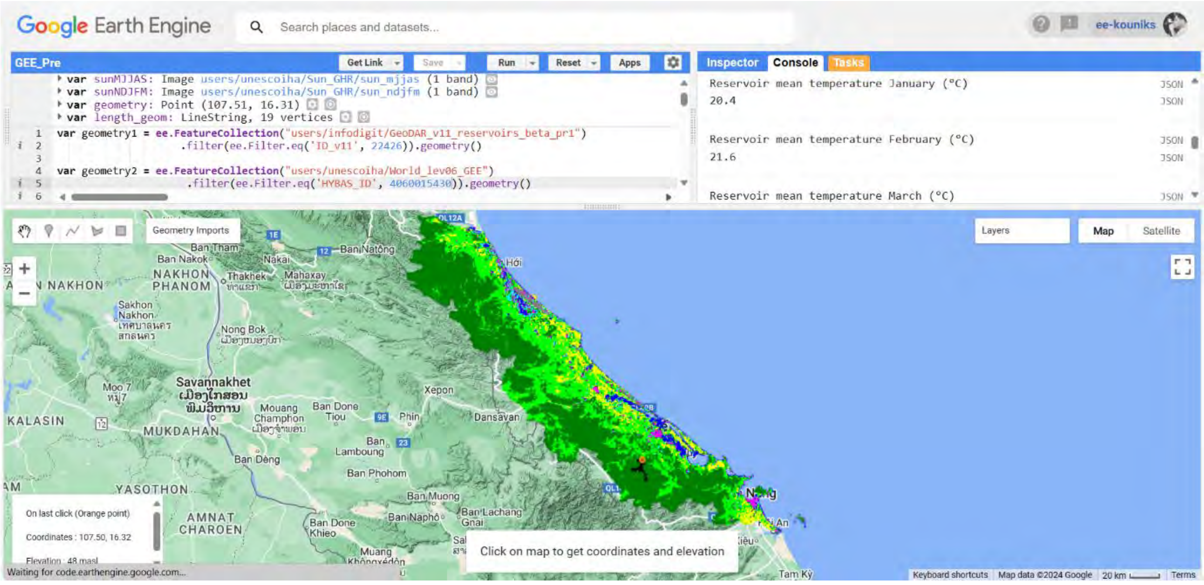
Catchment Details



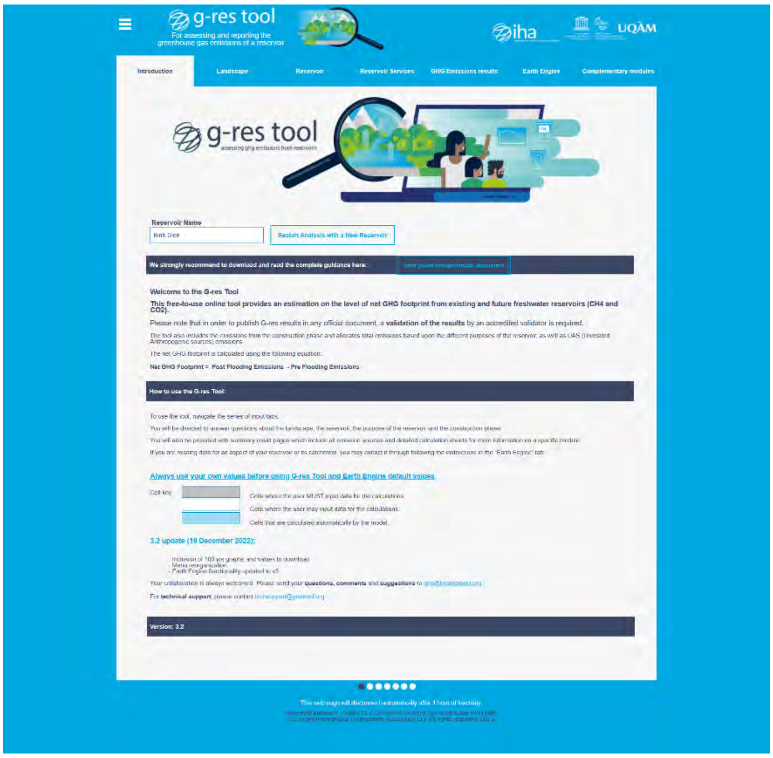
Estimated Emission

AI.2. Binh Dien

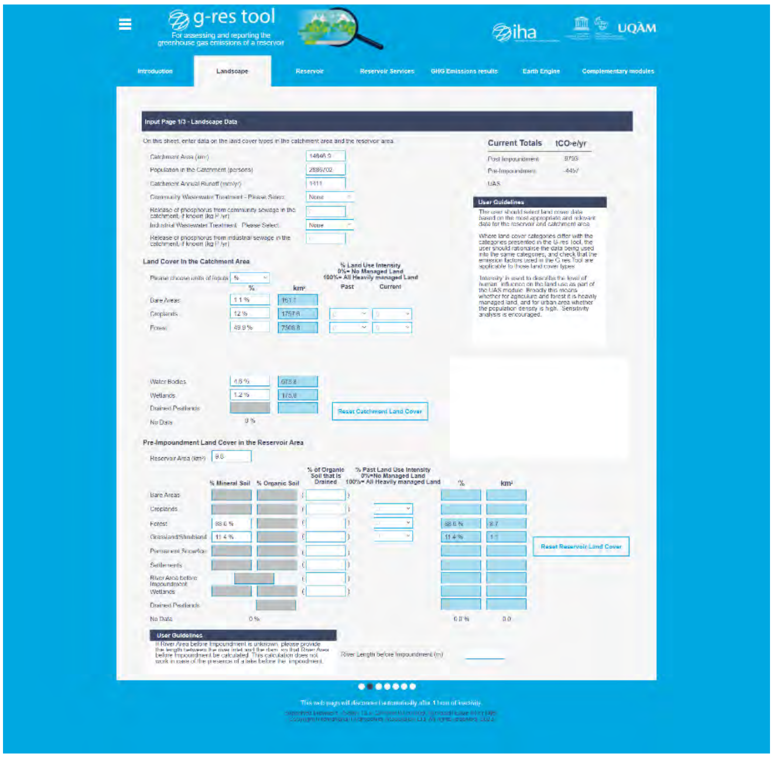
GEE Code for extracting mandatory input parameters.



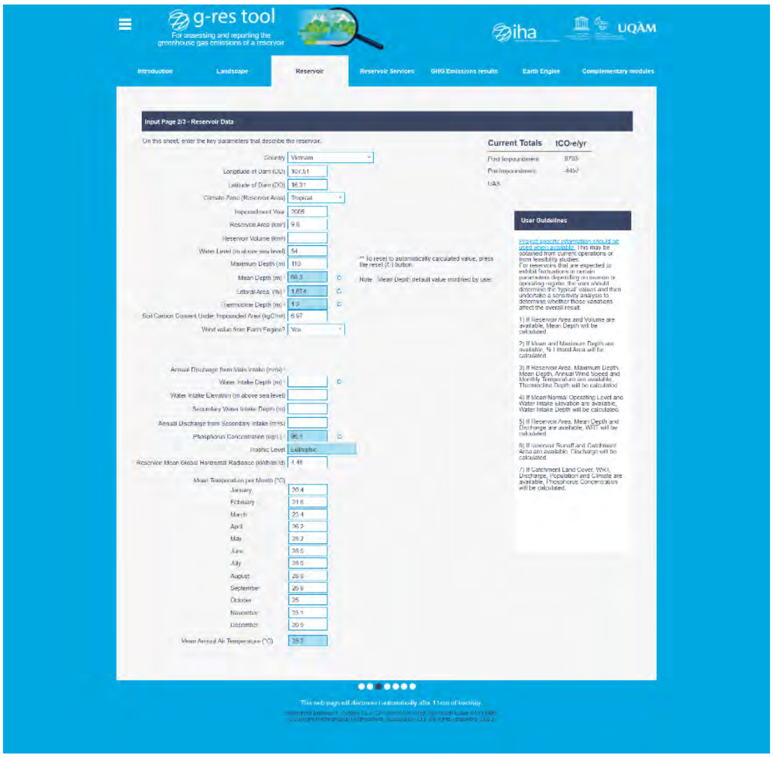
G-res Interface



Reservoir Details



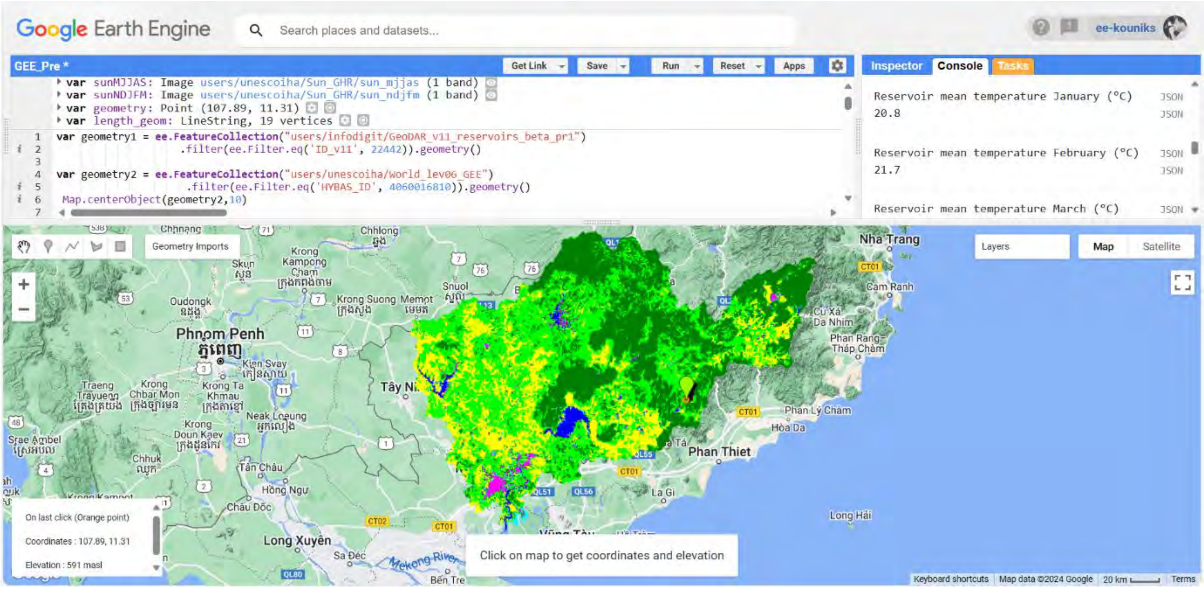
Catchment Details



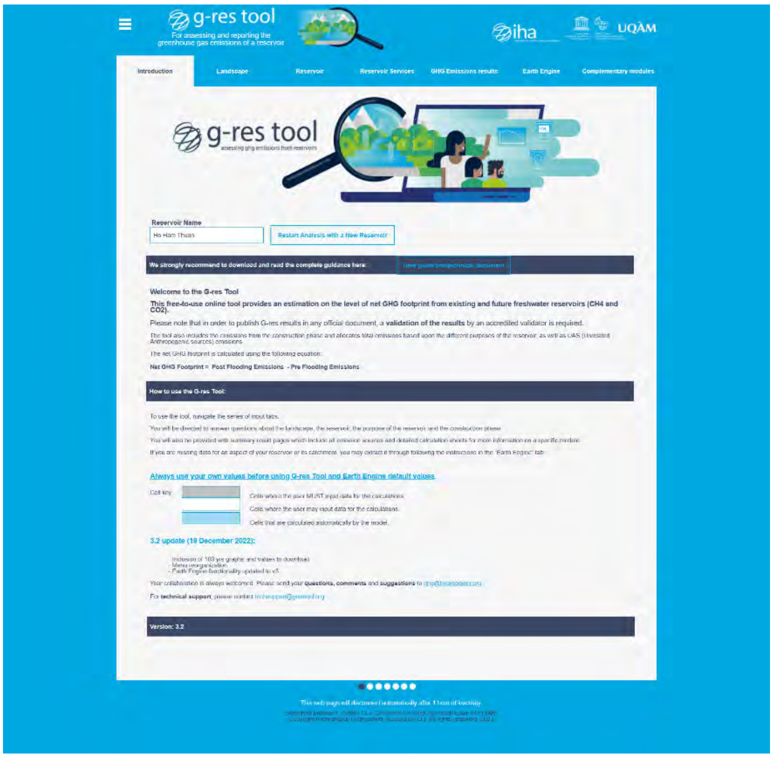
Estimated Emission

AI.3. Ho Ham Thuan

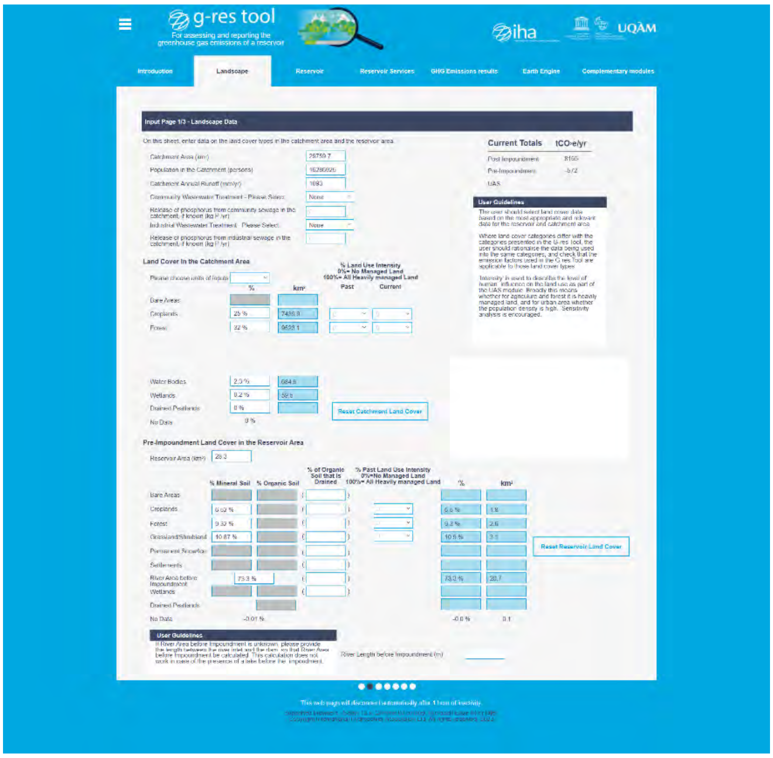
GEE Code for extracting mandatory input parameters.



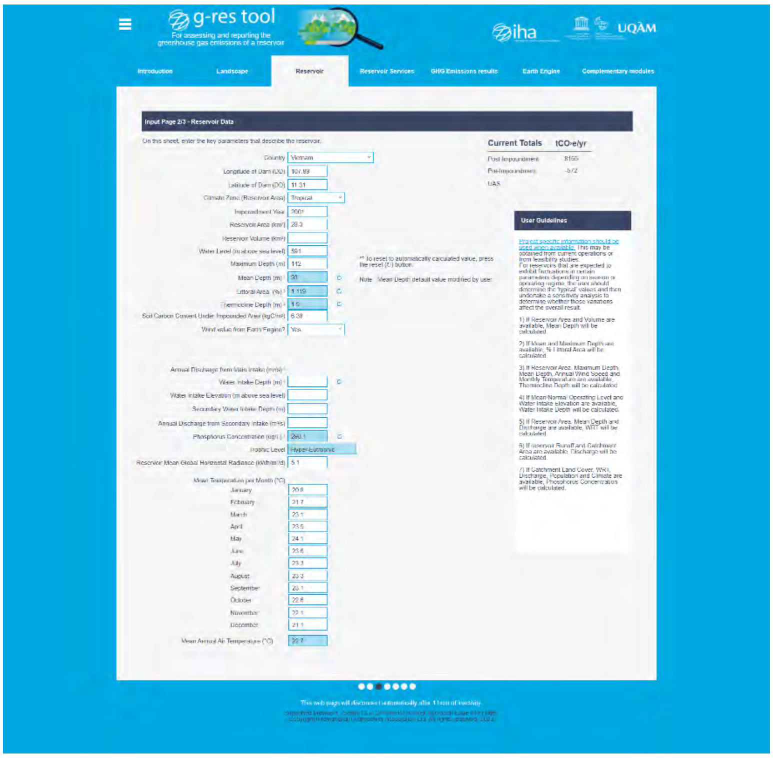
G-res Interface



Reservoir Details



Catchment Details



Estimated Emission

AI.4. Ho Hoa Binh

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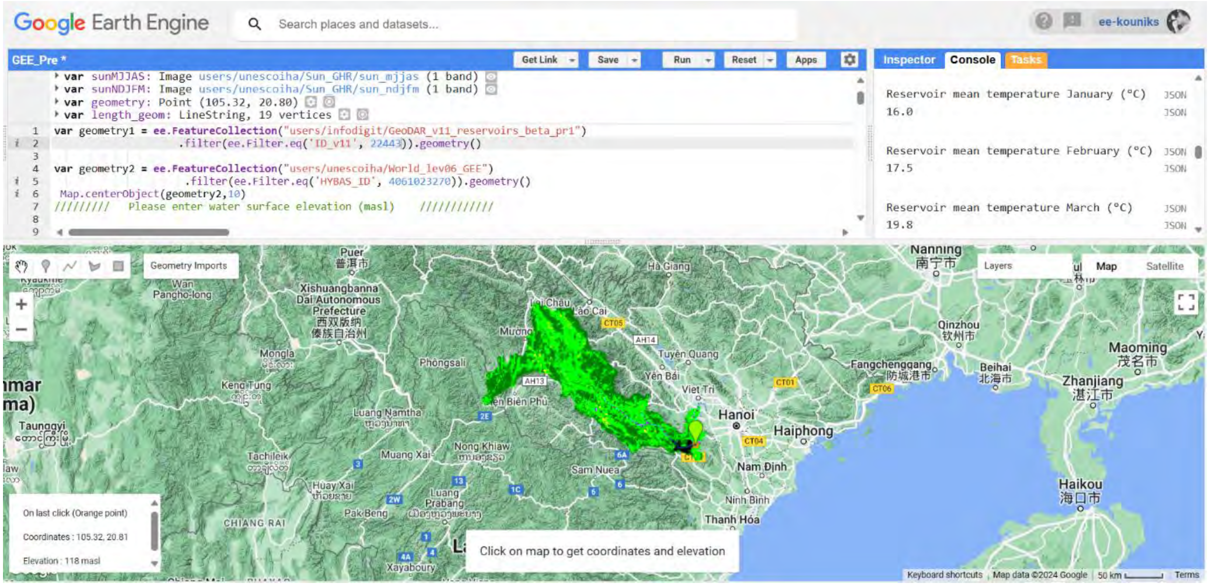

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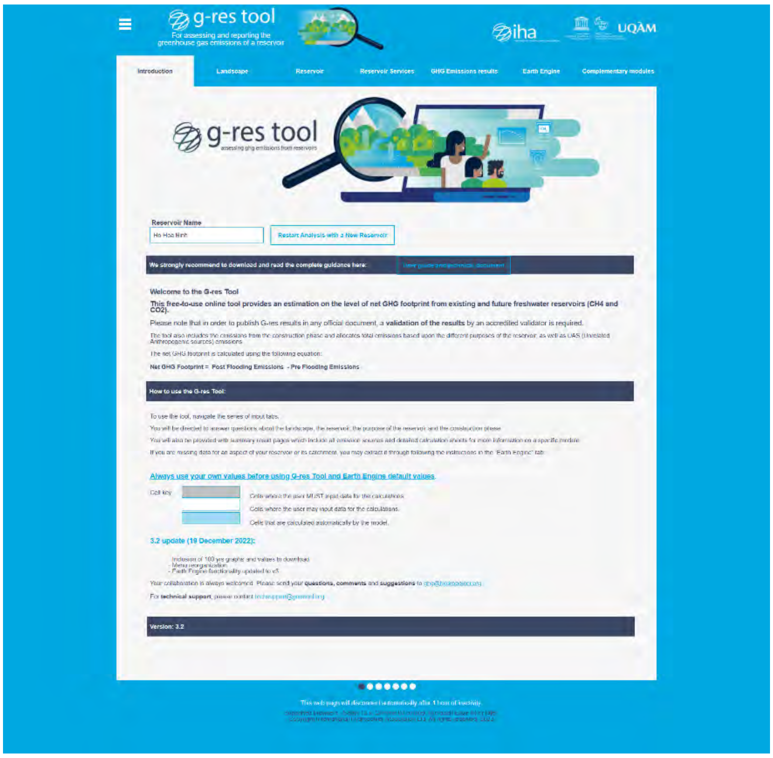

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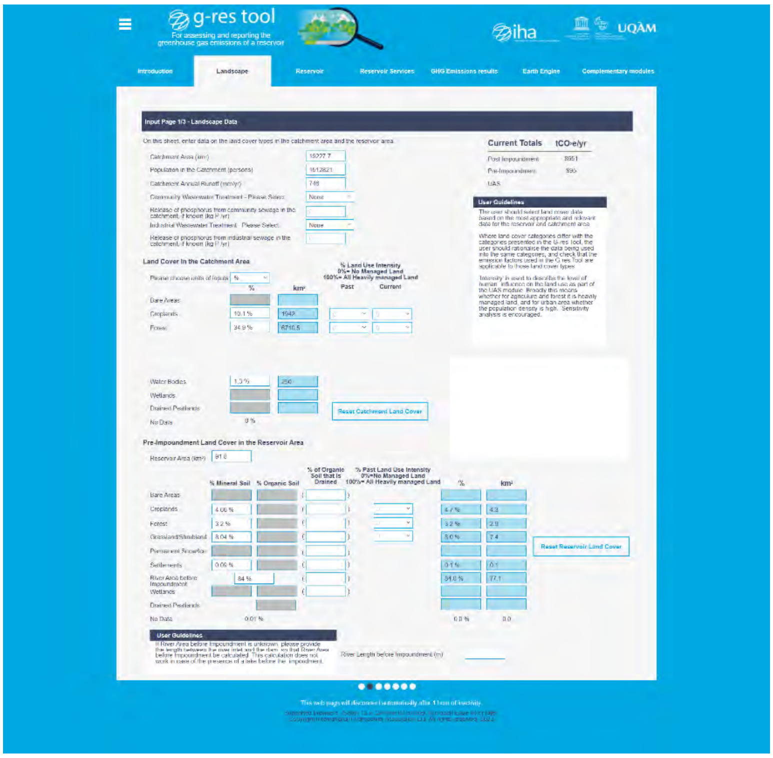

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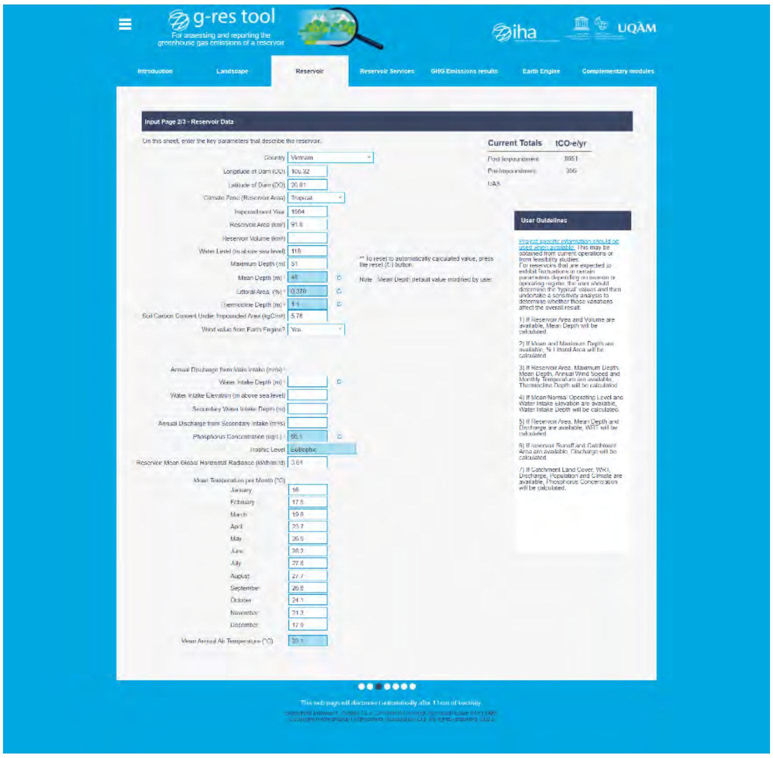
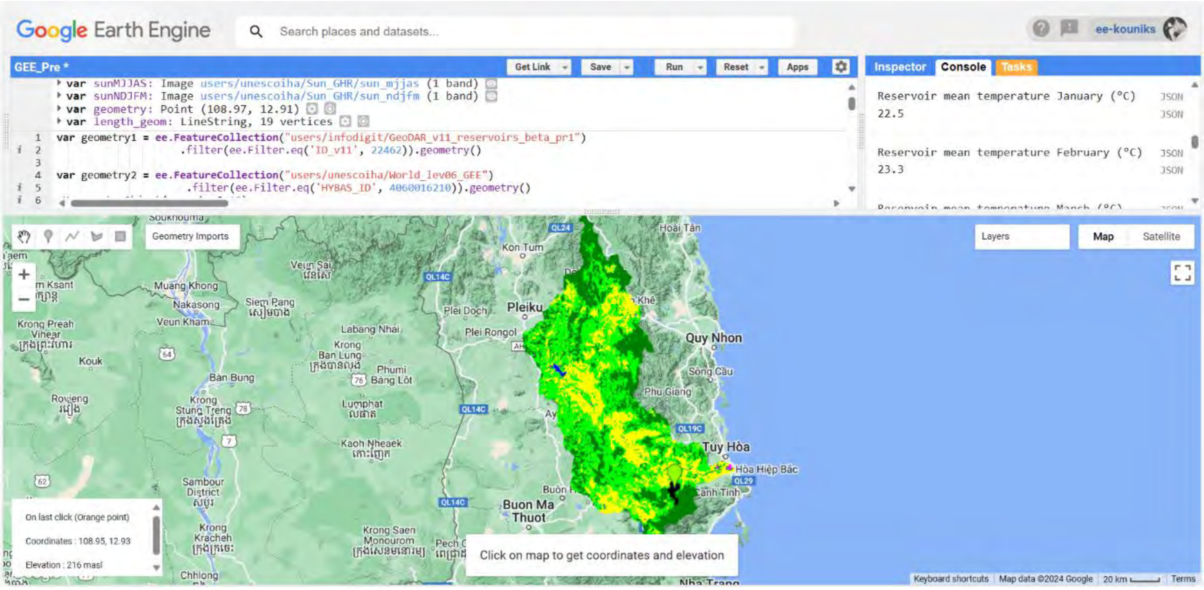


Estimated Emission

AI.5. Ho Song Hinh

GEE Code for extracting mandatory input parameters.



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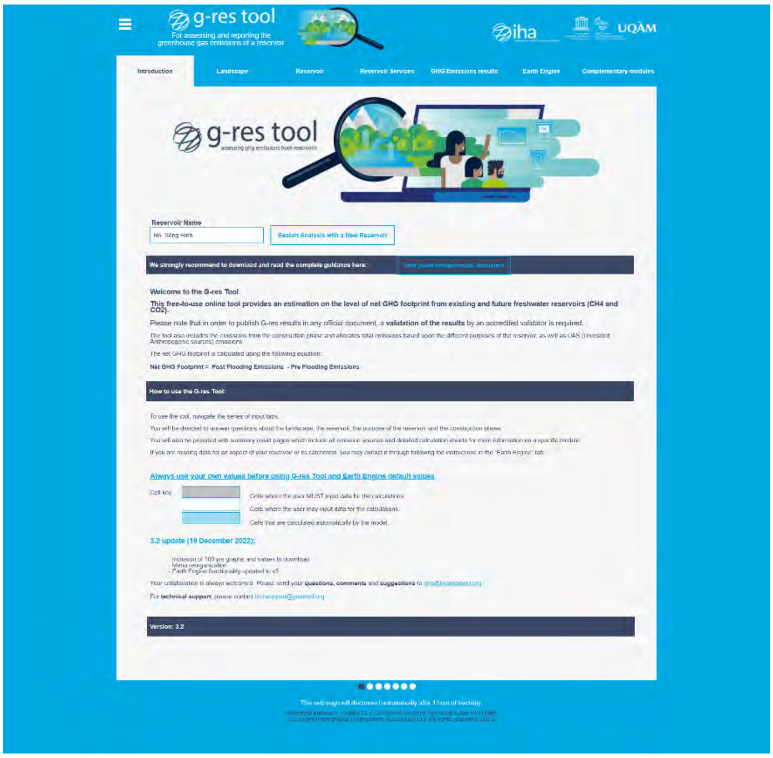

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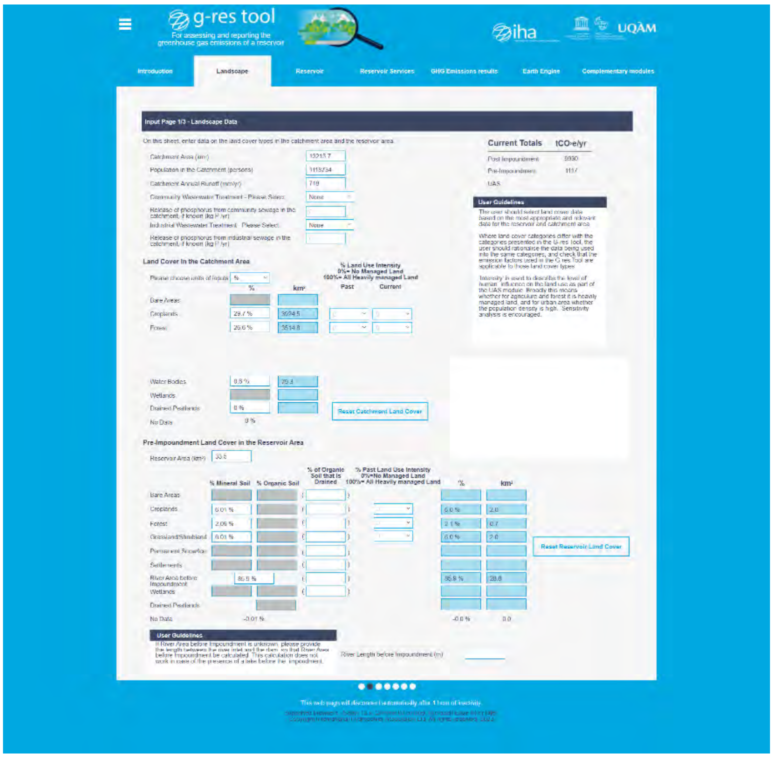

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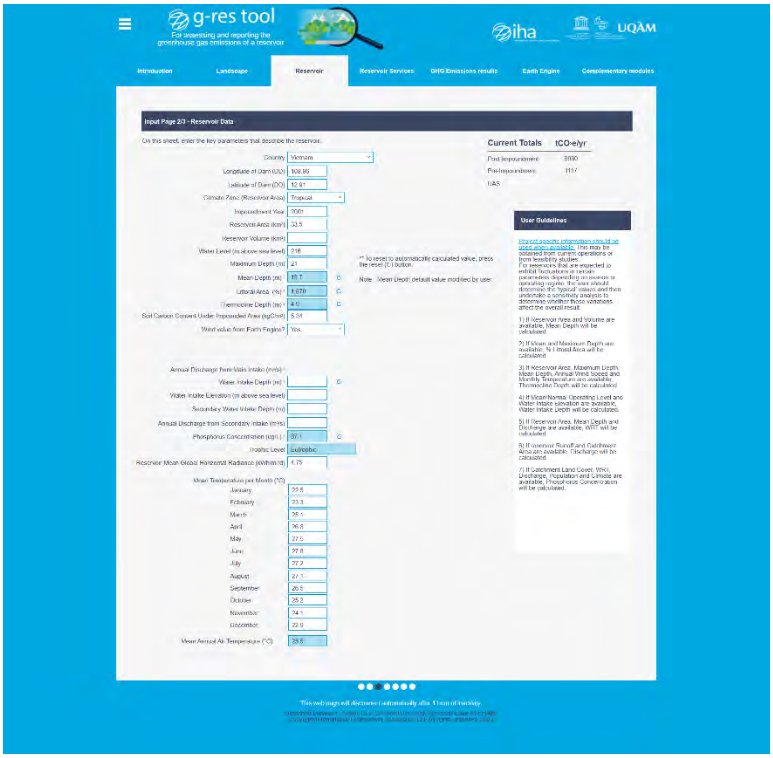
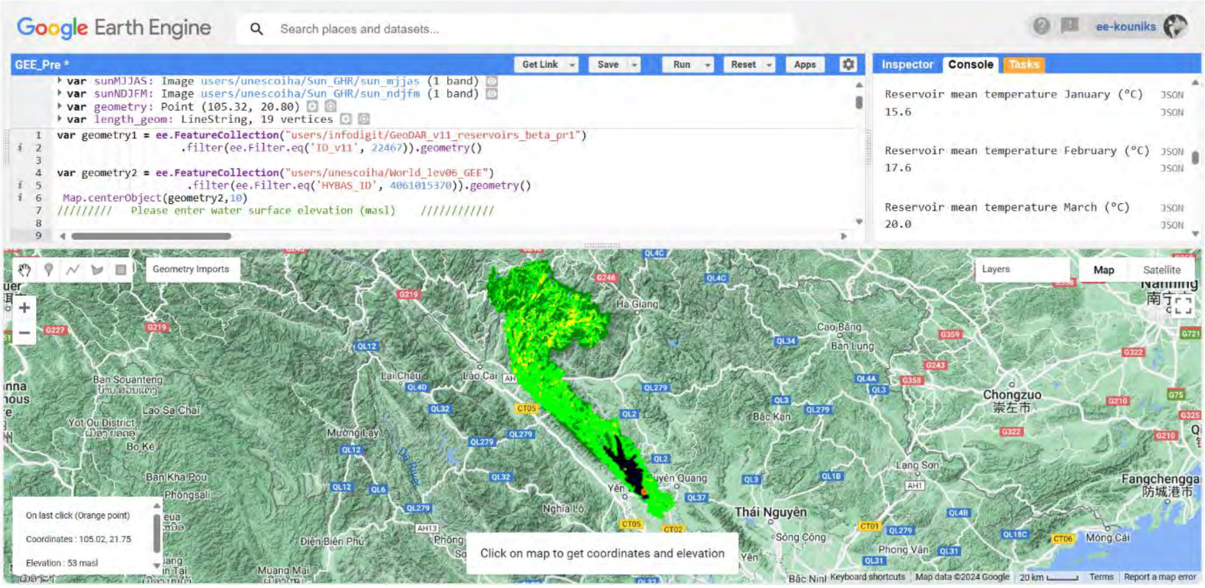


Estimated Emission

AI.6. Thac Ba

GEE Code for extracting mandatory input parameters.



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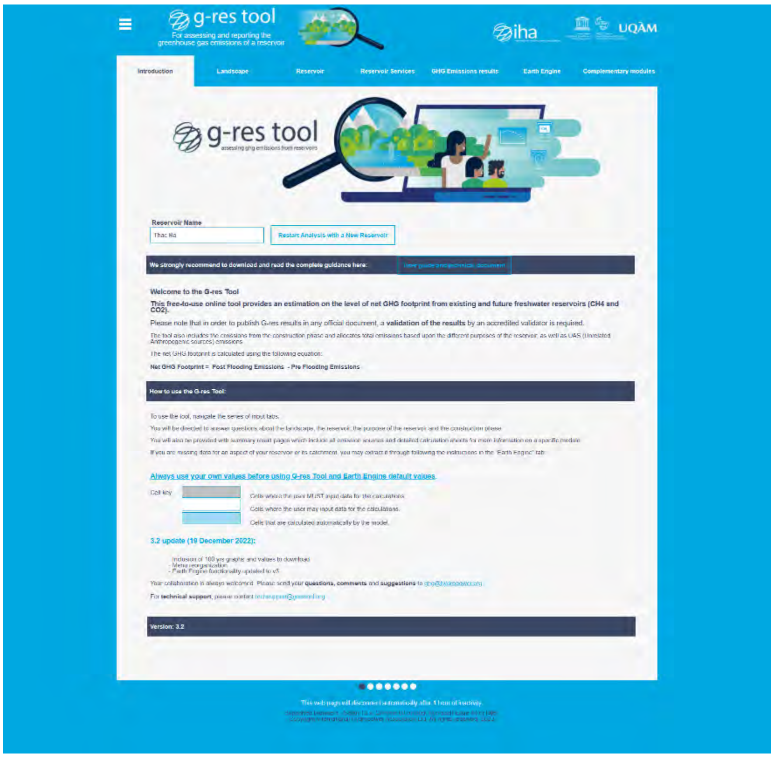

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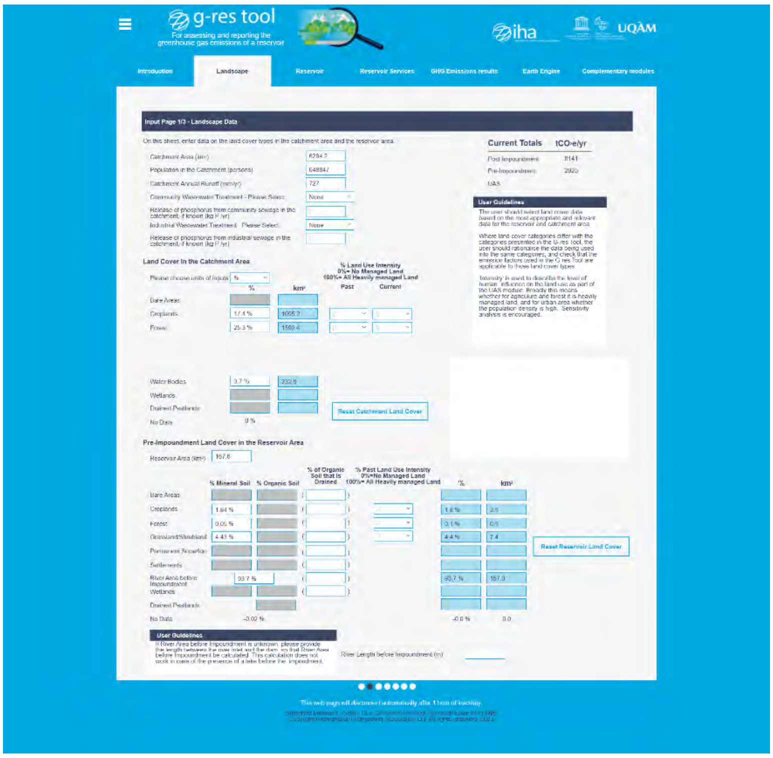

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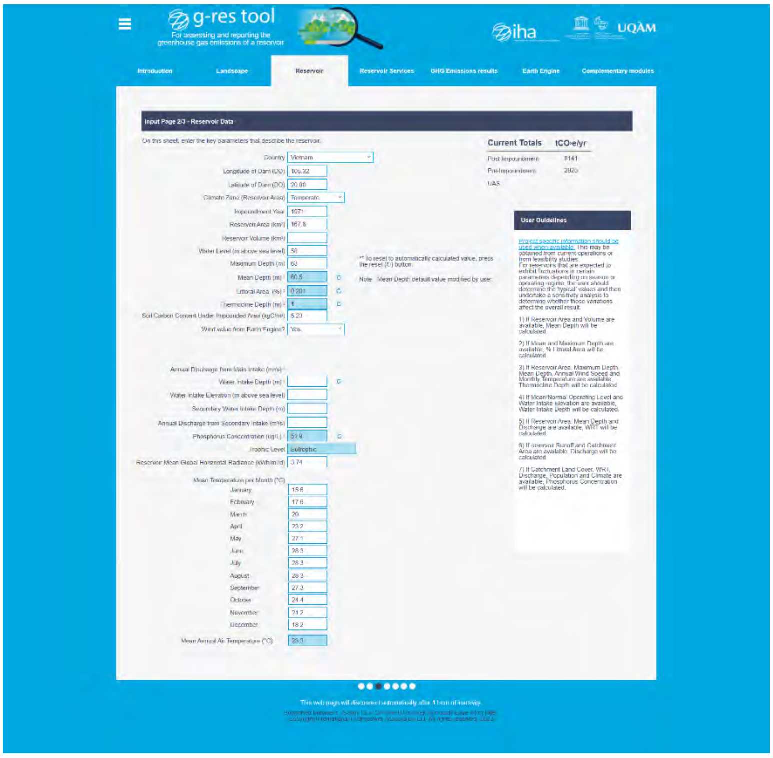
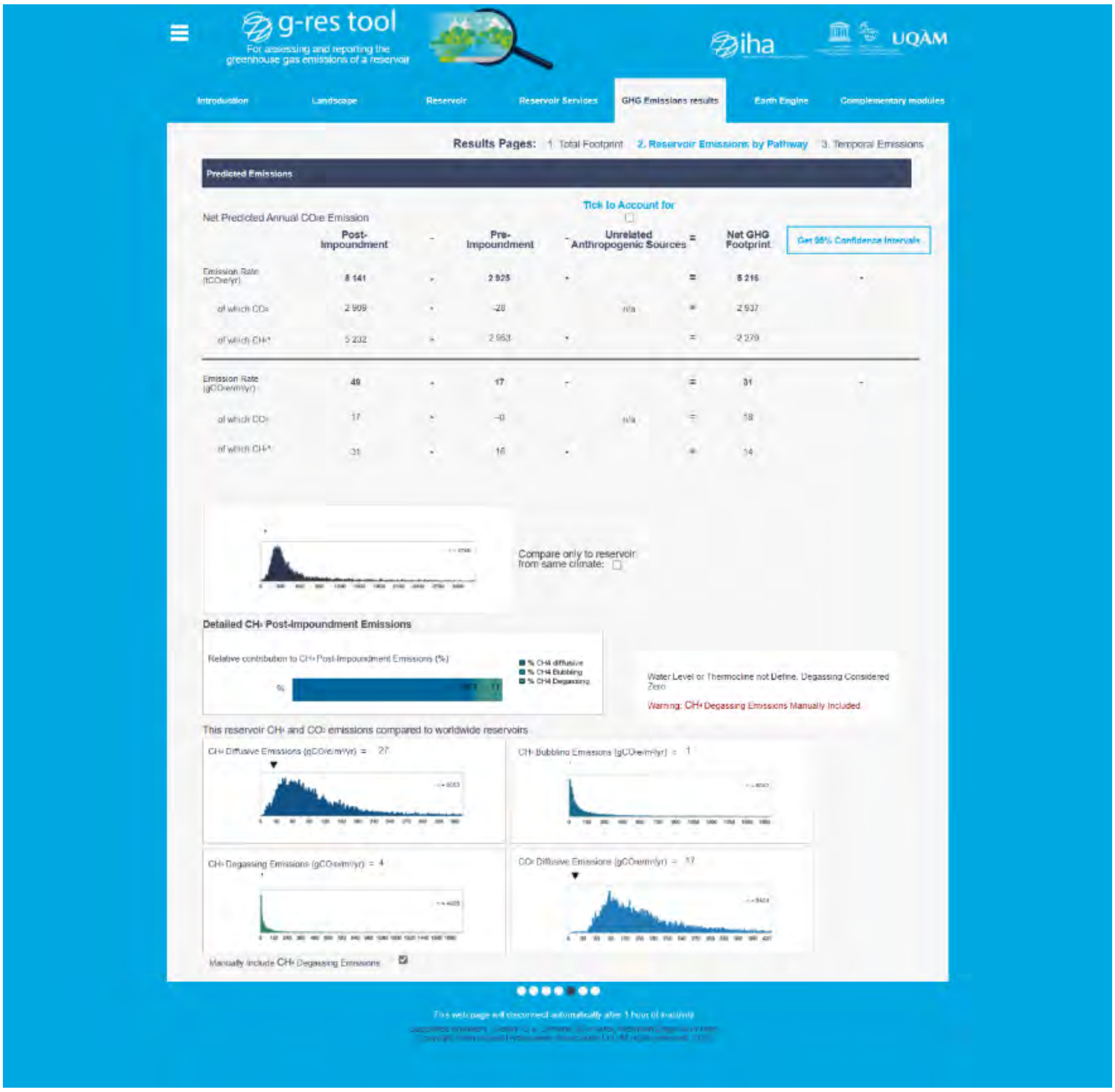
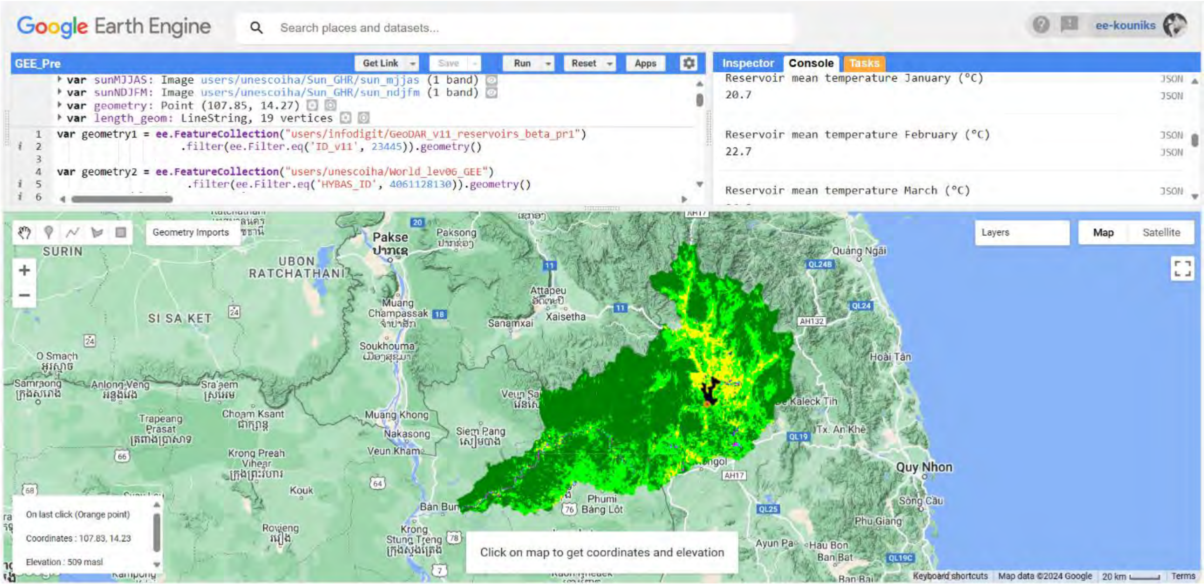


Estimated Emission



AI.7. Yali

GEE Code for extracting mandatory input parameters.



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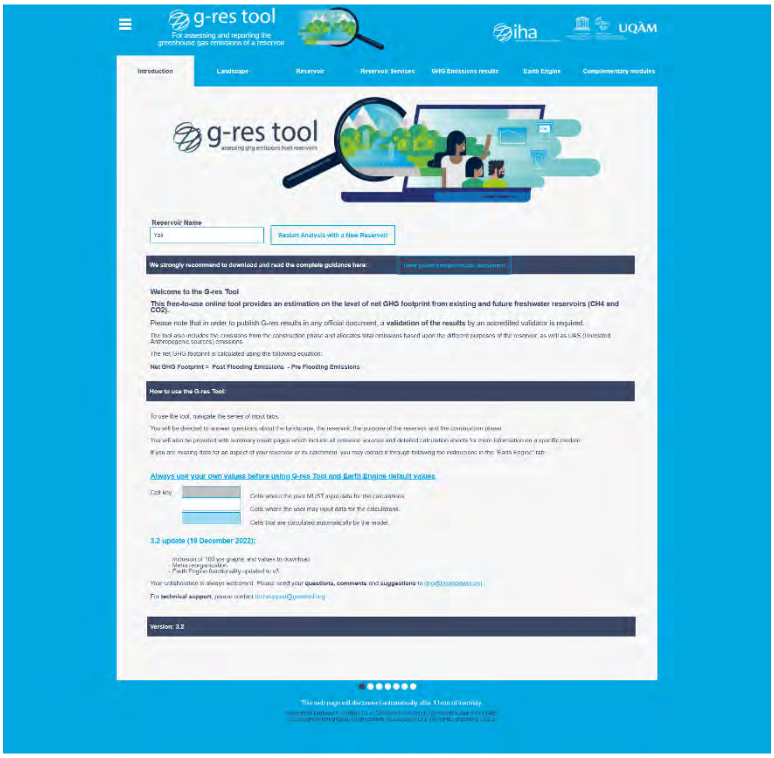

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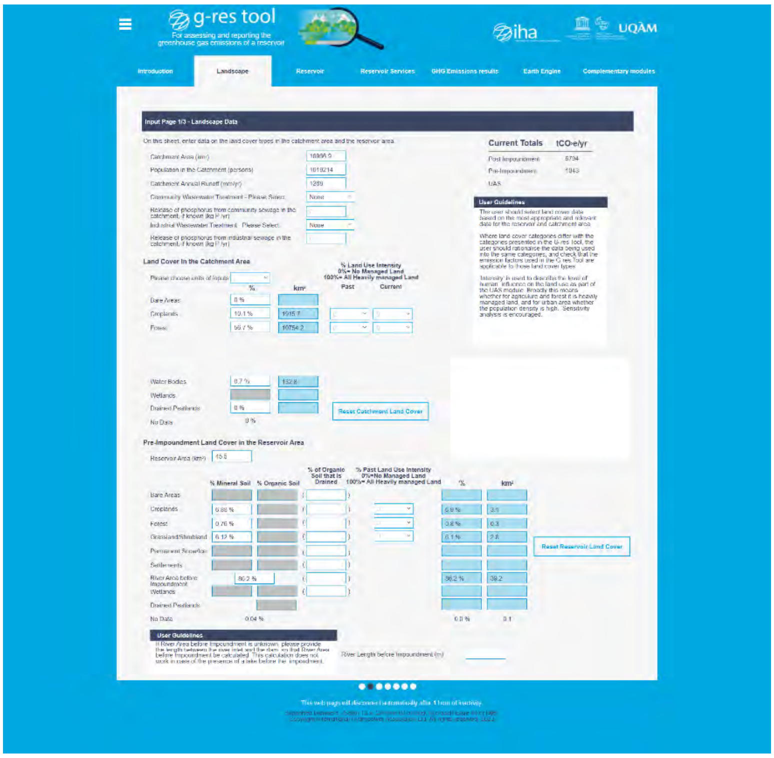
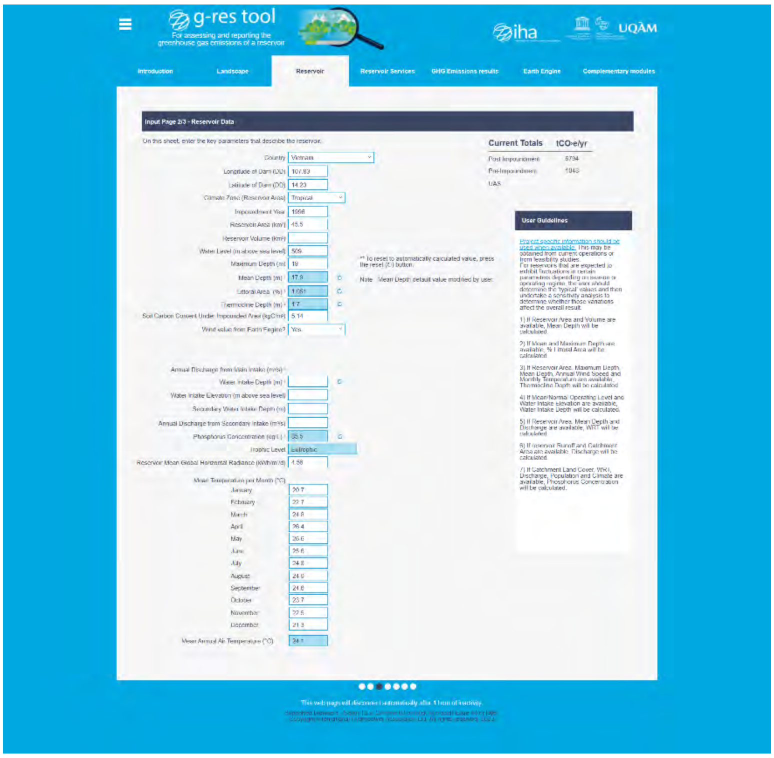


Catchment Details



Estimated Emission

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