The Global Lakes Explorer: A basin-to-global scale data visualisation application for the assessment of nutrient emissions to lakes

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Abstract:

Phosphorus and nitrogen are critical plant nutrients, essential for fertiliser production and global food security. However, poor management across the anthropogenic nutrient cycles leads to losses associated with pollution of water bodies, driving eutrophication, biodiversity loss, and methane emissions. Addressing these interconnected challenges requires a sustainable, integral, and where possible, circular approach across the entire nutrient cycle. However, data on phosphorus and nitrogen emissions and impacts are fragmented across sectors and lack standardisation. Here, we introduce a new open-access web-based application: the 'Global Lakes Explorer', which harmonises phosphorus and nitrogen emissions data alongside socio-economic and biodiversity risk factors spanning over 50 variables from multiple open data sources, covering more than 40,000 lake catchments worldwide. It enables users to visualise and download information on nutrient emissions across sectors, including agriculture, aquaculture, and wastewater, alongside socio-economic and environmental indicators. The app supports integrated governance on sustainable nutrient management in lake catchments by providing hindcasted emission data (1970-2015) in addition to future scenarios relating to shared socio-economic pathways (2015–2070) under various development projections. In this paper, we present several potential use cases for the app, including scenarios in which stakeholders can visualise and download forecasted nutrient emissions for their lake catchment of choice. This open access tool is intended to help identify potential nutrient pollution risk areas, support national governments in targeting efforts where they can have the greatest impact, and provide a foundation for more informed, collaborative, and context-specific nutrient management strategies.

Keywords:

modelling, nutrients, eutrophication, circular economy, freshwater, sustainable development, phosphorus, nitrogen

1. Introduction

Phosphorus and nitrogen play essential roles in the biological functioning of all living organisms, and our dependence on phosphate and nitrogen fertilisers underpins and sustains global food production (Cordell & White, 2014). However, poor management across agriculture, aquaculture, and wastewater systems can result in phosphorus losses to water bodies (Beusen et al., 2016a; Chen & Graedel, 2016), driving eutrophication, biodiversity loss (WWF, 2025), and methane emissions via increased prevalence of anoxic environments (Beaulieu et al., 2019; WWQA Ecosystems, 2023). Likewise, nitrogen from atmospheric deposition, agriculture, wastewater, and industrial sources also accumulates in lakes, compounding eutrophication pressures alongside phosphorus inputs (Bergström & Jansson, 2006; Gao et al., 2020; Mccrackin & Elser, 2010). Safe nutrient thresholds have already been exceeded globally, albeit heterogeneously (Carpenter & Bennett, 2011; Fanning & Raworth, 2025; Rockström et al., 2009). Unsustainable nutrient management has contributed to an 84% decline in freshwater species populations since 1970 and placing over a quarter of these species at risk of extinction (Sayer et al., 2025). The recovery of these freshwater ecosystems can be slow, non-linear, and incomplete (Jeppesen et al., 2017; McCrackin et al., 2017a). Harm to freshwater ecosystems can also result in reduced drinking water quality, property devaluation, and decreased tourism (Darwall et al., 2018; Janssen et al., 2021; Mishra, 2023; Overmyer et al., 2005; Wolf & Klaiber, 2017). Meanwhile, nutrient pollution from terrestrial environments to marine ecosystems can create widespread instances of eutrophication and the creation of anoxic dead-zones (Kirchman, 2021). Global demands for fertilisers can be more sustainably met through a transition to circular nutrient trade and usage systems where nutrient use is optimised and losses minimised and recycled for food production (Brownlie et al., 2021). In the absence of coordinated, cross-sector and transdisciplinary action, we run the risk of jeopardising the global food security and environmental goals. These include global objectives such as the Convention on Biological Diversity Kunming-Montreal Global Biodiversity Framework Target 7 to reduce nutrient losses by 50% by 2030 and Target 2 to bring 30% of degraded ecosystems under restoration by 2030 (Cordell & White, 2014; Gerten et al., 2020; Scholz & Wellmer, 2013; Springmann et al., 2018), in addition to emerging indicators and global assessment tools (Möhring et al., 2023).

The identification and management of pollution risks related to nutrient loading can be hindered by fragmented data on nutrient emissions, nutrient use efficiency, and their corresponding environmental impacts (Brownlie et al., 2022; Cordell & White, 2014; Darwall et al., 2018). Several valuable datasets exist, including the IMAGE-GNM nutrient loading models (Beusen et al., 2015), global fertiliser trade values (Chatham House, 2021), and HydroATLAS lake and basin hydrological characteristics (Linke et al., 2019). However, these resources currently lack spatial integration and harmonisation (Jwaideh et al., 2022). Data fragmentation can, in turn, contribute to disjointed policy development and can impede collaborative efforts towards sustainable nutrient management, for example, by increasing the risk of 'pollution swapping' between sectors (Halpern et al., 2022; MacDonald et al., 2011). There is therefore an opportunity to align these currently unharmonised datasets to visualise nutrient dynamics across sectors and across space, which would in turn allow us to identify nutrient resource hotspots and deficits on a global level. Through a coordinated integration of pre-existing data streams, we can enhance our collective ability to address knowledge gaps and reach global sustainability goals.

To address the specific challenges outlined, we collected and harmonised data from a variety of open-access databases spanning multiple temporal and spatial resolutions and have displayed them on a basemap to allow users to explore their variables of choice across global hydrological basins, countries, and individual lake catchments. We have aggregated data to both the resolution of lake catchments, and to larger Level 3 HydroBASINS which represent standardised hydrological units that delineate drainage areas based on river network topology and watershed boundaries (Linke et al., 2019). This offers a highly informative and spatially relevant summarisation of data that will be relevant to a range of academic, industry, and lay-users. Users can download data from the interface for use in their own analyses. The core objective of this app is to visualise cross-sector nutrient emissions and their impacts at a global scale by bringing existing datasets together and re-aggregating existing data to hydrologically meaningful spatial units for the benefit of the wider community of researchers, lake restoration practitioners, and governmental policymakers. We have aligned the app with key international biodiversity and sustainability frameworks such as the Global Biodiversity Framework (e.g. GBF Targets 2 and 7) and the UN Sustainable Development Goals (SDGs). Here, we describe the data included in the app, explain the functionality of the interface, present a potential use-case example, and discuss possible research and industry questions that could be addressed using this product.

2. Data and Methods

We developed the Global Lakes Explorer to support evidence-based decision-making by providing open access to harmonised, policy-relevant data on cross-sector phosphorus and nitrogen use, environmental pressures, and global trade and management indicators. We designed the app based on scientific robustness and user accessibility to ensure the platform is intuitive for a wide range of stakeholders, including researchers, policymakers, and practitioners in various agricultural sectors. We developed the app using the Shiny Golem framework in R (Fay et al., 2021), and full version control was maintained via a GitHub repository. The sections below outline and justify our methods for spatial resolution, data selection, app functionality, quality assurance, and evaluation.

2.1) Spatial resolution

BasinATLAS is a dataset of polygon layers that depict sub-basin hydrological boundaries at a global scale (HydroBASINS), enhanced with a global compendium of hydro-environmental characteristics (HydroATLAS) (Linke et al., 2019). These sub-basins have 12 spatial scales, ranging from coarse resolution (level 1) to fine resolution (level 12). Level 3 vectorised polygons were selected as our foundational spatial unit for displaying all variables at a global scale, conveying ~country-level information without using (potentially contestable) geopolitically defined national borders. The Level 3 BasinATLAS polygons have 56 associated variables (hydrology, physiography, climate, land cover, soils, geology, and anthropogenic), across 281 unique polygons, available at all levels, including source data and citations.

To display lakes and catchments on the app, we utilised the newly published Lake TopoCat (Sikder et al., 2023) dataset, a global lake drainage topology and catchment database. Lake TopoCat identifies ~ 1.46 million outlets for ~ 1.43 million lakes larger than 10 ha and delineates 77.5×106 km^2 of lake catchments covering 57% of the Earth's landmass excluding Antarctica. We used these data to 1) extract lake names and geometries for all lakes over 250 hectares (>40,000 globally), and 2) extract the geometries of the lake catchments all selected lakes.

2.2) Data selection

To display the magnitude of phosphorus and nitrogen usage across nutrient input types (e.g. groundwater, surface run-off) and across a variety of nutrient-emitting sectors, we used data from IMAGE-GNM (Integrated Model to Assess the Global Environment-Global Nutrient Model, Beusen et al., 2015, 2016b, 2022) and extracted the following variables: P and N loads from surface and groundwater runoff from natural and agricultural land, P and N loads from weathering reaching surface water, P and N loads from allochthonous organic matter inputs to rivers, P and N loads from aquaculture and waste-water (sewage) to surface waters. These variables can be displayed on the Map Explorer via a drop-down menu entitled 'Nutrient Data' on the main app at the HydroBASIN level 3 spatial resolution. Each of these variables covers the time period 1970 - 2070 (in 5-year time increments), with any year beyond 2015 representing projections based on five Shared Socio-Economic Pathways (SSPs) (Kriegler et al., 2014; O'Neill et al., 2016), which are globally standardised scenarios describing alternative trajectories of future socio-economic development and associated environmental pressures: SSP1 (Sustainability), SSP2 (Middle of the road), SSP3 (Regional rivalry), SSP4 (Inequality) and SSP5 (Fossil-fuelled development). NetCDF files from IMAGE-GNM were extracted into per-SSP / per-variable aggregated TIFFs and analysed individually using the selected hydrological catchments defined in Lake TopoCat. Mean (per area) catchment nutrient values were calculated based on area-weighted apportioned values from the underlying IMAGE-GNM data, then the mean values were used to calculate total values for the catchment using its area. The data is available to download at the catchment-level when the user selects a lake catchment and downloads the automatically generated CSV.

To make the Global Lakes Explorer policy-relevant, we display variables that are indicators of the Global Biodiversity Framework (GBF) Targets 2 and 7. Each GBF Target has "headline indicators", "component indicators", and "complementary indicators" as identified by the monitoring framework for the Kunming Montreal Global Biodiversity Framework (UNCBD, 2022). Using these GBF indicators as a theoretical basis, corresponding indicators from within our starting dataset (BasinATLAS) and/or freely available datasets can be selected.

GBF Target 2 is defined as 'Restore 30% of all Degraded Ecosystems' and focuses on ensuring protection and restoration for 30% of all degraded terrestrial, inland water, coastal and marine ecosystems. These ecosystems have all undergone significant habitat loss within the last century (e.g. 87% habitat loss in wetlands over the last 300 years [Davidson, 2014]), and the target is supported by indicators such as Area Under Restoration, extent and type of ecosystem, connectivity of ecosystems, and can be complemented by a variety of external indices including on biodiversity health, land use, species richness, and tree cover (CBD, 2025a). We extracted the following HydroATLAS variables to represent GBF Target 2 in the app: natural discharge, land surface runoff (Doll et al., 2003), global aridity index (Zomer et al., 2022), land cover classes and extent (Bartholomé & Belward, 2005), wetland type classes and extent (Lehner & Döll, 2004), and protected area extent (Deguignet et al., n.d.). These variables can be displayed on the Map Explorer via a drop-down menu entitled 'Ecosystem Data' on the main app at the HydroBASIN level 3 spatial resolution. They are also available to download at the catchment-level when the user selects a lake catchment and downloads the automatically generated CSV.

GBF Target 7 is defined as 'Reduce Pollution to Levels That Are Not Harmful to Biodiversity' and focuses on reducing risk of pollution to biodiversity and ecosystem functions by more sustainably managing nutrient use while also ensuring food security and livelihoods. This target specifically explores the polluting effects of mismanagement of phosphorus and nitrogen, aiming to reduce excess nutrients lost to ecosystems, making use of indices such as the Index of Coastal Eutrophication Potential, fertiliser flow, and trends in nutrient use and loss across sectors (CBD, 2025b). Variables related to this target were extracted from global open-source databases with strong spatial coverage, and included:

phosphate fertiliser imports and exports in tonnes by country (Chatham House, 2021), Chlorophyll-*a* remote sensing anomalies (UN SDG Goal 14), phosphorus and nitrogen use efficiency (Ludemann et al., 2024), and population density (CIESIN, 2025a). These variables are available for download on a tab entitled 'Socio-economic variables' and can be visualized in spatial polygons representing UN defined country borders (United Nations Geospatial, 2025). Full metadata for all data sources used in the app can be viewed in **Table S1**.

2.3) App functionality

The landing page of the app (Tab 1: 'Map Explorer') includes a large Leaflet basemap (Cheng, 2019). Users can click anywhere on the base map to display the lake polygons from the LakeTopoCat database, within their respective level 3 HydroBASIN. Users can select variables from the 'Phosphorus Data', 'Nitrogen Data' or 'Environmental Data' dropdown menus to display their selected data in the form of a choropleth map on the Leaflet object, at the HydroBASIN level 3 resolution. Each of the variables in the 'Nutrient Data' category can be presented at any time-point between 1970 and 2070, and at any SSP projection, as determined by a year slide and projection selection tool on the map. When a variable is displayed, pop-ups are generated in the corners of the map containing information on data references, legends, and units.

When a user clicks into the map (either with or without a variable selected from the dropdown menu), the lakes within the selected level 3 HydroBASIN appear on the map as defined by their geometries from the Lake TopoCat data. When a user clicks on one of these lakes, a pop-up modal card appears containing a statistical fact-file about the selected lake and its corresponding catchment. This card includes a Leaflet map showing the lake nested within the catchment, lake name, lake size, lake type, land-use class, all countries intersecting the catchment, population density (people per km^2), annual natural discharge, aridity index and Hylak ID (a unique identifier for each lake used in both the HydroATLAS and LakeTopoCat databases). Users can use a drop-down menu to view time-series projections of phosphorus and nitrogen emissions from different sectors (e.g. agriculture, cropland, pasture) from 1970-2070, following different SSPs from the year 2015 onwards. The y axis of this graph can be displayed as total values across the catchment, relative % values across sectors, or average values per km^2/yr. Alongside these plots is a legend containing definitions of these SSPs. Users can also download the available GNM and GBF2 data in CSV format for the selected lake. Metadata files are also available to download as a Microsoft Word document.

A tab entitled 'Socio-economic data' contains a CSV download link and metadata file for all variables described under the 'GBF 7' category, which are aggregated to country-level resolution. On this tab we showcase two potential use-cases for this data. The first is an interactive leaflet map of national phosphate import and export totals, with accompanying bar charts of the top 10 global exporters and importers of phosphate fertiliser (Chatham House, 2021). The second is an interactive fact-file showing information about phosphate fertiliser trade, nutrient use efficiency, mean deprivation index (CIESIN, 2025b) and red list index (IUCN, 2025) value for each country. The user selects a country using either a drop-down menu or by selecting a country on the interactive map or bar chart and can then view these variables on a series of slider scales, which also report the maximum and minimum values globally to aide comparison between countries.

Other tabs in the app include 'About', which introduces the core objective of the upCycle project and the use-case for the app. The 'How to Use' tab hosts a link to a video tutorial explaining the functionality of the app for potential users. This tab also contains a step-by-step guide explaining how a user can explore global data, navigate to a region and lake catchment of choice, examine the statistics card, download data for their catchment and conduct their own analyses (with starter scripts provided in R and Python). The 'Data Sources' tab includes full references and copyright information, and licensing information for each of the datasets used in the app. We also describe the spatial and temporal resolution of each of the datasets, and list any variables available for download from either the lake statistics pop-up card or from the Socio-economic data tab. There is also a tab listing the full Terms and Privacy Conditions for the app.

2.4) Evaluation

We evaluated the quality of the aggregated catchment-level IMAGE-GNM P data in the Global Lakes Explorer by comparing it to observed and independently modelled phosphorus loads for Loch Leven (Scotland) and Lake Villarica (Chile; **see Appendix 1 for details**). Overall, the app captures the general magnitude of total phosphorus loads for both lakes, and the relative contributions of diffuse versus point sources are well represented. For both catchments, diffuse runoff was consistently identified as the dominant phosphorus source, while point sources such as wastewater were also reflected in the model outputs.

We qualitatively and quantitatively evaluated the user-experience of the app to ensure it was ready for public deployment. We designed an anonymous feedback form with Likert-scale questions asking users to report the ease of using the app, and whether the app was informative, intuitive and accessible. The form also includes long-format questions where users can report bugs, constructive design feedback, and issues with accessibility. This form was distributed to 10 external reviewers in October 2025, and their feedback was incorporated into the final app.

We embedded Google Analytics into the Shiny app to track user behaviour, including click origins and unprompted interactions with the interface. Regular internal reviews during the development period allowed us to identify areas needing further improvement and clarity. Once deployed, we conducted load testing to confirm that app's stability under high user volumes. Additionally, to test usability of the app, we held internal focus group 'hackathons' whereby participants independently navigated the app, downloaded data for lakes of their choice, and produced data visualisations with correct referencing.

2.5) FAIR Data Principles

The FAIR data principles - Findable, Accessible, Interoperable, and Reusable - provide a framework to digital assets to adhere to so that they can easily be discovered, understood and navigated effectively by lay users (Wilkinson et al., 2016). By adhering to FAIR principles in the design and deployment of the Global Lakes Explorer, we promote open research, ensure reproducibility and can optimise the long-term value and impact of this product. We aimed for the app to be widely accessible to a range of stakeholders spanning multiple sectors, including policymakers, environmental researchers, and agricultural industry representatives.

Findable

The Global Lakes Explorer is easily discoverable via a simple URL pathway. It is linked through multiple partner platforms including the uPcycle project website, the UKCEH website, the public uPcycle LinkedIn channel, and via the UNEP Knowledge Hubs. The tool has been promoted to key external partners and stakeholders at international meetings (e.g. the ESPP Aquaculture Meeting in Norway 2025 and the Sustainable Phosphorus Summit in Ghana 2025) to ensure targeted visibility and uptake.

Accessible

The app is designed to provide an intuitive, user-friendly interface with clear and consistent labelling of elements, embedded guidance, and a full metadata catalogue for all datasets. A video tutorial is available via the 'How to use' tab, featuring image captions, subtitles, and an accompanying transcript. The app design is colourblind-friendly, for example using 'Viridis' colour palettes (Garnier et al., 2024) in both the maps and the time-series plots. To support accessibility in low-bandwidth environments, the

Leaflet maps are optimised to minimise data load times. We have also provided example R and Python scripts in the 'How to Use' tab for users who may want to load downloaded data and perform their own analyses.

Interoperable

The app was tested across multiple browsers and operating systems. All spatial data layers follow widely used geospatial standards and naming conventions. File download options are provided in universally accessible formats, and the data is interoperable using standard file formats (e.g. CSV). The 'How to Use' tab includes sample code for loading and using the published dataset in both R and Python.

Reusable

The underlying codebase for the app is openly available via a dedicated GitHub repository. Metadata files accompany all datasets available for download from the app. Long-term hosting and technical support are ensured through UKCEH servers.

3. Case study

Here, we present a potential case study to showcase how a hypothetical stakeholder may successfully interact with the app. In this case study, a local environmental authority may wish to review cropland phosphorus budgets for their local lake catchment to inform short and long-term nutrient management planning. In the example shown in **Fig. 1**, we use the catchment of Loch Leven (Fife, Scotland). Using the Map Explorer page, the user could first select their variable of interest (e.g. cropland phosphorus budget from the IMAGE-GNM dataset) across Level 3 HydroBASINs and then zoom in to the Level 3 HydroBASIN that contains Loch Leven, to investigate how it compares to neighbouring basins.

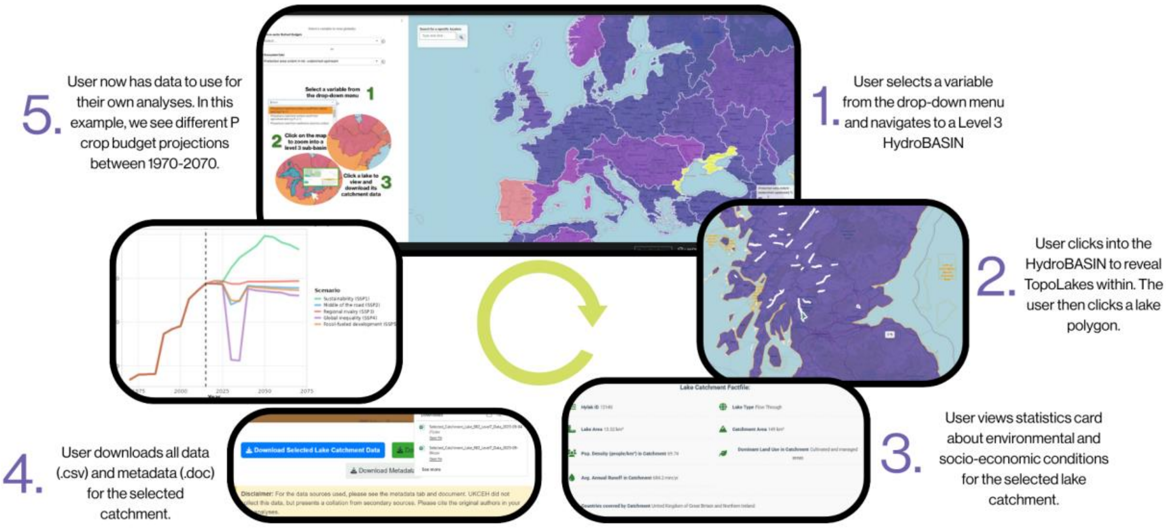

Figure 1: A diagram showing a potential use-case where a user 1) explores variables at HydroBASIN level 3 on the map explorer, 2) selects a lake (e.g. Loch Leven, Fife, Scotland), 3) views catchment-level statistics, 4) downloads metadata and a CSV containing data for their selected catchment, 5) conducts their own analyses about their selected lake catchment using the downloaded data.

Clicking on the Loch Leven TopoLake polygon brings up the pop-up modal containing a fact-file box summarising land use, population density, biodiversity indicators, and other relevant environmental and socio-economic data for the catchment. The user can then download a CSV and metadata file for that catchment and open using an app or coding platform of their choice (e.g. R, Python, SPSS, Excel), for example to analyse and plot the cropland phosphorus budget trends from 1970–2070 across different Shared Socioeconomic Pathways (SSPs). These projections can be used to visualise potential futures for phosphorus emissions under different development scenarios and inform decision-making in the catchment alongside the use of *in-situ* data. This kind of functionality allows users to put harmonised global data into a local context and could help inform nutrient mitigation strategies or support alignment with international sustainability targets. For a full comparative analysis of data downloaded from the app versus in-situ Loch Leven data, see **Appendix 1**, which represents a QA ground-truthing exercise that follows this process.

4. Discussion

Phosphorus and nitrogen usage are critical components of Earth system stability in the Anthropocene (Carpenter & Bennett, 2011; Rockström et al., 2009, 2020), and our continued transgression of this planetary boundary could compromise freshwater biodiversity, local economic prosperity, and global food security (Diaz & Rosenberg, 2008; Gerten et al., 2020). The long-term environmental fate of phosphorus and nitrogen is context-dependent and deeply intertwined with spatially variable agricultural practices, ecosystem sensitivities, and socio-economic pressures. While the impacts of phosphorus and nitrogen-based pollution into freshwater and marine ecosystems are well documented (WWQA Ecosystems, 2023), the data needed to understand and manage both these impacts, and the sources of phosphorus and nitrogen emissions remains unaligned across industrial sectors and spatial scales. Harmonised datasets that connect nutrient use with environmental and socio-economic indicators are essential for enabling both international collaboration and more targeted, local-scale responses. The Global Lakes Explorer provides a marked improvement in the visibility of nutrient emissions across sectors and lake catchments, particularly for member states with limited data availability. It brings these data together in a single, intuitive platform and allows users to explore interconnected variables at global, regional, and catchment scales. The app provides an early assessment tool that can support the development of national monitoring and assessment programmes and helping to identify ecosystems in need of priority action and fostering dialogue between sectors on circular economy and nature-based solution approaches for sustainable nutrient management. By visualising downloadable, policy-relevant data in an accessible format, it can also contribute to progress towards global frameworks such as the GBF Targets and SDG Indicator 6.3.2 (CBD, 2025b, 2025a; UNEP, 2025).

Use Cases

The app can support a wide range of use cases, from academic research through to the development of local policy mitigation strategies. Variables can be compared across space to identify potential hotspots of risk in places where, for example, fertiliser inputs are high, but nutrient use efficiency is low, and which intersect with high-risk wetland landscape classifications. It can also be used to highlight areas of opportunity, where changes to land management or investment in circular nutrient management approaches might have the most impact. Because the data is harmonised and available at multiple scales, users can look across countries, basins, or zoom right into individual catchments. This makes the tool useful not just for research, but also for policy development, stakeholder reports, and environmental planning. The tool can therefore act as a key resource for local agencies or governments to design nutrient mitigation strategies, local sustainability plans, or compliance with GBF and SDG targets (McCrackin et al., 2017b; Mogollón et al., 2021). Furthermore, policymakers and NGOs can use the app to generate intuitive, accessible, data-driven visuals to promote awareness and stakeholder engagement on the risks of nutrient mismanagement and eutrophication.

Data Transparency and Next Steps

The app is reliant on third-party datasets, particularly modelled outputs from IMAGE-GNM (Beusen et al., 2015, 2016b, 2022), which introduces any biases inherent to the original datasets. As a result, we have integrated metadata and data citations consistently throughout the app. This aligns with FAIR data principles and ensures that users can interpret data responsibly. While the global datasets in our app provide useful scaffolding for data analysis, visualisation and policy ideation, the capacity to download data at the catchment-scale allows users to enhance their own analyses with locally collected data. We therefore encourage users to augment their existing data (e.g. ground-truthed fertiliser application, local biodiversity monitoring, site-specific water clarity data) with data freely downloadable from the app to support specific use-cases and help to close spatial and temporal data gaps. As new datasets emerge (for example, updated nutrient loading models, wastewater outputs, global food security data), we aim to continuously update the app to ensure its relevance, accuracy, and usefulness to stakeholders across sectors. Updates to the data could include updated IMAGE-GNM data as it is published, annually updated socio-economic metrics, and the addition of relevant but as-yet unpublished global datasets. Furthermore, feedback from ongoing stakeholder workshops will allow us to further tailor the app for specific end-users such as urban planners, aquaculture and agriculture managers and policymakers. As users interact with the app and use the tool for their own projects, we would welcome them to communicate their outputs with the app development team in order to showcase their work as part of an in-app 'Innovation Hub'.

5. Conclusion

The Global Lakes Explorer's design responds to calls for transparent, accessible, and actionable phosphorus data by providing a globally harmonised dataset designed to support integrated phosphorus and nitrogen management, encompassing environmental, socio-economic, and nutrient emission data. The app interface provides intuitive navigation of datasets across multiple spatial scales, from broad Level 3 HydroBASINs down to over 40,000 individual lake catchments. Data are freely downloadable, consistently documented, and adhere to FAIR data principles. We have demonstrated a practical use case using data from the catchment of Loch Leven to illustrate how stakeholders can navigate to a catchment of choice, assess nutrient emissions across sectors, and download relevant data to perform their own analyses. Taken together, the Global Lakes Explorer serves as a foundational tool to support multinational and cross-sector collaboration in the pursuit of sustainable nutrient management and environmental restoration.

Contributions:

This manuscript was conceived through discussions between EG, BS, PT, WB, IL and EZ. Initial consultations on data sourcing were conducted by PT, AB, MS, AT and MF. Initial design of the dashboard was led by MT, PT and EZ. EG led the long-term development evaluation of the dashboard.

Initial dashboard evaluation was completed by EG, EZ, BS, PT, WB, IL, EK, AM, CM, AV, and LM. Detailed evaluation of the near-completed dashboard was completed by MS, IL, SM, JM, IV, SW and JZ. EG wrote the manuscript with feedback provided by all co-authors. The manuscript and dashboard have been funded by the UNEP GEF uPcycle project (GEF ID: 10892), secured and managed by BS, WB and IL.

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Appendix 1: App Data Ground-truthing

Methods:

To assess the validity of the aggregated catchment-level IMAGE-GNM data in the Global Lakes Explorer, we compared this output against existing in-situ monitoring and modelled data for two of the lake catchments featured on the app; Loch Leven (Scotland), and Lake Villarica (Chile). Loch Leven (Hylak ID: 13140) is a shallow, eutrophic lake with a lake surface area of 13.32 km^2, with agriculture dominating the land-use within the catchment. In this ground truthing exercise, we used modelled phosphorus loading data from the SEPA Plus+ model (Donnelly et al., 2011) and monitored point- and diffuse- source P loading data (May et al., 2017). Lake Villarica (Hylak ID: 982) is a volcanic, eutrophic flow-through lake with a lake surface area of 171.85 km^2. In this ground truthing exercise, we used monitored phosphorus loading data from 2017 and 2021 compiled by the Ministerio del Medio Ambiente (MMA, 2025).

For both lake catchments, we extracted the data from the Global Lakes Explorer to retrieve the catchment-aggregated IMAGE-GNM P loading data for the SSP2 ('middle of the road') scenario pathway for comparison with the in-situ data for the lakes. The IMAGE-GNM data is only available in 5-year increments, whereby the in-situ data was only available for specific years. Therefore, for the Lake Villarica data (whereby the in-situ data was only available for 2017 and 2021), we extracted data representing 2015 and 2020 from the app. For the Loch Leven data (whereby the in-situ data was an aggregation of sampling spanning 2015 and 2016), we extracted data representing 2015 from the app. We ensured the units aligned between all data sources, converting t P yr^{-1} in the in-situ data to kg P yr^{-1} to match the units in the app. Where possible, we aggregated the in-situ data outputs into P source categories to correspond to the categories available via the app (e.g. natural versus agricultural surface run-off, waste-water, aquaculture, weathering), mapping the observed source types to a more universal P loading classification scheme.

Results:

Loch Leven

The app data captures the overall TP load magnitude reasonably well, with the app reporting 14.6 t P yr^{-1}, which is slightly lower than the SEPA Plus+ reported value of 15.6 t P yr^{-1} and higher than the monitored value of 11.8 t P yr^{-1} (**Fig. S1**). While the monitored data could not be aggregated into finer categories, all three of the dataset types reported diffuse run-off (largely from agricultural land) as being the greatest contributor of P to Loch Leven in 2015.

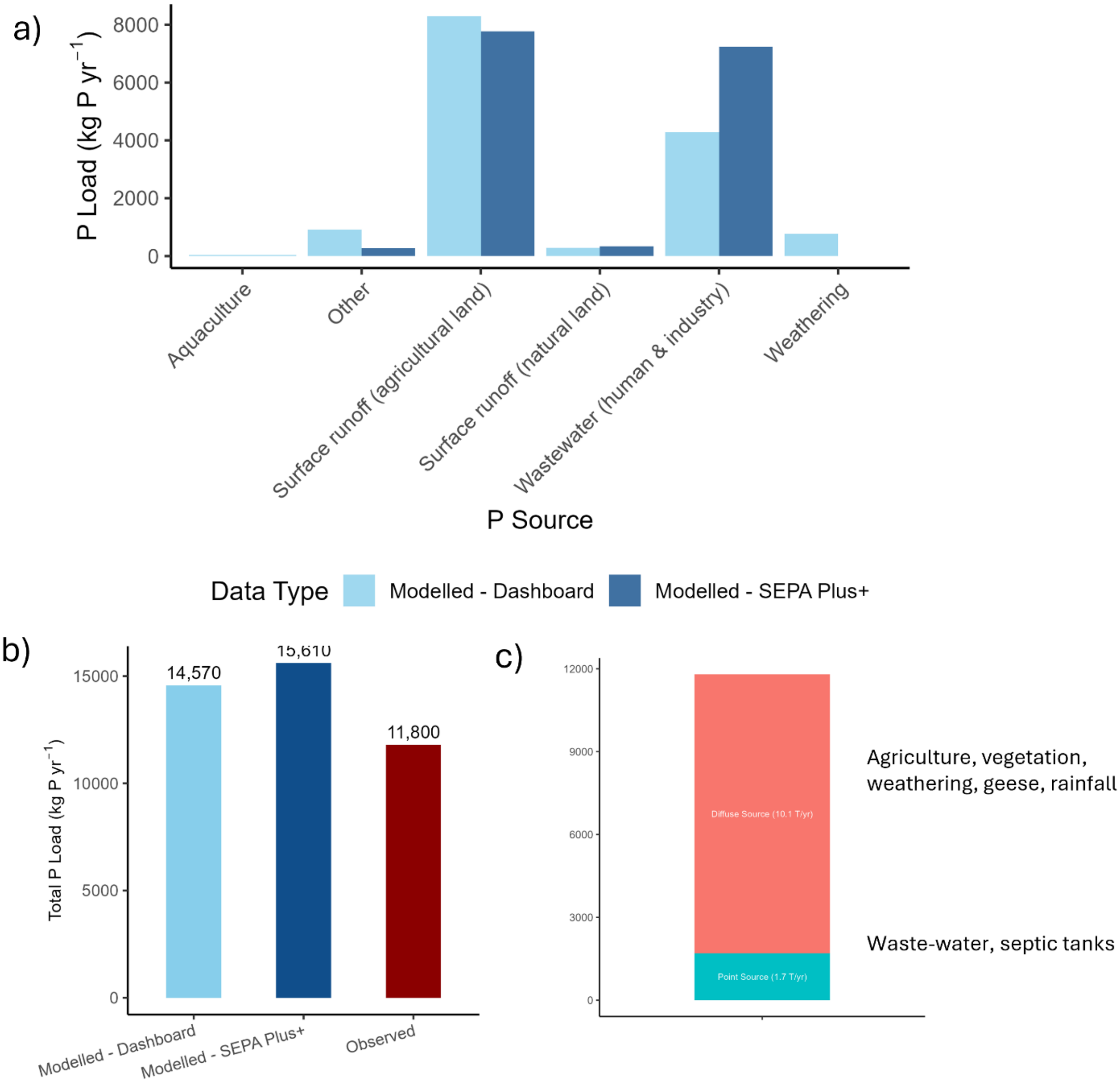

Figure S1: Comparison of total phosphorus (TP) loads to Loch Leven from different data sources for the year 2014/2015. The bar chart on the left shows TP loads from the App model (blue), the SEPA Plus+ model (Donnelly et al., 2011) (light blue), and observed data from May et al. (2017) (red). The bar chart on the right breaks down the observed P load from May et al. (2017) into point source (1.7 T/yr) and diffuse source (10.1 T/yr) contributions.

Lake Villarica

Total P loads for Lake Villarica were 163 t P in 2017 and 173 t P in 2021 according to observed data, and the App model captured the general magnitude of P loads, with a slight underestimation bias of −1.45% relative to observed data (**Fig. S2**).Diffuse runoff from agricultural land was the dominant phosphorus source in both 2015 and 2020 (101 t P in 2015; 101 t P in 2020). Vegetation inputs were negligible in both datasets, and notably the app specifically reported no aquaculture contribution to P loading, despite this being reported as the second highest contributor to P loading in the catchment by

MMA (2025). Overall, total phosphorus contributions remained largely stable between 2015 and 2020, with minimal change for diffuse runoff (−0.1%) and slight increases for sewage (~11%) and weathering (~27%).

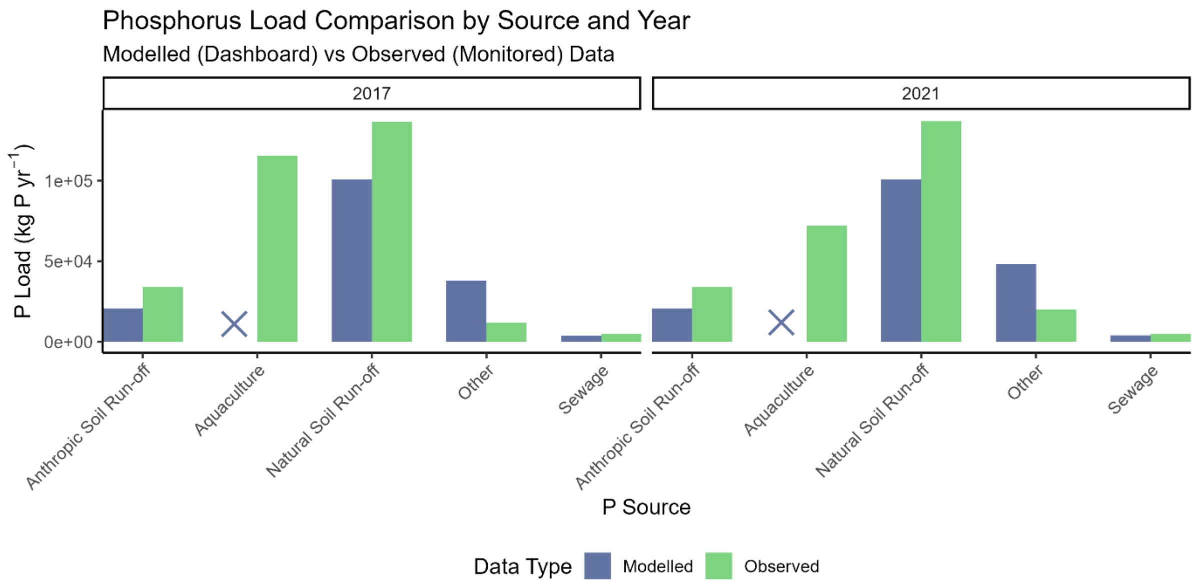

Figure S2: Comparison of total phosphorus (P) loads to Lake Villarica for the years 2015 (app)/2015(observed) and 2020(app)/2021(observed). The bar chart shows total P loads from different sources from the App model (blue), the SEPA Plus+ model (MMA 2025) (green).

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Table S1: Data sources, metadata, and variables used in the Global Lakes Explorer

Data Source	Description	Scope	Category	Time Coverage	License / Terms	Data Portal	Key Variables Used
Nitrogen and Phosphorus Emissions (IMAGE GNM)	Modelled nitrogen and phosphorus delivery to surface waters using the Global Nutrient Model with SSP projections.	Global	Nutrients	1970–2070 (5-year intervals)	CC BY 4.0	https://dataportaal.pbl.nl/downloads/IMAGE/GNM/	SSPx_P and SSPx_N river runoff, groundwater, vegetation, aquaculture, cropland, deposition, and sewage variables
BasinATLAS (HydroATLAS)	Sub-basin physical, hydrological, climatic, and land-use characteristics.	Global	Catchments	Varies	CC BY 4.0	https://www.hydrosheds.org/hydroatlas	HYBAS_ID, SUB_AREA, UP_AREA, discharge, runoff, aridity, land cover variables

Cropland Nutrient Efficiency (FAOSTAT)	Nitrogen and phosphorus efficiency indicators for cropland nutrient balances.	Global	Nutrients	1961–2020 (annual)	CC BY-NC-SA 3.0 IGO	https://www.fao.org/faostat/en/#data/ESB	N_efficiency_year, P_efficiency_year
Index of Coastal Eutrophication Potential	Indicator measuring national contributions to coastal eutrophication risk.	Global	Environment	2000–2023 (annual)	UN Terms of Use	https://www.un.org/en/about-us/terms-of-use	Extreme, High, and Moderate chlorophyll anomaly indicators
Resource Trade – Phosphorus (Chatham House)	International trade flows of phosphorus and nitrogen commodities.	Global	Nutrients	2000–2022 (annual)	Chatham House (2021)	https://resourcetrade.earth/	P_import_year, P_export_year, N_import_value, N_export_value
GloboLakes	High-resolution global	Global	Catchments	2005–2010	Open Government	https://catalogue.ceda.ac.uk/uuid/84d4f66b668241328df0c43f8f3b3e16	Lake_name, Hylak_id

	limnology dataset describing lake properties.			(annual)	Licence v3		
Lake-TopoCat	Global database of lake drainage topology and connectivity.	Global	Catchments	Varies	CC BY 4.0	https://zenodo.org/records/7916729	Hylak_id, Lake_area, Lake_type
UN Countries Boundaries (UN Geodata)	Simplified global administrative boundaries following UN standards.	Global	Demographic	Not applicable	CC BY 4.0 (UN disclaimers apply)	https://geoportal.un.org/	nam_en, sub_reg
Population Density (GPWv4)	Gridded Population of the World population density estimates.	Global	Demographic	2000–2020 (5-year intervals)	Citation required (SEDAC)	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11	pop_dens

IUCN Red List Index	Composite indicator tracking global extinction risk trends.	Global	Biodiversity	2024	Free for non-commercial use	https://www.iucnredlist.org/assessment/red-list-index	gbf7_RLI_2024
Global Mean Deprivation Index (GRDI v1)	Gridded multidimensional deprivation index from socio-demographic and satellite data.	Global	Demographic	2024	Citation required (SEDAC)	https://sedac.ciesin.columbia.edu/data/set/povmap-grdi-v1	gbf7_mean_deprivation_2024

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