

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

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51
52 **Abstract:**

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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

88 Phosphorus and nitrogen play essential roles in the biological functioning of all living organisms, and
89 our dependence on phosphate and nitrogen fertilisers underpins and sustains global food production
90 (Cordell & White, 2014). However, poor management across agriculture, aquaculture, and wastewater
91 systems can result in phosphorus losses to water bodies (Beusen et al., 2016a; Chen & Graedel, 2016),
92 driving eutrophication, biodiversity loss (WWF, 2025), and methane emissions via increased prevalence
93 of anoxic environments (Beaulieu et al., 2019; WWQA Ecosystems, 2023). Likewise, nitrogen from
94 atmospheric deposition, agriculture, wastewater, and industrial sources also accumulates in lakes,
95 compounding eutrophication pressures alongside phosphorus inputs (Bergström & Jansson, 2006; Gao
96 et al., 2020; Mccrackin & Elser, 2010). Safe nutrient thresholds have already been exceeded globally,
97 albeit heterogeneously (Carpenter & Bennett, 2011; Fanning & Raworth, 2025; Rockström et al., 2009).
98 Unsustainable nutrient management has contributed to an 84% decline in freshwater species populations
99 since 1970 and placing over a quarter of these species at risk of extinction (Sayer et al., 2025). The
100 recovery of these freshwater ecosystems can be slow, non-linear, and incomplete (Jeppesen et al., 2017;
101 McCrackin et al., 2017a). Harm to freshwater ecosystems can also result in reduced drinking water
102 quality, property devaluation, and decreased tourism (Darwall et al., 2018; Janssen et al., 2021; Mishra,
103 2023; Overmyer et al., 2005; Wolf & Klaiber, 2017). Meanwhile, nutrient pollution from terrestrial
104 environments to marine ecosystems can create widespread instances of eutrophication and the creation
105 of anoxic dead-zones (Kirchman, 2021). Global demands for fertilisers can be more sustainably met
106 through a transition to circular nutrient trade and usage systems where nutrient use is optimised and
107 losses minimised and recycled for food production (Brownlie et al., 2021). In the absence of coordinated,
108 cross-sector and transdisciplinary action, we run the risk of jeopardising the global food security and
109 environmental goals. These include global objectives such as the Convention on Biological Diversity
110 Kunming-Montreal Global Biodiversity Framework Target 7 to reduce nutrient losses by 50% by 2030
111 and Target 2 to bring 30% of degraded ecosystems under restoration by 2030 (Cordell & White, 2014;
112 Gerten et al., 2020; Scholz & Wellmer, 2013; Springmann et al., 2018), in addition to emerging
113 indicators and global assessment tools (Möhring et al., 2023).

114

115 The identification and management of pollution risks related to nutrient loading can be hindered by
116 fragmented data on nutrient emissions, nutrient use efficiency, and their corresponding environmental
117 impacts (Brownlie et al., 2022; Cordell & White, 2014; Darwall et al., 2018). Several valuable datasets
118 exist, including the IMAGE-GNM nutrient loading models (Beusen et al., 2015), global fertiliser trade
119 values (Chatham House, 2021), and HydroATLAS lake and basin hydrological characteristics (Linke
120 et al., 2019). However, these resources currently lack spatial integration and harmonisation (Jwaideh et
121 al., 2022). Data fragmentation can, in turn, contribute to disjointed policy development and can impede
122 collaborative efforts towards sustainable nutrient management, for example, by increasing the risk of

123 'pollution swapping' between sectors (Halpern et al., 2022; MacDonald et al., 2011). There is therefore
124 an opportunity to align these currently unharmonised datasets to visualise nutrient dynamics across
125 sectors and across space, which would in turn allow us to identify nutrient resource hotspots and deficits
126 on a global level. Through a coordinated integration of pre-existing data streams, we can enhance our
127 collective ability to address knowledge gaps and reach global sustainability goals.

128

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

145

146 **2. Data and Methods**

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

155

156 **2.1) Spatial resolution**

157

158 BasinATLAS is a dataset of polygon layers that depict sub-basin hydrological boundaries at a global
159 scale (HydroBASINS), enhanced with a global compendium of hydro-environmental characteristics
160 (HydroATLAS) (Linke et al., 2019). These sub-basins have 12 spatial scales, ranging from coarse
161 resolution (level 1) to fine resolution (level 12). Level 3 vectorised polygons were selected as our
162 foundational spatial unit for displaying all variables at a global scale, conveying ~country-level
163 information without using (potentially contestable) geopolitically defined national borders. The Level
164 3 BasinATLAS polygons have 56 associated variables (hydrology, physiography, climate, land cover,
165 soils, geology, and anthropogenic), across 281 unique polygons, available at all levels, including source
166 data and citations.

167

168 To display lakes and catchments on the app, we utilised the newly published Lake TopoCat (Sikder et
169 al., 2023) dataset, a global lake drainage topology and catchment database. Lake TopoCat identifies
170 ~ 1.46 million outlets for ~ 1.43 million lakes larger than 10 ha and delineates 77.5×10^6 km² of lake
171 catchments covering 57% of the Earth's landmass excluding Antarctica. We used these data to 1) extract
172 lake names and geometries for all lakes over 250 hectares (>40,000 globally), and 2) extract the
173 geometries of the lake catchments all selected lakes.

174

175 **2.2) Data selection**

176

177 To display the magnitude of phosphorus and nitrogen usage across nutrient input types (e.g.
178 groundwater, surface run-off) and across a variety of nutrient-emitting sectors, we used data from
179 IMAGE-GNM (Integrated Model to Assess the Global Environment-Global Nutrient Model, Beusen et
180 al., 2015, 2016b, 2022) and extracted the following variables: P and N loads from surface and
181 groundwater runoff from natural and agricultural land, P and N loads from weathering reaching surface
182 water, P and N loads from allochthonous organic matter inputs to rivers, P and N loads from aquaculture
183 and waste-water (sewage) to surface waters. These variables can be displayed on the Map Explorer via
184 a drop-down menu entitled 'Nutrient Data' on the main app at the HydroBASIN level 3 spatial
185 resolution. Each of these variables covers the time period 1970 - 2070 (in 5-year time increments), with
186 any year beyond 2015 representing projections based on five Shared Socio-Economic Pathways (SSPs)
187 (Kriegler et al., 2014; O'Neill et al., 2016), which are globally standardised scenarios describing
188 alternative trajectories of future socio-economic development and associated environmental pressures:
189 SSP1 (Sustainability), SSP2 (Middle of the road), SSP3 (Regional rivalry), SSP4 (Inequality) and SSP5
190 (Fossil-fuelled development). NetCDF files from IMAGE-GNM were extracted into per-SSP / per-
191 variable aggregated TIFFs and analysed individually using the selected hydrological catchments

192 defined in Lake TopoCat. Mean (per area) catchment nutrient values were calculated based on area-
193 weighted apportioned values from the underlying IMAGE-GNM data, then the mean values were used
194 to calculate total values for the catchment using its area. The data is available to download at the
195 catchment-level when the user selects a lake catchment and downloads the automatically generated
196 CSV.

197

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

204

205 GBF Target 2 is defined as ‘Restore 30% of all Degraded Ecosystems’ and focuses on ensuring
206 protection and restoration for 30% of all degraded terrestrial, inland water, coastal and marine
207 ecosystems. These ecosystems have all undergone significant habitat loss within the last century (e.g.
208 87% habitat loss in wetlands over the last 300 years [Davidson, 2014]), and the target is supported by
209 indicators such as Area Under Restoration, extent and type of ecosystem, connectivity of ecosystems,
210 and can be complemented by a variety of external indices including on biodiversity health, land use,
211 species richness, and tree cover (CBD, 2025a). We extracted the following HydroATLAS variables to
212 represent GBF Target 2 in the app: natural discharge, land surface runoff (Doll et al., 2003), global
213 aridity index (Zomer et al., 2022), land cover classes and extent (Bartholomé & Belward, 2005), wetland
214 type classes and extent (Lehner & Döll, 2004), and protected area extent (Deguignet et al., n.d.). These
215 variables can be displayed on the Map Explorer via a drop-down menu entitled ‘Ecosystem Data’ on
216 the main app at the HydroBASIN level 3 spatial resolution. They are also available to download at the
217 catchment-level when the user selects a lake catchment and downloads the automatically generated
218 CSV.

219

220 GBF Target 7 is defined as ‘Reduce Pollution to Levels That Are Not Harmful to Biodiversity’ and
221 focuses on reducing risk of pollution to biodiversity and ecosystem functions by more sustainably
222 managing nutrient use while also ensuring food security and livelihoods. This target specifically
223 explores the polluting effects of mismanagement of phosphorus and nitrogen, aiming to reduce excess
224 nutrients lost to ecosystems, making use of indices such as the Index of Coastal Eutrophication Potential,
225 fertiliser flow, and trends in nutrient use and loss across sectors (CBD, 2025b). Variables related to this
226 target were extracted from global open-source databases with strong spatial coverage, and included:
227 phosphate fertiliser imports and exports in tonnes by country (Chatham House, 2021), Chlorophyll-*a*

228 remote sensing anomalies (UN SDG Goal 14), phosphorus and nitrogen use efficiency (Ludemann et
229 al., 2024), and population density (CIESIN, 2025a). These variables are available for download on a
230 tab entitled ‘Socio-economic variables’ and can be visualized in spatial polygons representing UN
231 defined country borders (United Nations Geospatial, 2025). Full metadata for all data sources used in
232 the app can be viewed in **Table S1**.

233

234 *2.3) App functionality*

235

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

245

246 When a user clicks into the map (either with or without a variable selected from the dropdown menu),
247 the lakes within the selected level 3 HydroBASIN appear on the map as defined by their geometries
248 from the Lake TopoCat data. When a user clicks on one of these lakes, a pop-up modal card appears
249 containing a statistical fact-file about the selected lake and its corresponding catchment. This card
250 includes a Leaflet map showing the lake nested within the catchment, lake name, lake size, lake type,
251 land-use class, all countries intersecting the catchment, population density (people per km²), annual
252 natural discharge, aridity index and Hylak ID (a unique identifier for each lake used in both the
253 HydroATLAS and LakeTopoCat databases). Users can use a drop-down menu to view time-series
254 projections of phosphorus and nitrogen emissions from different sectors (e.g. agriculture, cropland,
255 pasture) from 1970-2070, following different SSPs from the year 2015 onwards. The y axis of this graph
256 can be displayed as total values across the catchment, relative % values across sectors, or average values
257 per km²/yr. Alongside these plots is a legend containing definitions of these SSPs. Users can also
258 download the available GNM and GBF2 data in CSV format for the selected lake. Metadata files are
259 also available to download as a Microsoft Word document.

260

261 A tab entitled ‘Socio-economic data’ contains a CSV download link and metadata file for all variables
262 described under the ‘GBF 7’ category, which are aggregated to country-level resolution. On this tab we

263 showcase two potential use-cases for this data. The first is an interactive leaflet map of national
264 phosphate import and export totals, with accompanying bar charts of the top 10 global exporters and
265 importers of phosphate fertiliser (Chatham House, 2021). The second is an interactive fact-file showing
266 information about phosphate fertiliser trade, nutrient use efficiency, mean deprivation index (CIESIN,
267 2025b) and red list index (IUCN, 2025) value for each country. The user selects a country using either
268 a drop-down menu or by selecting a country on the interactive map or bar chart and can then view these
269 variables on a series of slider scales, which also report the maximum and minimum values globally to
270 aide comparison between countries.

271

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

282

283 **2.4) Evaluation**

284

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

292

293 We qualitatively and quantitatively evaluated the user-experience of the app to ensure it was ready for
294 public deployment. We designed an anonymous feedback form with Likert-scale questions asking users
295 to report the ease of using the app, and whether the app was informative, intuitive and accessible. The
296 form also includes long-format questions where users can report bugs, constructive design feedback,

297 and issues with accessibility. This form was distributed to 10 external reviewers in October 2025, and
298 their feedback was incorporated into the final app.

299

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

306

307 **2.5) FAIR Data Principles**

308

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

316

317 **Findable**

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

324

325 **Accessible**

326 The app is designed to provide an intuitive, user-friendly interface with clear and consistent labelling
327 of elements, embedded guidance, and a full metadata catalogue for all datasets. A video tutorial is
328 available via the 'How to use' tab, featuring image captions, subtitles, and an accompanying transcript.
329 The app design is colourblind-friendly, for example using 'Viridis' colour palettes (Garnier et al., 2024)
330 in both the maps and the time-series plots. To support accessibility in low-bandwidth environments, the
331 Leaflet maps are optimised to minimise data load times. We have also provided example R and Python

332 scripts in the 'How to Use' tab for users who may want to load downloaded data and perform their own
333 analyses.

334

335 Interoperable

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

340

341 Reusable

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

345

346 3. Case study

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



354

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

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

371

372 **4. Discussion**

373 Phosphorus and nitrogen usage are critical components of Earth system stability in the Anthropocene
374 (Carpenter & Bennett, 2011; Rockström et al., 2009, 2020), and our continued transgression of this
375 planetary boundary could compromise freshwater biodiversity, local economic prosperity, and global
376 food security (Diaz & Rosenberg, 2008; Gerten et al., 2020). The long-term environmental fate of
377 phosphorus and nitrogen is context-dependent and deeply intertwined with spatially variable
378 agricultural practices, ecosystem sensitivities, and socio-economic pressures. While the impacts of
379 phosphorus and nitrogen-based pollution into freshwater and marine ecosystems are well documented
380 (WWQA Ecosystems, 2023), the data needed to understand and manage both these impacts, and the
381 sources of phosphorus and nitrogen emissions remains unaligned across industrial sectors and spatial
382 scales. Harmonised datasets that connect nutrient use with environmental and socio-economic
383 indicators are essential for enabling both international collaboration and more targeted, local-scale
384 responses. The Global Lakes Explorer provides a marked improvement in the visibility of nutrient
385 emissions across sectors and lake catchments, particularly for member states with limited data
386 availability. It brings these data together in a single, intuitive platform and allows users to explore
387 interconnected variables at global, regional, and catchment scales. The app provides an early assessment
388 tool that can support the development of national monitoring and assessment programmes and helping

389 to identify ecosystems in need of priority action and fostering dialogue between sectors on circular
390 economy and nature-based solution approaches for sustainable nutrient management. By visualising
391 downloadable, policy-relevant data in an accessible format, it can also contribute to progress towards
392 global frameworks such as the GBF Targets and SDG Indicator 6.3.2 (CBD, 2025b, 2025a; UNEP,
393 2025).

394 *Use Cases*

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

408 *Data Transparency and Next Steps*

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

423 specific end-users such as urban planners, aquaculture and agriculture managers and policymakers. As
424 users interact with the app and use the tool for their own projects, we would welcome them to
425 communicate their outputs with the app development team in order to showcase their work as part of
426 an in-app ‘Innovation Hub’.

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428 **5. Conclusion**

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

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444 **Contributions:**

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446 This manuscript was conceived through discussions between EG, BS, PT, WB, IL and EZ. Initial
447 consultations on data sourcing were conducted by PT, AB, MS, AT and MF. Initial design of the
448 dashboard was led by MT, PT and EZ. EG led the long-term development evaluation of the dashboard.
449 Initial dashboard evaluation was completed by EG, EZ, BS, PT, WB, IL, EK, AM, CM, AV, and LM.
450 Detailed evaluation of the near-completed dashboard was completed by MS, IL, SM, JM, IV, SW and
451 JZ. EG wrote the manuscript with feedback provided by all co-authors. The manuscript and dashboard
452 have been funded by the UNEP GEF uPcycle project (GEF ID: 10892), secured and managed by BS,
453 WB and IL.

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697 **Appendix 1: App Data Ground-truthing**

698

699 Methods:

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701 To assess the validity of the aggregated catchment-level IMAGE-GNM data in the Global Lakes
702 Explorer, we compared this output against existing in-situ monitoring and modelled data for two of the
703 lake catchments featured on the app; Loch Leven (Scotland), and Lake Villarica (Chile). Loch Leven

704 (Hylak ID: 13140) is a shallow, eutrophic lake with a lake surface area of 13.32 km², with agriculture
705 dominating the land-use within the catchment. In this ground truthing exercise, we used modelled
706 phosphorus loading data from the SEPA Plus+ model (Donnelly et al., 2011) and monitored point- and
707 diffuse- source P loading data (May et al., 2017). Lake Villarica (Hylak ID: 982) is a volcanic, eutrophic
708 flow-through lake with a lake surface area of 171.85 km². In this ground truthing exercise, we used
709 monitored phosphorus loading data from 2017 and 2021 compiled by the Ministerio del Medio
710 Ambiente (MMA, 2025).

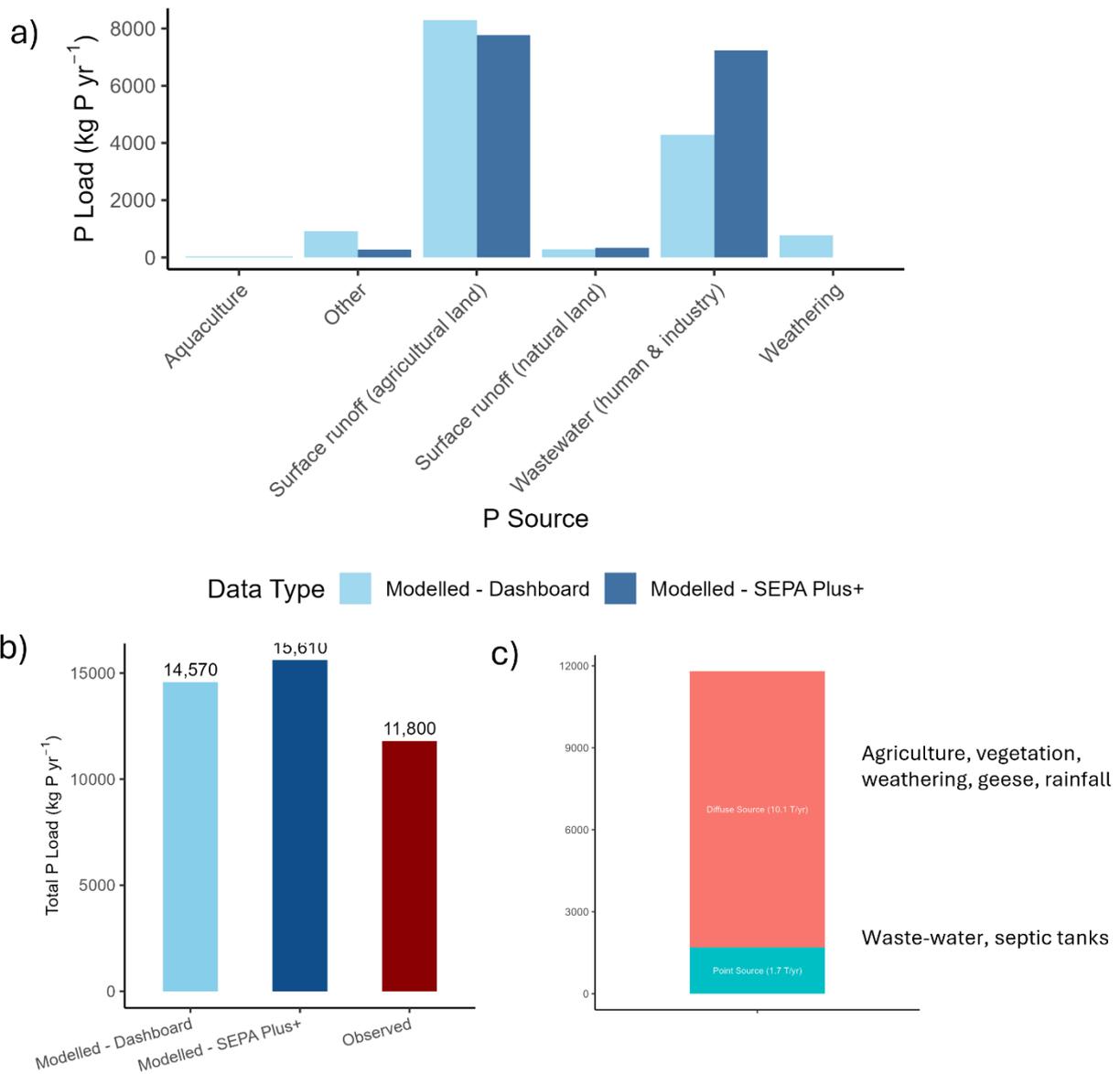
711 For both lake catchments, we extracted the data from the Global Lakes Explorer to retrieve the
712 catchment-aggregated IMAGE-GNM P loading data for the SSP2 ('middle of the road') scenario
713 pathway for comparison with the in-situ data for the lakes. The IMAGE-GNM data is only available in
714 5-year increments, whereby the in-situ data was only available for specific years. Therefore, for the
715 Lake Villarica data (whereby the in-situ data was only available for 2017 and 2021), we extracted data
716 representing 2015 and 2020 from the app. For the Loch Leven data (whereby the in-situ data was an
717 aggregation of sampling spanning 2015 and 2016), we extracted data representing 2015 from the app.
718 We ensured the units aligned between all data sources, converting t P yr⁻¹ in the in-situ data to kg P yr⁻¹
719 to match the units in the app. Where possible, we aggregated the in-situ data outputs into P source
720 categories to correspond to the categories available via the app (e.g. natural versus agricultural surface
721 run-off, waste-water, aquaculture, weathering), mapping the observed source types to a more universal
722 P loading classification scheme.

723

724 Results:

725 **Loch Leven**

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



731

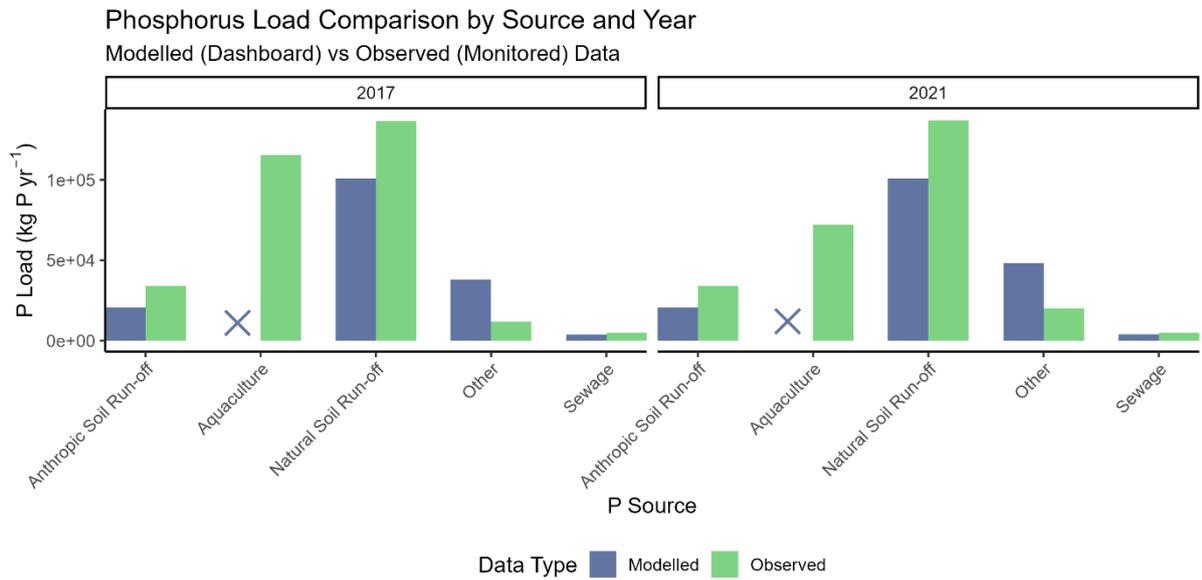
732 **Figure S1:** Comparison of total phosphorus (TP) loads to Loch Leven from different data sources for
 733 the year 2014/2015. The bar chart on the left shows TP loads from the App model (blue), the SEPA
 734 Plus+ model (Donnelly et al., 2011) (light blue), and observed data from May et al. (2017)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

737

738 Lake Villarica

739 Total P loads for Lake Villarica were 163 t P in 2017 and 173 t P in 2021 according to observed data,
 740 and the App model captured the general magnitude of P loads, with a slight underestimation bias of
 741 -1.45% relative to observed data (**Fig. S2**). Diffuse runoff from agricultural land was the dominant
 742 phosphorus source in both 2015 and 2020 (101 t P in 2015; 101 t P in 2020). Vegetation inputs were
 743 negligible in both datasets, and notably the app specifically reported no aquaculture contribution to P
 744 loading, despite this being reported as the second highest contributor to P loading in the catchment by

745 MMA (2025). Overall, total phosphorus contributions remained largely stable between 2015 and 2020,
 746 with minimal change for diffuse runoff (-0.1%) and slight increases for sewage (~11%) and weathering
 747 (~27%).



748

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

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755 **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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