Method Article

Frameworks for mapping lake ecosystem services. An example from Lithuania

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ARTICLE INFO

ABSTRACT

Lake ecosystems are essential for human well-being. Due to its transboundary nature, connecting terrestrial and aquatic habitats, its environmental processes and functions support a wide array of ecosystem services (ES). Hence, despite its importance in supporting socio-ecologic systems, these freshwater ecosystems are highly impacted due to anthropogenic influence. ES may shed light on the importance of maintaining and restoring lake ecosystems. Hence, despite the increased effort in the last decades to provide robust spatial information, most scientific studies still follow a qualitative approach that carries a great deal of uncertainty and is not uptake by decision-makers. It is necessary to develop quantitative and robust methodologies for mapping ES, especially in the aquatic realm. This study develops several frameworks to map ES in lake ecosystems. Important to highlight is that this study.

- develops a quantitative multi-method (biophysical and statistical) toolbox for lake ES multi-temporal mapping.
- covers five ES from Provisioning, Regulating & Maintenance, and Cultural sections, namely: (1) Fibres and other materials for construction; (2) Water used for non-drinking purposes; (3) Maintenance of nursery populations; (4) nutrient regulation; and (5) recreation.
- addresses three dimensions of ES: supply, flow; and demand.

Specifications table

Subject area:	*Environmental Science*
More specific subject area:	*Ecosystem Services*
Name of your method:	*Multi-Method for lakes ecosystem services mapping*
Name and reference of original method:	*N.A.*
Resource availability:	*ESRI ArcGIS 10.8*
	QGIS 2.22
	RStudio

Background

Freshwater ecosystems, such as lakes, are essential for supporting socio-ecologic systems [1]. Lake ecosystems support terrestrial and aquatic biodiversity, playing an important role in ecological processes at different spatial scales [2,3]. These ecosystems also provide an array of benefits for human well-being through the deliverance of ecosystem services (ES) [1]. Despite its essential role, for example, providing water for drinking purposes, lake ecosystems have been heavily impacted by anthropogenic socio-economic activities [4]. To reverse this is essential to show the benefits of preserving and conserving the natural environment. The concept of ES goes in line with this narrative. Since 2005, after the Millennium Ecosystem Assessment [5], the scientific development of the ES concept has increased exponentially [6]. One of the most common outputs is the translation of ES assessments into a spatial representation, i. e., mapping. To this day, several methodological advances have been achieved in ES mapping [7,8]. From simple expert matrices (e.g., [9]) to complex modelling approaches (e.g. [10]). Hence, there is a strong polarisation towards the terrestrial environment. The availability and development of assessment and mapping methodologies for lake ES are lagging. In parallel to this, there is an increasing inclusion of lake ES assessments and mapping into policies and directives at European (e.g., Water Framework Directive [11]) and international (e.g., United Nations Sustainable Development Goals (SDGs) [12]). However, to support decision-making, several authors have stressed the importance of scientifically sound and robust results (e.g., [13]). The problem is that for many years, ES assessment and mapping were done qualitatively (based on perceptive knowledge, e.g., expert elicitation), and this type of assessment and ES assessments generally carries many uncertainties [14]. It is then necessary to develop quantitatively (based on empirical data, e.g., biophysical modeling) and data-driven ES mapping methodologies to bridge these gaps.

Quantitative ES mapping and assessment are generally done via biophysical modeling, using indicators (e.g., *chlorophyll a concentration*) as proxies to represent ecological processes or socio-economic phenomena [7]. Thus, this type of assessment relies heavily on available data. Hence, this is one of the main problems identified by the ES research community: need for more data. This is even more pronounced for aquatic ecosystems in general and lake ecosystems in specific [1]. Due to the efforts within several initiatives like the Water Framework Directive and the United Nations Sustainable Development Goals, data for monitoring lake ecosystems became more available, and it is now possible to rely on it for ES mapping. Also, the role of Remote Sensing has increased exponentially since its advance is seen as a promising approach to overcome the lack of observational data in lake ecosystems [15]. Therefore, new methodological approaches for lake ES mapping should rely on these two components: quantitative and/or remote sensing. To fully comprehend ES, assessing and mapping their complexity is necessary. ES encompasses multiple dimensions: (1) supply, corresponding to the mechanisms responsible for generating the ES; (2) flow, which is the transfer of the ES from supply to demand areas; and finally, (3) demand, which represents the need of the society for ES [7]. In this study, we developed different methodological frameworks, using several indicators (e.g., biophysical, social) to map and assess lakes ES from a Spatio-temporal perspective. This is essential for the complete understanding of ES in lake ecosystems. We exemplify these frameworks for lake ecosystems in Lithuania from a multi-temporal perspective.

Methodological frameworks

One of the complete databases with a spatial representation of lakes is the HydroLAKES database from HydroSHEDS (www.hydrosheds.org) [16]. HydroLAKES is a database that maps global-scale water bodies with more than 10 hectares. It is a complete database, which was the reason for choosing this database to define the lake ecosystems to be analyzed in this study. Lake polygons were acquired (as a shapefile) from HydroLAKES database version 1.0, accessed in February 2021. Since lakes are transboundary ecosystems that connect aquatic and terrestrial realms, there are processes and functions related to providing ES that go beyond the water body limit. Therefore, we establish a buffer area of 5 km around the water body to analyze, for example, the influence of land use changes in the provision of ES. We follow the 5 km buffer after Mushtaq and Pandey [17]. The buffer area was delimited using the "Buffer" tool of ArcGIS 10.8 [18], based on the HydroLAKES polygons within Lithuania.

The ES analyzes are studied within the "Lithuanian lake ecosystem services: impacts of climate and land-use change" (LACLAN) Project. This project utilises the "Common International Classification on Ecosystem Services" (CICES) version 5.1 [19].

Land use land cover information in the 5 km buffer around the lake was based on Corine Land Cover data (CLC) (land.copernicus.eu). CLC data is widely used for ES mapping and assessment in Europe. Furthermore, CLC data cover several periods starting from 1990 and is open access.

All layers were processed to 30 m resolution using the ETRS89_LAEA coordinate system. To put all layers into this format, it was necessary to (1) resample some raster layers, which was done in ArcGIS 10.8, using the "Resample" tool; and (2) reproject some layers, which was also done in ArcGIS 10.8 but using the "Project" and "Reproject" tools.

All data information used for assessing and mapping the lake ES is available in Table S1 in the Supplementary Materials.

Provisioning ES: fibres and other materials for construction

Supply: The supply of fibres and other materials for construction ES refers to all materials from plants used instead of nutritional purposes [20]. This ES was calculated using an indicator related to reed areas present around the lake (Fig. 1).

Since no data were available in Lithuania on the spatial distribution and extent of reed to be analyzed in a multi-temporal perspective, this method incorporated remote sensing data to estimate it. We adapted methodological frameworks to detect reed areas around the lake using vegetation indices (e.g., [21,22]). Landsat Satellite Imagery (TM 5 and ETM 8) was selected due to its long temporal data availability and medium resolution (30 m). Satellite data processing was implemented using the Google Earth
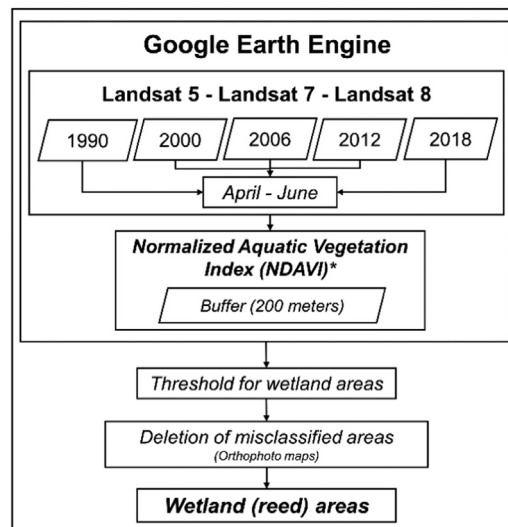
Fig. 1. Methodological framework for assessing the mapping "Fibres and other materials for construction" supply.

Engine Platform (GEE) [23]. GEE is a cloud-based platform for geospatial processing analysis, with enormous datasets and satellite imagery available. Within the GEE and using Landsat imagery, we calculated the Normalised Difference Aquatic Vegetation Index (NDAVI) by Villa et al. [24] to map reed areas around the lakes:

$$NDAVI = \frac{(NIR\,band - Blue\,band)}{(NIR\,band + Blue\,band)}$$

We selected images with a temporal constraint of one year and only comprising the months of May to September to reduce the effects of snow cover and dry vegetation, as in other studies. A buffer area of 200 m was defined around the lakes based on the lake polygons. This was done *a priori* in ArcGIS 10.8. Since the objective was to map ES from a multi-temporal perspective, NDAVI was calculated for 1990, 2000, 2006, 2012,and 2018. The resulting product (NDAVI) was post-processed in ArcGIS 10.8 to isolate a value range which would coincide with reed areas using orthophoto maps extracted from the Lithuanian Geoportal (www.geoportal.lt) for the corresponding years. Finally, we removed the misclassified using orthophoto maps and calculated the area in a 200 m buffer around the lakes. Detailed steps are described below:

Buffer area: the 200 m buffer area was calculated in ArcGIS 10.8 using the "Buffer" tool, defining 200 m as "distance" and choosing "OUTSIDE_ONLY" for the "Side Type". The resulting shapefile was uploaded to GEE as an "asset".

NDAVI: we used atmospherically corrected surface reflection data from the Landsat TM sensor available on GEE (e.g., LAND-SAT/LT05/C02/T1_L2 – courtesy of the U.S. Geological Survey). A temporal restriction was implemented using ".filterDate" argument for a year (e.g., .filterDate('1990–01–01', '1990–12–31')), and "Filter.calendarRange" argument for the month's May to September (e.g., "filter(ee.Filter.calendarRange(5,9,'month')"). Also, a restriction for cloud cover was implemented for images with less than 10% cover using the argument ".filterMetadata('CLOUD_COVER', 'less_than', 10)". To filter images only covering Lithuania, we drew a Region of Interest (ROI) polygon within GEE as an input to the ".filterBounds" argument. A cloud mask was applied based on a standard script within GEE (e.g., "maskL457sr"), which also includes the implementation of Landsat scaling factors. After this, a composite of images was condensed to one image based on an arithmetic mean using the argument ".median()". We chose only some bands from the median product (e.g., B1–B5, B7) using the argument "select()". We clipped the resulting image using the 200 m lake polygons shapefile as input, using the argument ".clip()". The calculation of NDAVI was implemented within the GEE, choosing the Near Infrared (NIR) and Blue bands of Landsat 5 and Landsat 8, respectively. The variable "ndavi" was normalised using the argument ".normalizedDifference()" and exported as GeoTiff file using the argument "Export.image.toDrive(). In ArcGIS 10.8, NDAVI threshold values were defined based on visual adjustment of reed areas using orthophoto maps. A reclassification was done using ArcGIS 10.8 "Reclassify" tool to define the values within the threshold. The reclassified raster was converted to polygons using ArcGIS 10.8 "Raster to Polygon". The misclassified polygons were deleted. This was done for each lake and year. The identified reed polygons were intersected with the 200 m buffer polygon with reed polygons, using ArcGIS 10.8 "Intersect" tool. The "Dissolve" tool aggregated all reed polygons for each lake (based on lake ID information of the HydroLAKES database). The total reed area per lake was calculated by adding a new field to the "table of contents" of the dissolved shapefile and using the "Calculate geometry", and then dividing the reed area by the lake polygon area (information available in the HydroLAKES database).

Provisioning ES: water used for non-drinking purposes

Supply: The supply of water used for non-drinking purposes ES was calculated based on the lake water volume availability (Fig. 2).
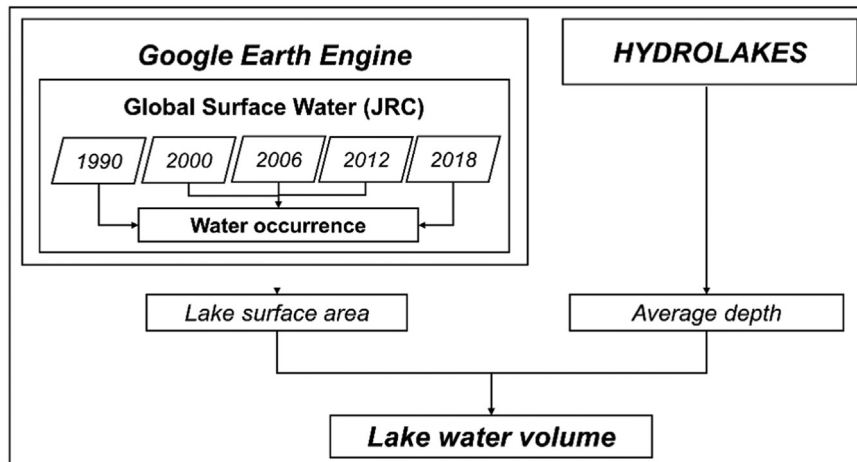
Fig. 2. Methodological framework for assessing the mapping "Water used for non-drinking purposes" supply.

Since there was no data available for all lakes in Lithuania, it was necessary to find a proxy. Based on literature (e.g., [25,26]), a theoretical relation of water volume can be inferred based on surface water area and average lake depth. The lake's average depth was acquired from the HydroLAKES database, and the water surface water extent was acquired from the Global Surface Water database of the Joint Research center [27]. The water extent was calculated for 1990, 2000, 2006, 2012, and 2018. The theoretical water volume was calculated by multiplying the water extent by the average depth for each lake.

First, the lake surface area was calculated by importing the Global Surface Water product "JRC Yearly Water Classification History, v1.4" ("JRC/GSW1_4/YearlyHistory") within the GEE platform. A year filter was applied using the argument ".filter(ee.Filter.eq('year',))" (e.g., "filter(ee.Filter.eq('year', 2020)"). This was done for each year analyzed. The image was acquired by using the argument ".first()", and the surface extent of permanent water was extracted using the argument " Eq. (3)" (which is the band for permanent water). The resulting image was clipped using the argument ".clip()" using the lake 5 km buffer lake polygons shapefile as an input asset and exported as a GeoTiff file using the argument Export.image.toDrive()

In ArcGIS 10.8, the raster image was transformed to polygons using the tool "Raster to Polygon", and the final surface water extent area was calculated by adding a new field in the "table of contents" in ArcGIS and using the "Calculate Geometry" tool. Based on lake ID, the area and average water depth information were joined using the function "join" in ArcGIS.

The final step was done by adding a new field in the "table of contents" and using the "field calculator" function. Surface water extent was multiplied by the average water depth.

Flow: The flow of water for non-drinking purposes ES was calculated based on the irrigation channels present in the 5 km buffer area around the lakes (Fig. 3).

It represents the potential water flow from the lake polygons to agricultural areas. We utilised data from the INSPIRE (Waterbody) database (www.inspire.ec.europa.eu). Based on (1) how many irrigation lines cross the lake polygons and (2) the length of the irrigation line, we calculated the flow of this ES.

The shapefile "water lines" was added to ArcGIS 10.8 and clipped using the 5 km buffer area of the lake polygons shapefile as the input layer using the "Clip" tool. The number of connections (irrigation lines) crossing each lake was calculated using the "Dissolve" within each lake buffer area. The "Dissolve" tool was used again to sum the length of the water lines crossing each lake (information in the original database). Both shapefiles were joined using "Spatial Join" based on lake ID, and the total flow was calculated by adding a new field in the "table of contents" and using the "Field Calculator" function of ArcGIS 10.8. Finally, multiplication was done based on the number of connections and the length of connection for each lake.

Demand: The demand for water for non-drinking purposes ES was calculated based on the agricultural areas within the 5 km buffer of lake polygons (Fig. 4).

We used the Corine Land Cover (CLC) (www.land.copernicus.eu) data for 1990, 2000, 2006, 2012,and 2018. The CLC level 3 data were reclassified into nine LULC classes: 1 - urban; 2 - cropland, 3 - grassland; 4 - woodland and forest; 5 - heathland and shrub; 6 - sparsely vegetated areas; 7 - wetlands; 8 - rivers and lakes; and 9 - marine inlets and transitional waters. This reclassification was based on the "Mapping and Assessment of Ecosystems and their Services" (MAES) ecosystem types [28].

In ArcGIS 10.8, the CLC was reclassified based on MAES ecosystem types using the "Reclassify" tool. The reclassified raster was transformed into polygons using the "Raster to Polygon" tool. In this case, we selected the LULC class 2 – cropland using the "select by attribute" function of ArcGIS 10.8 and extracted the polygons as a new shapefile. We then intersected the polygons with the 5 km buffer lake polygon shapefile using the "Intersect" tool. We used ArcGIS 10.8 "Dissolve" tool using lake ID to get all polygons aggregated per lake. A new field in the "table of contents" was added, and using the "Calculate Geometry" function, calculate the croplands area per lake.
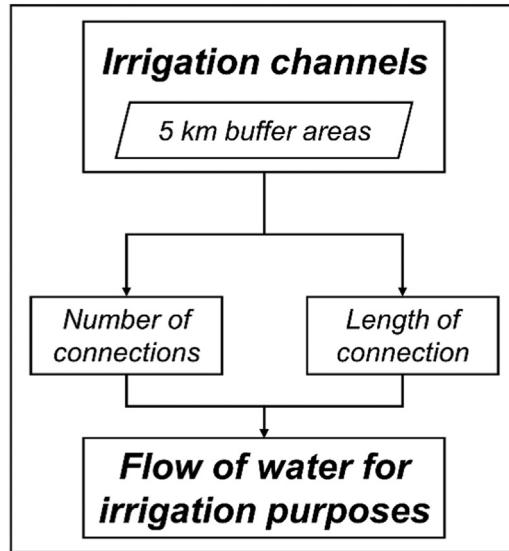
Fig. 3. Methodological framework for assessing the mapping "Water used for non-drinking purposes" flow.
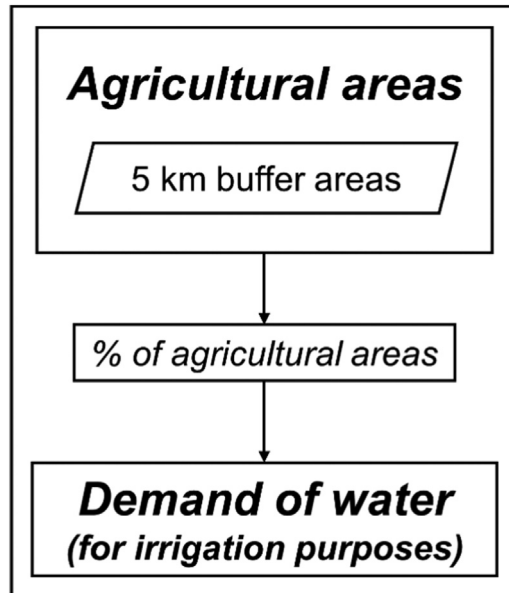

Fig. 4. Methodological framework for assessing the mapping "Water used for non-drinking purposes" demand.

The % of agricultural areas per lake was calculated by adding a new field in the "table of contents" using the "Field calculator" function and dividing the cropland area by the 5 km buffer area of each lake polygon. This was done for each year analyzed.

Regulating & maintenance ES: maintenance of nursery populations

Supply: The Maintenance of nursery populations ES was calculated based on important elements for fish populations to thrive: food, water quality and refugia [29] (Fig. 5).

The Environmental Protection Agency State Monitoring of lake ecosystems within the Ministry of Environment of Lithuania (https://aaa.lrv.lt/lt/veiklos-sritys/vanduo) collects samples on different hydro-chemical and physical parameters. Chlorophyll *a* and water transparency were available from the parameters sampled, which we utilised to represent food availability and water quality, respectively. Although the samples have a considerable temporal availability (from 2001 to 2021), the monitoring only covers some lakes in Lithuania. Therefore, to acquire data for all studies, it was necessary to utilise remote sensing imagery as a proxy for the parameters chosen. This was done by doing a band ratio regression using monitored data and selecting the best band combination to
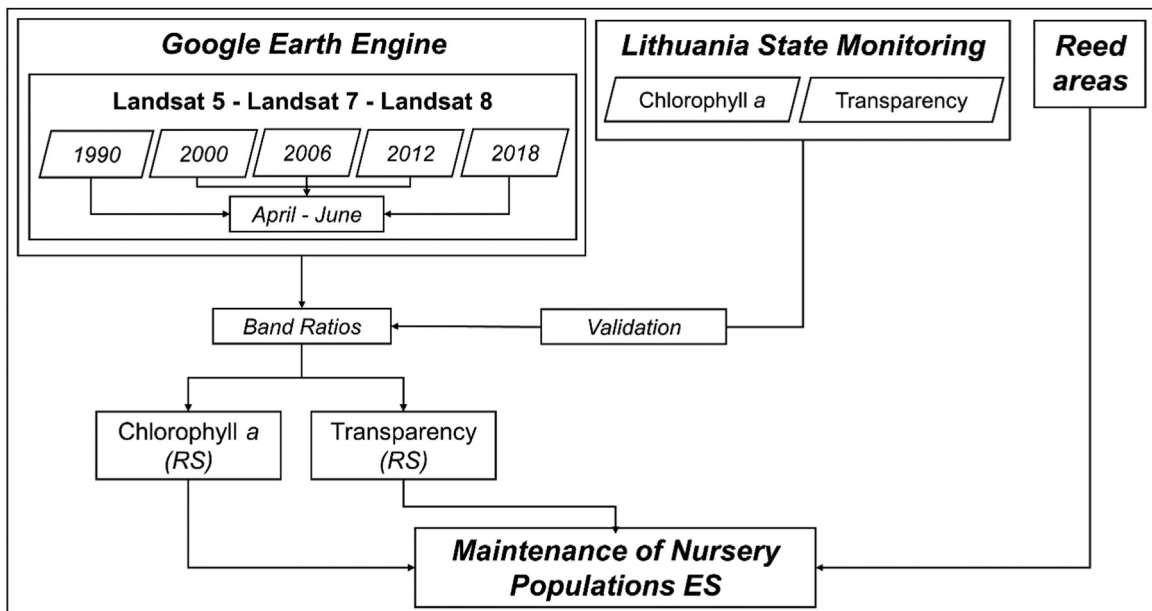
Fig. 5. Methodological framework for assessing the mapping "Maintenance of nursery populations" supply.

represent the parameter. This approach is widely used and well-established (e.g., [30,31]). Refugia was represented using reed areas as a proxy (calculated in step 2.1.1). Detailed steps are described below:

Monitoring data and points: Since this study covers the years 1990, 2000, 2006, 2012, and 2018, we extracted monitoring data for only these years (if available). The lake coordinates were acquired from the monitoring database. Hence, not all lake coordinates were available. The missing coordinates were acquired using Google Earth Pro-software based on the lake name. All monitored lakes coordinates were added to ArcGIS 10.8 as "csv" file, and the information was converted into points using the "display X and Y" function. These points were then exported as shapefile and added as an asset to the GEE platform.

Band Ratios: The band ratios were computed GEE platform following a similar procedure as in 2.1.1. We used atmospherically corrected surface reflection data from the Landsat TM sensor available on GEE (e.g., LANDSAT/LT05/C02/T1_L2 – courtesy of the U.S. Geological Survey) was used for analysis. A temporal restriction was implemented using ".filterDate" argument for a year (e.g., .filterDate('1990–01–01', '1990–12–31')) and "Filter.calendarRange" argument for the month's May to September (e.g., "filter(ee.Filter.calendarRange(5,9,'month')"). A cloud cover filter was implemented for images with less than 10% cover using the argument ".filterMetadata('CLOUD_COVER', 'less_than', 10)". To filter images only covering Lithuania, we drew a Region of Interest (ROI) polygon within GEE as an input to the ".filterBounds" argument. Finally, a cloud mask was applied based on a standard script within GEE (e.g., "maskL457sr"), including Landsat scaling factors' implementation. This resulted in a composite of images that condensed to one single image based on an arithmetic mean using the argument ".median()". Again, only some bands were chosen from the median products (e.g., B1–B5, B7) using the argument "select()". Only some bands were selected (e.g., B1–B5, B7) using the argument "select()", and the image was clipped using lake polygons shapefile as input, using the argument ".clip()". All possible band combinations (e.g., Band1/Band2) were calculated, normalised (e.g., ".normalizedDifference(['SR_B1', 'SR_B5'])") and added as bands to the clipped image, using the arguments ".addBands()" and ".map()".

Extract image information based on monitoring points. The monitoring points shapefile (asset) was used to extract information band ratios image using the argument ".sampleRegions()" within GEE, and the data was then exported as "csv" file using the argument "Export.table.toDrive()".

Monitoring and remote sensing data regression: The extracted data (csv file) was log10 transformed using the formula "LOG10()" processed in MS Excel 2016. We did multiple regressions using the monitoring data (for all years) and the remote sensing data (for all years). The band or band ratio that yielded the best overall r^2 was chosen as a proxy for the analyzed variable.

Extracting and normalising raster files (for all lakes and variables): The median image with all bands and band ratios was clipped using the lake polygons using the argument ".clip()" in GEE. The identified relevant band or band ratio was selected using the argument ".select()" and extracted as GeoTiff using the argument "Export.image.toDrive(). In RStudio software [32], using the formula $(x - minValue(x)) / (maxValue(x) - minValue(x))$, the remote sensed chlorophyll a and transparency raster files were normalised and extracted using the "WriteRaster()".

Final calculations: in ArcGIS 10.8 and using the "Zonal Statistics" tools, the mean value of the remote sensed parameters were computed using the lake polygon shapefile as the input layer. The reed areas shapefile (from step 2.1.1) values were normalised using the formula $(x - minValue(x)) / (maxValue(x) - minValue(x))$ by adding a new field in the "table of contents" and using the "Field
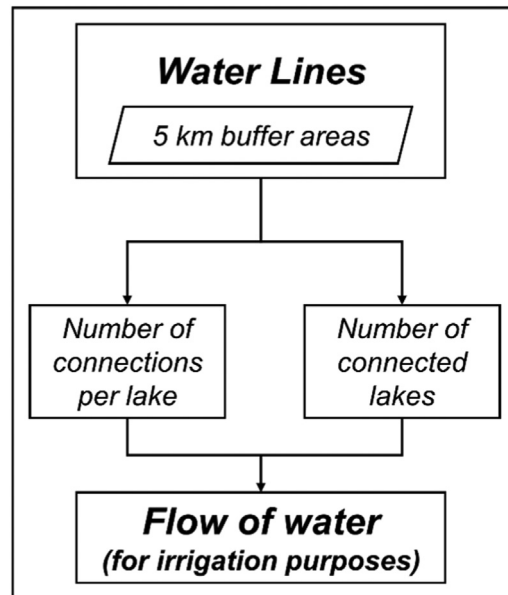
Fig. 6. Methodological framework for assessing the mapping "Maintenance of nursery populations" flow.

calculator" function. A "Spatial Join" was done based on the lake ID. Finally, a new field in the "table of contents" and using the "Field calculator" function, the three variables were overlayed (summed).

Flow: The connectivity between lakes was used as a proxy to represent the potential flow of fish populations. We utilised information on all water lines (irrigation, rivers and streams) crossing each lake polygon (Fig. 6).

We counted the number of connections between lakes and how many lakes connected through these water lines.

In ArcGIS 10.8, we added and clipped the water lines shapefile using the 5 km buffer area of the lake polygons shapefile as the input layer using the "Clip" tool. The number of connections (irrigation lines) was calculated by crossing each lake using the "Dissolve" within each lake buffer area. The number of connected lakes was calculated using the "Dissolve" tool for each water line (each line has an ID number from the original database), resulting in a corresponding number of lakes crossed. The final number of connected lakes was calculated by summing the total number of lakes crossed per each water line identified in step 3, using the "Dissolve" tool of ArcGIS 10.8. The final flow was calculated by adding joining data using the ArcGIS 10.8 "Spatial Join" tool based on lake ID. A new field was added in the "table of contents" and using the "Field calculator" function by multiplying the number of water line connections by the number of connected lakes.

Regulating & maintenance ES: nutrient regulation

Supply: The supply of nutrient regulation ES represents the capacity of an ecosystem to filter and remediate nuisances from the surrounding environment. This service is regulated by nitrogen fixation and denitrification in lake ecosystems. Five indicators represented this ES: chlorophyll a, Nitrate (NO3), Total Phosphorus (TP), Total Nitrogen (TN), and the percentage of forest cover around the lakes (Fig. 7).

These indicators were chosen based on spatial and temporal data availability. Chlorophyll represents a pathway of nitrogen fixation. Cyanobacteria are known for fixating nitrogen from the atmosphere [33], and chlorophyll has been widely used in other works as an indicator to represent this nutrient regulation mechanism (e.g., [34]). Nitrate (NO3) represents the mechanism of denitrification, which is the reduction of nitrate to gaseous forms of nitrogen [35]. This indicator has been used in other studies (e.g., [36]) as an integral part of nutrient regulation mechanisms. Total P and Total N are nutrient stocks within a body of water. Its amount is a "product" of nutrient regulation mechanisms. Finally, the percentage of forest cover is used as a proxy to represent filtration occurring in the area surrounding the water bodies. Forests are known for their capacity to filter and sequester nutrients, which are carried out by rainfall (e.g., [37]). The chlorophyll a, NO3, TP and TN were acquired based on the same process described in 2.3.1 by a regression equation between measured parameters and remote sensing data. Forest cover (%) was acquired following the same procedure in 2.2.3 for cropland areas, using the LULC class 4 – woodland and forests. Detailed steps are described below:

Monitoring data and points: Since this study covers the years 1990, 2000, 2006, 2012, and 2018, we extracted monitoring data for only these years (if available). The lake coordinates were acquired from the monitoring database. Hence, not all lake coordinates were available. The missing coordinates were acquired using Google Earth Pro-software based on the lake name. All coordinates were added to ArcGIS 10.8 as "csv" file and converted to points using the "display X and Y" function. These points were then exported as shapefile and added as an asset to the GEE platform.
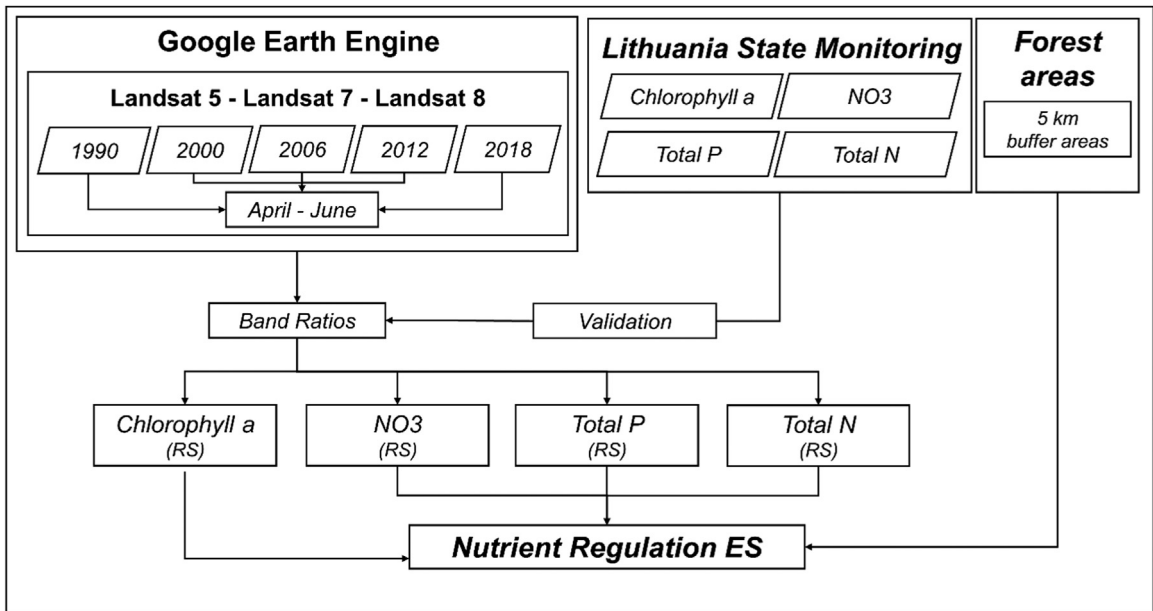
Fig. 7. Methodological framework for assessing the mapping "nutrient regulation" supply.

Band Ratios: band ratios were computed GEE platform following a similar procedure as in 2.1.1. We used atmospherically corrected surface reflection data from the Landsat TM sensor available on GEE (e.g., LANDSAT/LT05/C02/T1_L2 – courtesy of U.S. Geological Survey) was used for analysis. A temporal restriction was implemented using ".filterDate" argument for a year (e.g., .filterDate('1990–01–01', '1990–12–31')), and "Filter.calendarRange" argument for the months' May to September (e.g., "filter(ee.Filter.calendarRange(5,9,'month')"). A cloud cover restriction was also implemented for images with less than 10% cover using the argument ".filterMetadata('CLOUD_COVER', 'less_than', 10)". To filter images only covering Lithuania, we drew a Region of Interest (ROI) polygon within GEE as an input to the ".filterBounds" argument. A cloud mask was applied based on a standard script within GEE (e.g., "maskL457sr"), which also includes the implementation of Landsat scaling factors. The resulting composite of images was condensed to one single image based on an arithmetic mean using the argument ".median()"., and using the argument "select()", only some bands were chosen from the median products (e.g., B1–B5, B7).

The image was clipped by using lake polygons shapefile as input, using the argument ".clip()". All possible band combinations (e.g., Band1/Band2) were calculated and normalised (e.g., ".normalizedDifference(['SR_B1', 'SR_B5'])") and added as bands to the clipped image, using the arguments ".addBands()" and ".map()".

Extract image information based on monitoring points: the monitoring points shapefile (asset) was used to extract information band ratios image using the argument ".sampleRegions()" within GEE. The sampled data was then exported as "csv" file using the argument "Export.table.toDrive()".

Monitoring and remote sensing data regression: The sampled data log10 was transformed using the formula "LOG10()" in MS Excel 2016. A regression was done using the monitoring data (for all years) and the remote sensing data (for all years). The band or band ratio yielded the best overall r^2 as a proxy for the analyzed variable.

Extracting raster files (for all lakes and variables): the median image with all bands and band ratios were clipped using the lake polygons using the argument ".clip()" in GEE. The relevant band or band ratio was selected using the argument ".select()" and extracted as GeoTiff using the argument "Export.image.toDrive().

Normalising raster files: The remote sensed chlorophyll *a* and transparency raster files were normalised in RStudio using the formula (x - minValue(x)) / (maxValue(x)- minValue(x)) and extracted using the "WriteRaster()" argument in RStudio.

Forest areas: a reclassification of CLC based on MAES ecosystem types using the "Reclassify" tool of ArcGIS 10.8 and transformed to polygons using the "Raster to Polygon" tool. The LULC class "4 – woodland and forests" was selected using the "select by attribute" function of ArcGIS 10.8 and intersected with the 5 km buffer lake polygon shapefile using the "Intersect" tool. The ArcGIS 10.8 "Dissolve" tool uses lake ID to merge all forest polygons per lake. A new field was added in the "table of contents", and using the "Calculate Geometry" function, calculate the area of croplands per lake. Finally, the % of forest areas per lake was calculated by adding a new field in the "table of contents" using the "Field calculator" function and dividing the forest area by the 5 km buffer area of each lake polygon. This was done for each year analyzed.

Final calculations: in ArcGIS 10.8 and using the "Zonal Statistics" tools, the mean value of the remote sensed parameters were computed using the lake polygon shapefile as the input layer. The % of forest areas values were normalised using the formula (x - minValue(x)) / (maxValue(x)- minValue(x)) by adding a new field in the "table of contents" and using the "Field calculator" function
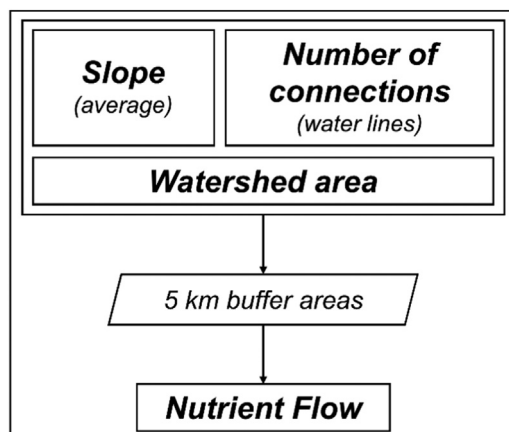
Fig. 8. Methodological framework for assessing the mapping "nutrient regulation" flow.
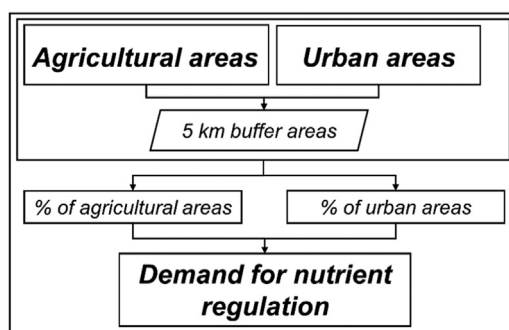

Fig. 9. Methodological framework for assessing the mapping "nutrient regulation" demand.

of ArcGIS 10.8. A "Spatial Join" was done based on the lake ID, and by adding a new field in the "table of contents" and using the "Field calculator" function, the variables were overlayed (summed).

Flow: The flow was calculated based on three indicators related to water transport to water bodies: slope, watershed area of each lake and n° of connections from the waterline (Fig. 8).

The slope was chosen to represent the steepness of the terrain, meaning that higher slope (average) values will, in theory, increase the runoff. The Watershed area represents the area of land that drains water into a specific water body. Higher areas, in theory, drain more water into a water body, thus increasing the nutrient flow. The number of water lines represents the pathways through which nutrients enter the water body.

The variable *slope* was calculated using the "Slope" tool of ArcGIS 10.8 based on the digital elevation model (DEM) for Lithuania with a 10 m resolution. The resulting raster was clipped using the 5 km buffer area of the lakes polygons shapefiles as input layers. Using ArcGIS 10.8 "Zonal Statistics" tool, we calculated the average slope for each lake, using the 5 km buffer area shapefile as the input layer. The variable *number of water lines crossing each lake* was previously calculated in step 2.3.2. The variable *watershed area* of each lake was available in the HydroLAKES database. The final calculation was done by joining all variables using the "Spatial Join" tool in ArcGIS 10.8 based on lake ID. A new field was added in the "table of contents", and using the "Field calculator" function, the values were normalized following the formula $(x - minValue(x)) / (maxValue(x) - minValue(x))$. The final flow was calculated by adding a new field in the "table of contents" using the ArcGIS 10.8 "Field calculator" function by summing the normalized values of the three variables.

Demand: The demand for nutrient regulation was calculated based on the two most common sources of nutrient loads to lake ecosystems: agricultural and urban areas (Fig. 9).

Agricultural and urban areas were extracted from CLC for 1990 ,2000, 2006 ,2012, and 2018, following the same procedure as in 2.2.3.

Urban areas: we reclassify the CLC based on MAES ecosystem types using the "Reclassify" tool of ArcGIS 10.8. and transformed the resulting raster to polygons using the "Raster to Polygon" tool. We selected the LULC class "1 – urban" using the "select by attribute" function of ArcGIS 10.8 and extracted the polygons as a new shapefile. We then intersected the polygons with the 5 km buffer lake polygon shapefile using the "Intersect" tool. We used the "Dissolve" tool of ArcGIS 10.8 using lake ID to aggregate all urban areas polygons per lake. Add a new field in the "table of contents", and using the "Calculate Geometry" function, calculate the area of
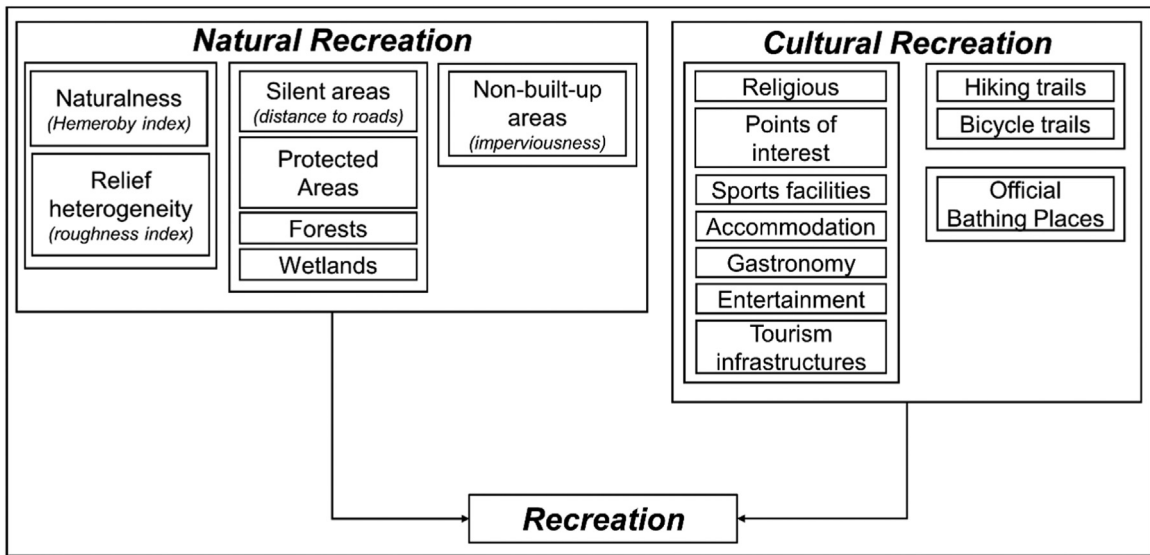
Fig. 10. Methodological framework for assessing the mapping "recreation" supply.

croplands per lake. The % of urban areas per lake was calculated by adding a new field in the "table of contents" using the "Field calculator" function and dividing the forest area by the 5 km buffer area of each lake polygon. This was done for each year analyzed.

Cropland areas: the % of cropland areas per lake was calculated precisely as above (for urban areas), but selecting the LULC class "2 – croplands".

Final calculation. Both processed shapefiles were joined using the "Spatial Join" tool of ArcGIS 10.8 based on lake ID, and the final demand was calculated by adding a new field in the "table of contents" using the "Field calculator" function by summing the two variables.

Cultural ES: recreation

Supply: Recreation ES was mapped based on the methodology developed by Kalinauskas et al. [38] and Inácio et al. [39]. This methodological approach defined recreation as an ES based on two components: natural and cultural recreation (Fig. 10).

Natural recreation includes all ecosystem elements that support a recreational experience in nature. For example, the presence of protected areas, where the ecosystem is, in theory, more preserved. Cultural recreation includes all anthropogenic elements related to heritage, religion, and infrastructure that facilitates recreation and allows a better experience in connection to nature. We have adapted, and modified elements within each recreation component targeted to lake ecosystems. In this work, we defined natural recreation based on the following variables: naturalness, relief heterogeneity, silent areas, protected areas, forest areas, wetlands, and non-built-up areas. Cultural recreation was defined based on the following variables: religious locations, points of interest, sports facilities, accommodation, gastronomy, entertainment, tourism-supporting infrastructures, hiking trails, biking trails, and official bathing places. Before modelling each recreation component, a multicollinearity test was performed to exclude potential collinear variables. We then modelled each component and overlayed the information, creating a final recreation ES index. Detailed steps are described below:

Natural recreation. *Naturalness was* calculated based on the Hemeroby index as in Walz and Stein [40]. This index measures the degree of human influence on landscape [40]. We calculated naturalness by reclassifying the LULC data (as in 2.2.3) by attributing a Hemeroby index. We clipped the resulting raster file using the 5 km buffer area around lakes. *Relief heterogeneity* was calculated based on the roughness index. It was calculated using a DEM. We calculated the roughness index in QGIS 2.22 [41], which has a dedicated "roughness" tool. *Silent areas* were calculated based on the distance to roads. For this, (1) we added a road network (primary, secondary, and tertiary) as shapefile to ArcGIS 10.8; (2) calculated distance based on the "Euclidean distance" tool of ArcGIS 10.8; (3) clipped the resulting raster file using the "Clip" tool using the 5 km buffer area around lakes; and (4) used the "Zonal Statistics" tool to calculate the mean distance for each lake based on the 5 km buffer area shapefile. *Protected areas* was calculated based on the distance to protected areas. For this (1) we added the protected areas shapefile in ArcGIS 10.8; (2) calculated the distance the "Euclidean distance" tool of ArcGIS 10.8; (3) clipped the resulting raster file using the "Clip" tool using the 5 km buffer area around lakes; and (4) used the "Zonal Statistics" tool to calculate the mean distance for each lake based on the 5 km buffer area shapefile. *Forests* were calculated based on the distance to woodland and forests. For this (1) we added the polygons of LULC class "4 - woodland and forests" (see step 2.2.3) as shapefile in ArcGIS in 10.8; (2) calculated the distance the "Euclidean distance" tool of ArcGIS 10.8; (3) clipped the resulting raster file using the "Clip" tool using the 5 km buffer area around lakes; and (4) used the "Zonal Statistics" tool to calculate the mean distance for each lake based on the 5 km buffer area shapefile. *Wetlands* were calculated
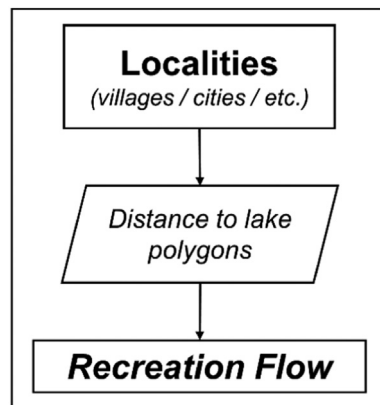
Fig. 11. Methodological framework for assessing the mapping "recreation" flow.

based on the distance to wetland areas. For this (1) we added the wetland polygons as shapefile in ArcGIS 10.8; (2) calculated the distance the "Euclidean distance" tool of ArcGIS 10.8; (3) clipped the resulting raster file using the "Clip" tool using the 5 km buffer area around lakes; and (4) used the "Zonal Statistics" tool to calculate the mean distance for each lake based on the 5 km buffer area shapefile. *Non-built-up areas* were calculated based on imperviousness. Imperviousness captures the percentage and change of soil sealing (www.land.copernicus.eu). For this, (1) we added the raster file into ArcGIS 10.8; (2) clipped the resulting raster file using the "Clip" tool using the 5 km buffer area around lakes; and (3) used the "Zonal Statistics" tool to calculate the mean distance for each lake based on the 5 km buffer area shapefile.

The variables *naturalness, relief heterogeneity, silent areas* were normalised following the formula (x - minValue(x)) / (maxValue(x)- minValue(x)) using the "raster calculator" tool in ArcGIS 10.8. The variables *protected areas, forests, wetlands,* and *non-built-up areas* were inverse-normalised following the formula (maxValue(x) - x) / (maxValue(x)- minValue(x)). The final natural recreation raster was created by overlaying the variables using the "Raster calculator" tool of ArcGIS 10.8.

Cultural recreation: all variables of this section were available as points. The processing of the variables followed the same procedure: (1) adding the points shapefile in ArcGIS 10.8; (2) calculating the density of points using the "Kernel density" tool of ArcGIS 10.8; (3) clipping the resulting raster files using the "Clip tool" of ArcGIS 10.8 using the 5 km buffer area around lakes; and (4) using the "Zonal Statistics" tool of ArcGIS 10.8 to calculate the mean density for each lake based on the 5 km buffer area around lakes. All variables were inverse-normalised following the formula (maxValue(x) - x) / (maxValue(x)- minValue(x)); using the "raster calculator" tool in ArcGIS 10.8 The final cultural recreation raster was created by overlaying the variables using the "raster calculator" tool in ArcGIS 10.8.

Natural + recreation: the final recreation ES was calculated by overlaying the natural recreation and cultural recreation raster files using the "raster calculator" tool of ArcGIS 10.8.

Flow: Recreational ES flow was calculated based on the proximity of all localities in Lithuania to lakes (Fig. 11).

This was done by using the "Near" tool of ArcGIS 10.8, using the localities point shapefile as the input layer and the lake polygons as "near layer".

Conclusion

- We provide a multi-temporal methodological framework to assess and map different lake ES. The development of new methods for mapping ES and its dimensions (supply, flow, and demand) is essential for a better understanding of ES dynamics.
- We do it based on a quantitative approach, which allows for more robust and reliable results. This type of approach is desirable and often required in decision-making processes. New methodologies and ES mapping outputs are essential pillars for reaching targets set by environmental policy instruments at national (e., Biodiversity 2030) and global (e.g., UN SDGs, Aichi Targets) scales.
- The multi-method framework was designed to assess and map ES in a simplified way to allow its replicability and transferability to other systems. Using open-access and freely available data from national, regional and international databases enables the applicability of the methods to different lake ecosystems (e.g., other European Lakes).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

M. Inácio: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **M. Das:** Writing – review & editing. **D. Barceló:** Writing – review & editing. **P. Pereira:** Supervision, Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

Acknowledgments

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2023.102015.

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