A framework of freshwater and saline lake typology classification through leveraging hydroclimate, spectral, and literature evidence

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Abstract

Separating saline and freshwater lakes is of immense importance for monitoring lentic ecosystems and assessing surface freshwater availability. However, conventional lake typology often relies on in situ salinity measurements, thus limiting the feasibility of a global application. To enable an effective workaround, we here propose and test a framework that classifies saline and freshwater lakes through systematic, integrated leveraging of hydrological, climatological, spectral, and literature evidence. In principle, saline lakes were sequentially identified if a lake is (1) located at the drainage terminal where salinity tends to build up as a result of lacking surface outflow (hydrological evidence), (2) distributed in an arid/semiarid climate with lacustrine evaporites visible from a high-resolution multispectral image (climatological and spectral evidence), or (3) documented to be (sub)saline or have measured salinity exceeding the maximum freshwater threshold (literature evidence). We applied the HydroSHEDS hydrography dataset, the Köppen-Geiger climate classification, and a large volume of spectral satellite images and literature to implement this framework. This framework was tested on the Tibetan Plateau using the Landsat-based, 30-m-resolution UCLA circa-2015 global lake mask, and the result was benchmarked against the Chinese national lake survey. Our collected literature shows a 95% agreement between the lake types classified using hydrological, climatological, and spectral evidence alone and those documented in the literature. After further corrections based on the literature evidence, our final classification reached an overall accuracy of nearly 70% in terms of lake count and 94% in lake area. Given such promising accuracies, we further applied our framework to Australia, showcasing its effectiveness for lake typology classification without additional in situ surveys across the world's most saline continent. While our method, in theory, results in a conservative recognition of saline lakes and should not be considered a complete substitute for in situ surveys, the proposed

38 framework demonstrates potential for performing global-scale freshwater and saline lake typology

39 classification with reasonable accuracies, using only remote sensing images, open-source

40 hydrography and climate data, and existing literature.

1. Introduction

Fresh surface water is one of the most important natural resources for ecosystems and human societies (Oki and Kanae, 2006; Schewe et al., 2014; Wada et al., 2011). There are more than one billion cubic kilometers of water on the Earth (Schlesinger and Bernhardt, 2013; Chahine, 1992; Jackson et al., 2001; Schmitt, 1995), but the storage of fresh water only accounts for about 3% of the water mass in the hydrosphere. However, only 0.5% of the freshwater supplies can be easily accessed by people, as over 80% of all available freshwater is stored in ice sheets and glaciers (Kashid and Pardeshi, 2014). Climate change and a growing and more affluent population are placing significant pressure on freshwater resources worldwide, which is likely to have increasingly negative consequences. The impacts of these challenges are numerous, including earlier and shorter melt seasons for snowpack and glaciers, reduced streamflow during summer and fall, and greater human consumptive water demands (Wada et al.; 2016; Barnett et al., 2005).

There are several major components of freshwater resources for human water consumption, including river flow, groundwater, and desalinated water. But the most readily accessible liquid water stock resides in lakes, ponds, and reservoirs (Oki and Kanae, 2006). River flow and lake storage are two main components of the surface water system. River flow includes discharge in the river/stream channels accumulated from surface runoff and base flow (Stricker, 1983), and lake storage contains water in two major types of lakes: freshwater lakes and saline lakes. While water in saline lakes may not be directly used for human consumption, saline lake systems have unique environmental and ecological functions, and they influence the biological dynamics of ecosystems that depend on the lakes (Jódar et al., 2020). Since freshwater and saline lakes offer different ecologic and societal benefits, it is important that we know where these types of lakes are located and their storage volume. The spatial distribution of freshwater and saline lakes, and their

4

64 interactive dynamics in area and storage, are of essential significance for monitoring surface

65 freshwater water availability and regional and global climate change (Alley et al., 1993). However,

66 because of the extensive distribution and dynamic nature in the global lake systems (Adrian et al.,

67 2009; Pekel et al., 2016; Smith et al., 2005; Song et al., 2016; Wang et al., 2012; Wang et al., 2014;

68 Wang et al., 2017; Yamazaki et al., 2015; Yao et al., 2019), our knowledge of their accurate

69 extents, quantity, and quality (including saline and freshwater typology) remains incomplete

70 (Messager et al., 2016; Cael et al., 2017).

71 Existing studies on global-scale lake abundance focus on lake quantity, areas, and volumes

72 (Messager et al., 2016; Cael et al., 2017). The Mullard Space Science Laboratory (MSSL) Global

73 Lakes Database (MGLD) has the locations and types (closed lakes/open lakes/reservoirs) of 1415

74 inland natural and artificial water bodies (Birkett and Mason, 1995). The Shuttle Radar

75 Topography Mission (SRTM) Water Body Data (SWBD) (SWBD, 2005; Slater et al., 2006)

76 constitutes water bodies with a total area of 2.76 million km^2. However, this dataset only collected

77 water bodies from 56°S to 60°N, limited by the spatial coverage of the SRTM. To fill in this

78 incomplete coverage, Carroll et al. (2009) created a comprehensive global water mask at 250-m

79 resolution by combining SWBD and MODIS imagery. About 254,000 water bodies larger than 0.1

80 km^2 were mapped in the Global Lakes and Wetlands Dataset (GLWD) (Lehner and Döll, 2004).

81 The Global Inland surface Waterbody dataset (GIW) (Feng et al., 2016) mapped global water

82 bodies from 30-m Landsat images, covering a total area of ~3.65 million km^2. However, some of

83 the included water bodies are ephemeral or intermittent, while some others were mapped

84 incompletely because of cloud contamination. In addition, there is no explicit distinction between

85 rivers and lakes/reservoirs. The more recently published HydroLAKES dataset mapped 1.42

86 million global lakes and reservoirs larger than 0.1 km^2. By considering the variability of not only

lake areas but also the terrain in the vicinity of the lakes, Messager et al. (2016) integrated a large number of documentation and geostatistical models to estimate the depth and volume of each inventoried lake/reservoir. One of the major limitations of HydroLAKES is the negligence of a great number of lakes smaller than 0.1 km^2.

Very recently, Birkett et al. (2022) produced a new database consisting of three individual lake and reservoir datasets with a total of 6,495 waterbody records: 1. Global Reservoir and Lakes Database (GREALD) with global water bodies larger than 100 km^2, 2. GREALD with water bodies (mid-low latitude open lakes and all-latitude reservoirs) with surface area 10-99 km^2, and 3. Global Ephemeral Lakes Database (GELD) with ephemeral lakes larger than 100 km^2. This database contributes to surface water level monitoring using satellite radar altimetry. All three datasets classified water bodies as reservoirs, open lakes, closed lakes, ephemeral lakes, and lagoons. However, these datasets do not classify the limited number of identified lakes as freshwater or saline lakes. Another recently published global lake dataset, GLAKES (Pi et al., 2022), contains 3.4 million global lakes and reservoirs and their area changes over the past four decades. It was produced using the Global Surface Water Occurrence (GSWO) dataset (Pekel et al., 2016) and deep learning methods. However, GLAKES also has no classification between freshwater and saline lakes, and the minimum lake size is 0.03 km^2. Among existing datasets, Sheng et al. (2016) produced a high-resolution global lake mask from cloud-free Landsat-8 images, which contains quality-controlled water extents of ~9 million perennial lakes and reservoirs larger than 0.004 km^2. The water extents correspond to representative inundation areas within the "stable lake season" during the initial 2.5 years (May 2013 to November 2015) of Landsat-8's operation (Lyons and Sheng, 2017; Sheng et al., 2016). This dataset, hereafter referred to as the "UCLA circa-2015 lake

109   dataset" or "circa-2015 lake dataset", substantially improved our understanding of the spatial

110   distribution of global lakes and reservoirs.

111   While these global waterbody datasets have advanced our understanding of the global

112   location, storage, and number of different types of surface water bodies, we still miss critical

113   information regarding the salinity of these water bodies. Distinguishing between freshwater and

114   saline lakes provides a more accurate estimation of available freshwater supplies for human

115   development (Abbott et al., 2019) and locates distinct ecosystems unique to lakes of different

116   salinities. Therefore, clearly understanding the locations of freshwater and saline lakes has

117   profound implications for water management and freshwater allocation. The most reliable way to

118   differentiate freshwater and saline lakes is to use the salinity of the lake water, although the

119   threshold of salinity that separates them varies depending on the purpose. In Hammer (1983) and

120   Wang (1993), a salinity of 0.05% is considered as the salinity threshold between freshwater and

121   saline lakes. However, due to the sheer number of global lakes and their diverse environmental

122   settings, it is practically impossible to determine the exact salinity of each lake.

123   Two widely used methods for distinguishing freshwater and saline lakes are field survey

124   and remote sensing (Harris, 1976; Ueda et al., 2000; Leidonald et al., 2019; Wang and Xu, 2008).

125   Both methods have advantages and limitations. Lake salinity can be obtained by directly

126   measuring the concentration of dissolved minerals in the water sample, or indirectly, it can be

127   inferred by measuring the density or conductivity of the lake water (Williams and Sherwood, 1994).

128   These field surveys provide high accuracy in salinity. However, field measurement prohibits large-

129   scale applications and is relatively time-consuming and costly. Compared to field surveys, remote

130   sensing provides a low-cost alternative to track the changes in salinity over time and space. For

131   example, soil salinization around lakes could be distinguished by using the unique signatures of

132 salts on multispectral or hyperspectral images (Safaee and Wang, 2020; Azarafza and Mokhtari,

133 2013; Wang and Xu, 2008; Abou et al., 2018). However, freshwater and saline lake classification

134 that relies on remote sensing methods is also challenging because satellite images are often affected

135 by changes in external environmental factors (Kim and Han, 2021; Huang et al., 2016), such as

136 the percentage of cloud coverage, atmospheric effects, and the sensor response. In addition, saline

137 lakes in different regions have various mineral constituents whose evaporites can exhibit different

138 spectral signatures and textures, and there are similarities between the spectral signatures of salts

139 and snow, ice, and impervious surface. Therefore, the accuracy of identifying saline lakes is

140 reduced compared to field survey and the salinity of the lakes is hard to be remotely quantified.

141 As a result, it is technically challenging to formulate a remote sensing algorithm that works

142 equivalently well for different individual lakes.

143   To strike a balance between applicability and accuracy, we here aim at developing and

144 validating a framework that leverages hydrological analysis, climatological evidence, spectral

145 remote sensing, and existing references to classify lake freshwater and saline types. The

146 organization of this paper is as follows. Section 2 introduces the testing and validation areas and

147 the used datasets. Section 3 uses the Tibetan Plateau as a testing site to describe the logic of our

148 lake type classification framework and showcase how it was implemented. The classification

149 results and the accuracy validation for the Tibetan Plateau are shown in Section 4, and in this

150 section, the classification approach is also applied in Australia as a case study. Section 5

151 summarizes our findings and discusses potential applications.

152

153 **2. Study areas and datasets used**

154 2.1 Study areas

155   We selected two study regions that are rich in saline lakes to demonstrate the efficacy of

156   our freshwater and saline lake classification framework. This general framework can be applied

157   globally. First, we applied our framework (see section 3 for more details) to the Tibetan Plateau.

158   The Tibetan Plateau has ample verified data classifying lakes as either saline or freshwater that

159   allowed us to extensively validate our approach. Once our model had been trained on the Tibetan

160   Plateau, we applied our framework to the entire continent of Australia to showcase the generality

161   and wide-applicability of our framework. Our rationale is that if our method can be effectively

162   applied in these saline lake-rich hotspots, it may in principle be applied at a global scale.

163   2.1.1 Tibetan Plateau

164   The Tibetan Plateau has an altitude of more than 4,000 meters and a land area of 2.5 million

165   km^2 (Zhang et al., 2011). One of the most well-known features is the large number and area of

166   lakes (Fig. 1). Zhang et al. (2014) estimated more than 32,000 lakes with a total area of over 43,000

167   km^2 on the entire Tibetan Plateau based on GeoCover 2000 Landsat imagery. Historically, the

168   Tibetan Plateau experienced substantive tectonic activities (Li and Fang, 1999) and glacial erosion,

169   resulting in a large number of depressions for the formation of terminal or endorheic lakes. As

170   rivers carry dissolved minerals into the terminal lakes but the lakes do not have a surface outlet,

171   salt is accumulated in the lakes through time. Moreover, there is plenty of solar radiation but

172   limited precipitation in the Tibetan Plateau, so the lake water becomes more saline as it evaporates.

173   The water cycle of the Tibetan Plateau, especially the dynamics in surface water storage,

174   can directly reflect the impacts of large-scale regional climate change. The Tibetan Plateau has a

175   complicated distribution of freshwater and saline lakes. Some of the largest saline lakes in China,

176   such as Qinghai Lake, Nam Co, and Siling Co, are all located on the Tibetan Plateau. The lakes in

177   the Tibetan Plateau are mainly terminal lakes, which are mostly saline, and are widely distributed

178   in the Changtang Plateau which has a large number of landlocked and arid watersheds. In the

179   context of climate warming and moistening in the Tibetan Plateau (Yang et al., 2014), terminal

180   lakes are more subject to expansion, indicating increasing relocation of freshwater resources

181   (mainly from increasing precipitation) to saline water resources (terminal lakes). In addition,

182   authoritative information of lake salinity and types on the Tibetan Plateau are accessible through

183   the Chinese national lake survey (CNLS) (see Section 3.7). For these reasons, the development

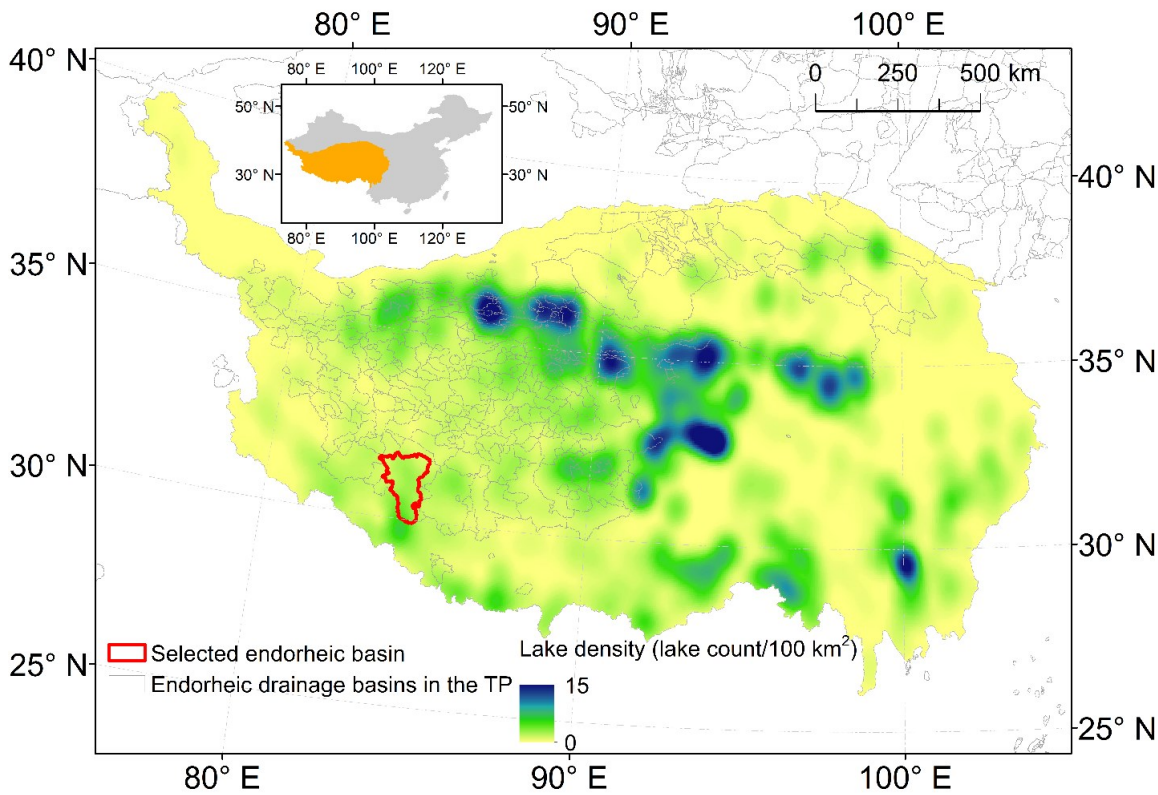184   and validation of our lake classification method are exemplified in the Tibetan Plateau.

185

186   **Fig. 1.** The studied Tibetan Plateau. Drainage basins in the Tibetan Plateau (including both

187   endorheic and exorheic basins) were derived from the HydroSHEDS 15-arc-second Drainage

188   Basins (Lehner et al., 2008). The background is lake count per $100\,km^2$ (generated from the UCLA

189   circa-2015 lake dataset) for the purpose of visualization. The inlet map shows the position of the

190   Tibetan Plateau in China.

191

192   2.1.2 Australia

193   Most of Australia is located in low and middle latitudes (10°S−40°S) and contains a variety

194   of climate zones (Sheng et al., 2016). The northeastern part of Australia has a tropical rainforest

195   climate, and the eastern part has a subtropical humid climate. There is relatively more precipitation

196   near coastal areas, and the southern part has a Mediterranean climate or a temperate maritime

197   climate (Oliver, 2005; Sheng et al., 2016).

198   The majority of the landmass in Australia is, however, dominated by arid and semiarid

199   climates (Byrne et al., 2008). The Tropic of Capricorn passes through the middle of Australia, thus

200   the main climate categories in Australia are the tropical and subtropical climate types. In terms of

201   the wind zone and the pressure zone in Australia, the area near the regression line (inside the

202   continent) is mainly controlled by the subtropical high-pressure zone (Wandres et al., 2016). The

203   suppressed precipitation forms a tropical desert climate in central Australia. Western Australia is

204   affected by the cooling and dehumidifying effects of the Australian cold current, so the west coast

205   also has a tropical desert climate (Beard, 1969). The extensive deserts are surrounded by savannas,

206   with high temperatures throughout the year and low precipitation. As a result of climatic aridity, a

207   large proportion of the landmass in Australia is landlocked or endorheic (Wang et al., 2018),

208   making it another hotspot with highly concentrated saline lakes. For these reasons, we selected

209   Australia as a showcase of our lake classification framework.

210

211   2.2 Datasets and pre-processing

212   2.2.1 Lake mask

213   Choosing an accurate and high-resolution lake mask plays an important role in classifying

214   freshwater and saline lakes. Fortunately, due to the advances in spectral and microwave remote

215   sensing on mapping surface hydrology, several datasets on global water bodies have been

216   produced successively (refer to Section 1). Among them, the UCLA circa-2015 lake dataset was

217   produced from about 60 thousand Landsat-8 scenes acquired during the initial 2.5 years of the

218   sensor operation (2013-2015). Lake extents were mapped using a self-adaptive algorithm that took

219   into account the unique spectral conditions of individual lakes to optimize land-water separation.

220   The mapped lakes were mosaicked to represent an intermediate inundation extent to minimize

221   seasonal and inter-annual variations. The automated mapping was then visually inspected and

222   improved through a semi-automated quality assurance and quality control (QA/QC) procedure

223   (Wang et al., 2014) to further improve the mapping quality.

224   The circa-2015 lake dataset contains more than 9 million perennial lakes and reservoirs

225   with a total area of 2.97 million km^2. In comparison with HydroLAKES, the circa-2015 lake

226   dataset has a higher spatial resolution, with a minimum lake size of 0.004 km^2 (~4 Landsat pixels)

227   as opposed to 0.1 km^2 in HydroLAKES. The circa-2015 lake dataset also removed many

228   commission errors (such as mountain and glacier shadows) as occasionally identified in

229   HydroLAKES, owing to the rigorous QA/QC process. The improved spatial detail for smaller

230   lakes in the circa-2015 dataset is illustrated in Fig. 2 for a focal region in the Canadian Shield

231   (around 66°13'N and 116°40'W). As a partial result of the paleo-glaciation processes, the

232   Canadian Shield possesses the highest lake density in the world today. Due to this improvement,

233   we selected the circa-2015 lake dataset as the primary lake mask to test and perform our freshwater

234   and saline lake classification. Our logic is that if we can validly apply our method to this higher-

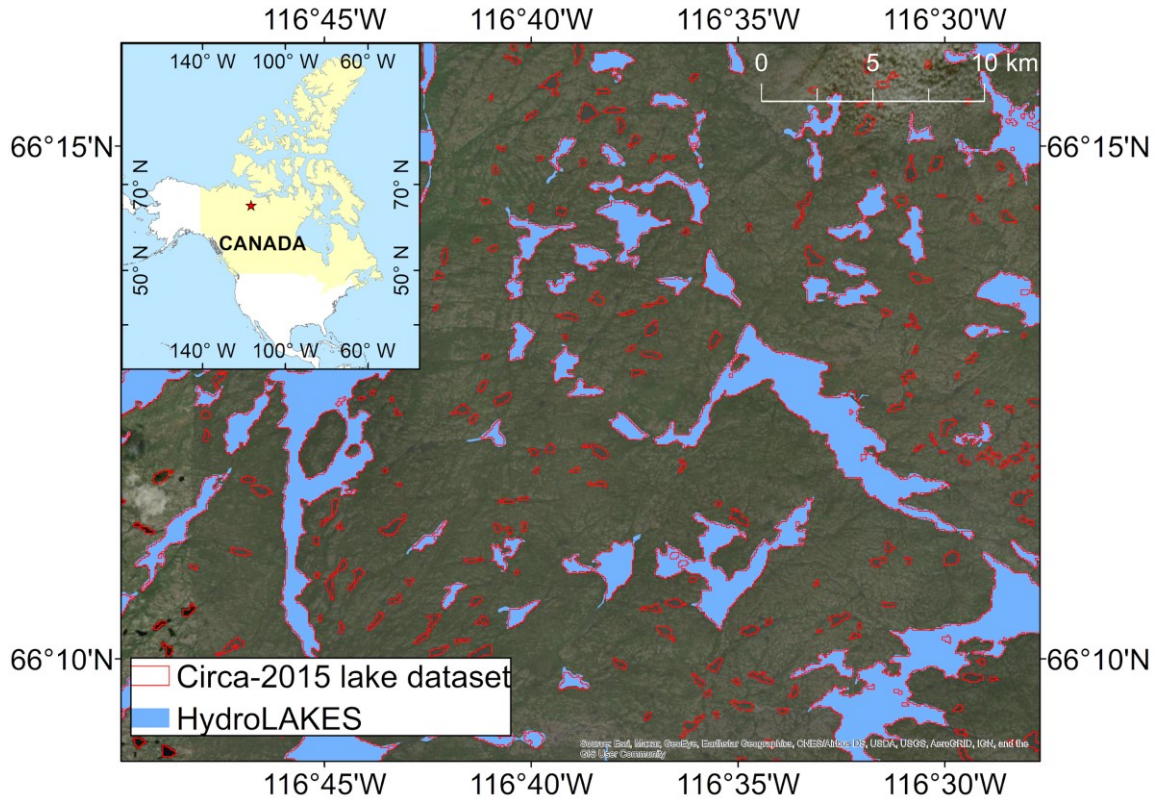235   resolution lake mask, our method may be applicable to coarser-resolution lake masks as well.

Fig. 2. Comparison between HydroLAKES and the UCLA circa-2015 lake dataset. The shown region is in the northern Canadian Shield (see inlet). Red (hollow) and blue (filled) polygons depict waterbody extents in the circa-2015 lake dataset and HydroLAKES, respectively.

2.2.2 Hydrography data

The HydroSHEDS dataset, which was developed from the SRTM Digital Elevation Model (DEM), depicts detailed hydrographic information, including river networks, drainage directions, and watershed boundaries (Lehner et al., 2008; https://www.hydrosheds.org/downloads). Multiple datasets were also assembled and compared during the development process. While hydrological adjustment was made through the use of automatic procedures, it also went through rigorous manual editing and quality control to remove spurious sinks and to delineate endorheic basins. The

13

248   version we used here has a resolution of 15 arc seconds (about 450 m at the equator), which is the

249   finest among the provided layers of river accumulation, river network, and drainage basins. We

250   pre-processed the data to extract endorheic basins from the exorheic basins (Fig. 3), by first

251   identifying inland sinks (terminal points) from the drainage direction layer, and then intersecting

252   the sink points with the drainage basins. The derived terminal points, endorheic/exorheic basins,

253   and the river networks within them were jointly used as the hydrological evidence for our lake

254   type classification (see Section 3.2).

255

256   2.2.3 Climate data

257   The 0.5-degree world map of Köppen-Geiger climate classification by Rubel and Kottek

258   (2010; accessed at http://koeppen-geiger.vu-wien.ac.at/shifts.htm) was used to help locate arid

259   and semiarid regions, where saline lakes have a higher chance to occur due to limited precipitation

260   but high potential evapotranspiration. This updated climate classification dataset includes a series

261   of digital world maps from 1901 to 2100 to capture the shift of global climate zones due to climate

262   change. The serial maps before 2000 were based on temperature and precipitation observations

263   acquired from the Climatic Research Unit (CRU) of the University of East Anglia and the Global

264   Precipitation Climatology Centre (GPCC) at the German Weather Service. We used the map for

265   1976-2000 to represent the most recent observation of global climate zones. Guided by our expert-

266   based experimentation, we merged the classes of arid climate (B), dry summer (S), and polar tundra

267   (T) to define the arid regions where saline lakes may likely occur. We included "polar tundra"

268   mainly because a large area of the Tibetan Plateau, which is arid and home to many saline lakes

269   (Section 2.1.1), was labeled as this class in the dataset. Merging these climate zones leads to about

270   40% of the global landmass (excluding Antarctica) and exceeds the maximum extent of the

271   conventional arid climates. However, it ensures our purpose of identifying saline lakes as

272   thoroughly as possible. As shown in Fig. 3, our processed global "arid zones" largely overlap with

273   endorheic basins, but it also supplements the latter by encompassing more drylands peripheral to
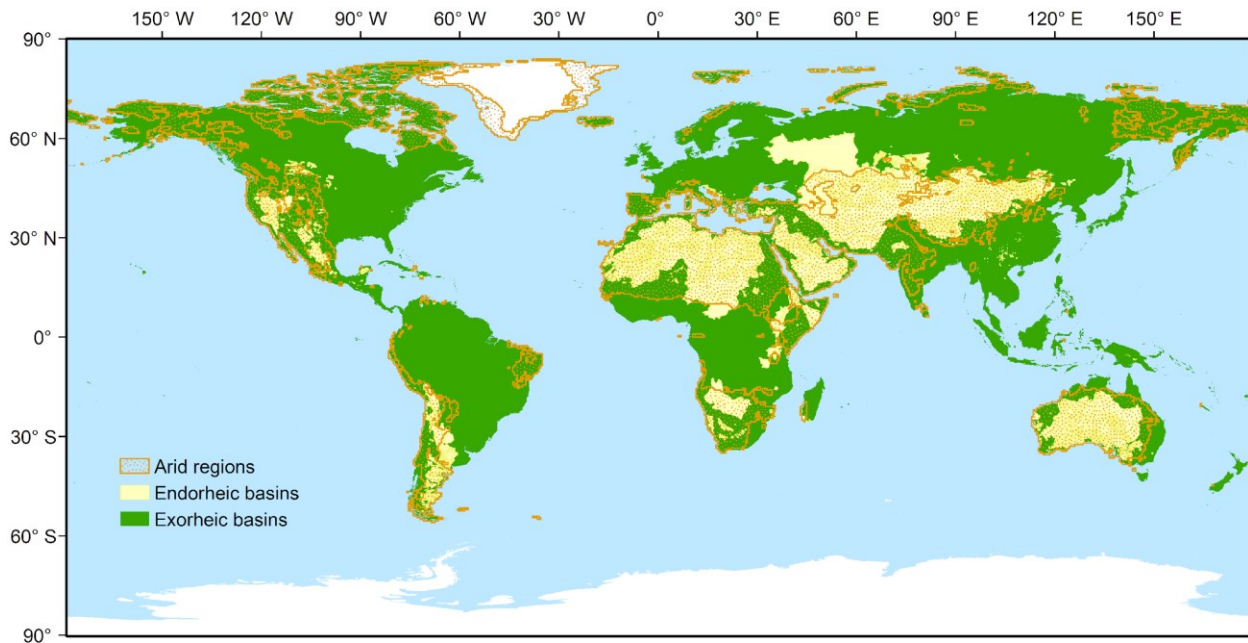
274   the endorheic regions.

Fig. 3. Global distribution of arid regions, endorheic basins, and exorheic basins. Endorheic basins
and exorheic basins were derived from the HydroSHEDS 15-second hydrography dataset (Lehner
et al., 2008). The global spatial distribution of arid regions was based on the Köppen−Geiger
Climate Classification (at 0.5-degree resolution) (Rubel and Kottek, 2010).

281   2.2.4 Satellite imagery

282   We referenced a large number of multi-source remote sensing images for visually

283   inspecting and detecting the spectral evidence (e.g., deposited evaporites and salt crusts) of saline

284   lacustrine environments. The primary reference is thousands of 30-m resolution Landsat-8 images,

285 which served as the mapping source for the circa-2015 lake dataset. In addition, we also referred

286 to higher-resolution images from Google Earth, Bing Maps, and the Esri World Imagery Map, to

287 assist in our visual interpretation of the spectral evidence.

288

289 2.2.5 Other literature

290 A large volume of existing literature and documents record the surveyed salinity and water

291 types of many lakes in the world. Although these records are mostly limited to large lakes, they

292 are useful auxiliary information to complement the other evidence for a systematic lake type

293 classification. Accordingly, we conducted an extensive literature review for the two study areas.

294 Examples include some of the well-referred books such as "Saline Lake Ecosystems of the World"

295 (Hammer, 1986), "Distribution of the World's Large Lakes" (Herdendorf, 1990), and the Chinese

296 Lake Catalogue (Wang and Dou, 1998), among others. The literature evidence was also used to

297 assess the effectiveness of our lake type classification using hydroclimate and spectral evidence

298 alone (see Section 3.7).

299

300 2.2.6 Validation data

301 Authoritative survey data that document detailed lake type and/or salinity for a particular

302 region are rare or poorly shared. For our study, we were able to access such a dataset based on

303 CNLS in the year 2006. CNLS documents survey-based lake types for 2,735 lakes and reservoirs

304 larger than 1 km^2 across China (Ma et al., 2010; Zhu et al., 2020), and applied a salinity threshold

305 of 0.1% to distinguish freshwater lakes and saline lakes. Then CNLS used more specific salinity

306 thresholds to classify saline lakes to three sub–categories: oligosaline lakes (salinity 0.1-2.4 %),

16

307 polysaline lakes (2.4-3.5 %), and hypersaline lakes (>3.5 %). This lake survey was used to validate

308 the accuracy of our typology results for the Tibetan Plateau.

309

310 **3. Methods**

311 3.1 Overview of the lake type classification framework

312 Our framework separated freshwater and saline lakes by following the decision tree in Fig.

313 4. In this decision tree, each of the 16 branches represents a unique combination of the binary

314 conditions (existence or absence) for the four general evidence types, i.e., hydrological,

315 climatological, spectral, and literature, which were used jointly to determine whether a lake is

316 likely saline. For clarity, we also translated this decision tree into a tabular format in Table 1. The

317 classification of lakes was based on four types of evidence, each with specific conditions that were

318 categorized as "primary" or "secondary". A "primary" condition or evidence means that the

319 presence of this condition alone (such as being at the drainage terminal) could already lead to a

320 high likelihood that a lake is saline unless there is literature evidence opposing this judgment. In

321 comparison, a "secondary" condition (such as being under arid climate or on the drainage pathway,

322 rather than at the terminal, of an endorheic basin) defines a favorable situation where primary

323 conditions (such as exhibiting lacustrine evaporites) may possibly occur, but this condition alone

324 is insufficient to conclude the lake type.

325 We aggregated the results of the 16 node scenarios to four general lake classes, depending

326 on the classified freshwater or saline type and the drainage position of the lake, i.e., whether being

327 on the drainage pathway or at the terminal. These four lake classes are terminal (closed) saline,

328 open (flow-through) saline, terminal (closed) freshwater, and open (flow-through) freshwater.

17

329　Among them, open saline lakes may include saline lagoons if the lakes are distributed along the

330　coast. We opted to inform the drainage positions (flow-through or terminal) along with the binary

331　water types (saline and freshwater), because the former provides additional useful information

332　indicative of lake retention time, water quality, and ecosystem functions. More details for each

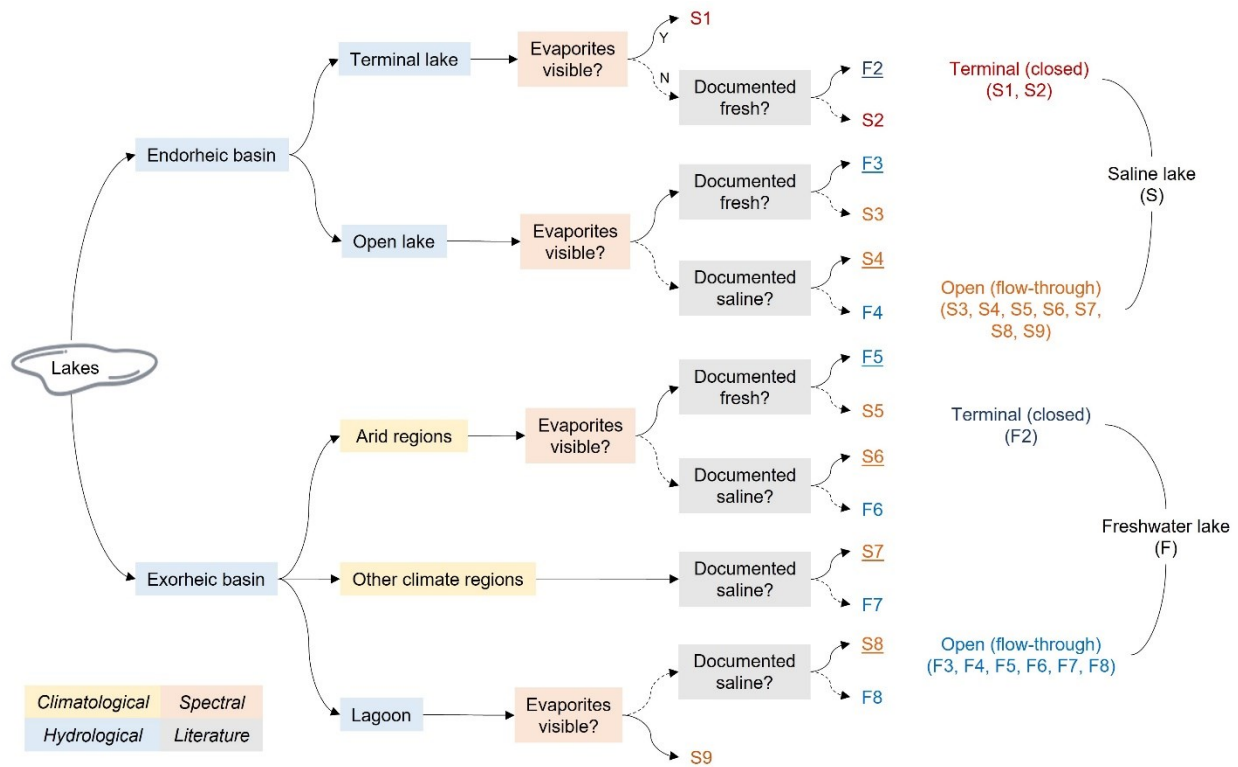333　type of evidence are explained in the following Method sections.

334

335　**Fig. 4.** Schematic flowchart illustrating the framework of classifying freshwater and saline lakes.

336　Solid arrows after a question indicate "Yes" whereas dashed arrows indicate "No". Classified lake

337　types are annotated as "S1" to "S9" and "F2" to "F8", with "S" indicating saline lakes and "F"

338　freshwater. Underscored types (e.g., "F2" and "S4") indicate results corrected by opposing

339　literature evidence. Detailed lake types were further grouped into four general classes (as color-

340　coded): terminal saline, open saline, terminal freshwater, and open freshwater. Here a "terminal"

18

341   or "open" lake means if the lake is located at the drainage terminal or pathway. Refer to Table 1

342   for more detail.

343

344   **Table 1.**   Detailed rules for classifying freshwater and saline lake types. Typology notations are

345   consistent with those in Fig. 4. Blank cells indicate this condition or evidence was less relevant

346   and was not verified. "Yes" in "opposing literature" indicates the classified lake type would have

347   been the opposite if using other evidence (hydroclimate and spectral) alone. Conditions that are

348   not labeled "primary" are "secondary" conditions.

Typology		*Hydrology*			*Climate*	*Spectral*	*Literature*
General classes	Specific types	Endorheic basin	Terminal lake (*primary*)	Coastal lagoon	Aridity	Evaporite (*primary*)	Opposing literature (*primary*)
Terminal saline	S1	Yes	Yes			Yes	No
	S2	Yes	Yes			No	No
Open saline	S3	Yes	No			Yes	No
	S4	Yes	No			No	Yes
	S5	No	No	No	Yes	Yes	No
	S6	No	No	No	Yes	No	Yes
	S7	No	No	No	No		Yes
	S8	No	No	Yes		No	Yes
	S9	No	No	Yes		Yes	No
Terminal freshwater	F2	Yes	Yes			No	Yes
Open freshwater	F3	Yes	No			Yes	Yes
	F4	Yes	No			No	No
	F5	No	No	No	Yes	Yes	Yes
	F6	No	No	No	Yes	No	No
	F7	No	No	No	No		No
	F8	No	No	Yes		No	No

349

350

351   3.2 Paradox of lake water and solute balances

352   We theorize that a saline lake may form when its water balance tends to be maintained at

353   the cost of a positive solute imbalance. We refer to this paradoxical condition as the "water-solute

354   imbalance", which can be explained by the equations below. The balance of lake water mass or

355   volume (V) through time (t) is governed by:

356
$$\frac{dV}{dt} = P + Q_{in} - Q_{out} - Q_g - E \tag{1}$$

357   where the main influxes include precipitation recharge on the lake surface (P) and surface inflow

358   to the lake (Q_{in}), and the main outflux terms are surface outflow from the lake (Q_{out}), infiltration

359   to the groundwater (Q_g), and lake surface evaporation (E). Among these fluxes, surface inflow,

360   surface outflow, and groundwater outflow carry minerals dissolved along the drainage paths, but

361   evaporation carries only water molecules. Assuming minerals in precipitation are limited, the

362   balance of soluble salts (S) in a lake is governed by:

363
$$\frac{dS}{dt} = S_{Q_{in}} - S_{Q_{out}} - S_{Q_g} + S_e \tag{2}$$

364   where the only exogenous influx comes from the solute supply carried by lake surface inflow

365   ($S_{Q_{in}}$), and the outfluxes are solute losses through surface outflow ($S_{Q_{out}}$) and seepage loss (S_{Q_g}).

366   In addition, endogenous sources such as geochemical and microbial processes within the lake itself

367   may also affect the lake's mineral balance, and we use S_e to notate the net effect of these

368   endogenous processes.

369   Assuming S_e has a limited contribution, dS accumulates if $S_{Q_{in}}$ exceeds the sum of $S_{Q_{out}}$

370   and S_{Q_g}. This happens when Q_{out} and Q_g, which carry $S_{Q_{out}}$ and S_{Q_g}, are limited or negligible,

371   leaving E the predominant outflux to balance out Q_{in}. Despite a possible water mass balance under

372   this condition, the lake experiences a positive imbalance (gain) of soluble salts and may eventually

373   turn saline. For the same reason, saline lakes are often intermittent or ephemeral in arid climates,

374   when Q_{in} is so limited that E can easily become disproportional, leading to a negative water mass

375   imbalance. Although endogenous biochemical processes (S_e) also modulate lake salinity, our

376   collected hydroclimate evidence below was guided based on this water-solute imbalance, which

377   essentially defines an overarching condition that lake outflux is dominated by evaporation.

378

379   3.3 Hydrological evidence

380   Most saline lakes occur in endorheic basins, especially at the drainage terminals (Hammer,

381   1986; Wang et al., 2018; Wang, 2020; Wurtsbaugh et al., 2017; Yang et al., 2017), because

382   endorheic hydrology well represents the above-described water-solute imbalance. Hydrologically,

383   the global continental surface is divided into exorheic and endorheic basins, depending on whether

384   surface flow from the basin can drain to the ocean (Fig. 3). Rivers in an endorheic basin do not

385   flow into the ocean, but instead drain to an inland terminus or sink. Lakes located at the sinks are

386   terminal or endorheic lakes, whereas lakes on the drainage paths or at the headwater are often

387   referred to as flow-through or open lakes. Note open lakes can be located in either endorheic or

388   exorheic basins. Since a terminal lake receives Q_{in} but produces no Q_{out}, water storage in most

389   terminal lakes can only be balanced out via E, leaving the dissolved minerals (solutes) in the lakes.

390   Through time, the water salinity in a terminal lake accumulates and the lake becomes saline.

391   Except significant infiltration and subsurface outflow (Q_g, such as Lake Chad), terminal lakes are

392   usually saline due to this landlocked hydrology. For this reason, we considered being at the sink

393   of an endorheic basin a primary condition, meaning that a terminal lake was usually assumed to

394   be saline unless there is opposing literature suggesting otherwise. In contrast with terminal lakes,

395   an open lake can be balanced out via both E and Q_{out}, limiting the likelihood of solute

396   accumulation in the lake. Therefore, we did not assume flow-through (open) lakes in an endorheic

397   basin to be saline without other evidence.

398   Lakes in an exorheic basin are, by definition, in the pathway of the drainage networks and

399   thus open to surface outflow. Since dissolved minerals are carried away by the surface outflow,

400   the salinity of open lakes often remains low. Lakes in exorheic basins are often freshwater, except

401   when located in very arid areas with high lake evaporation (see Section 3.3). Coastal lagoons are

402   usually shallow water bodies that are separated from the ocean by barrier islands and are subject

403   to tidal effects (Kjerfve et al., 1996). A lagoon can be both freshwater and saline or brackish

404   depending on its hydrodynamics with the ocean (Joyce et al., 2005; Emmanuel and Chukwu,

405   2010), so literature evidence is required to identify their water types.

406   Here a selected endorheic basin in the southern Tibetan Plateau (Fig. 5) is used to illustrate

407   our classification procedure throughout the methods. We first referred to HydroSHEDS to sort out

408   the drainage position of each lake in this basin. A terminal lake named Chabyer Co (Fig. 5a and

409   5b) was identified at the drainage sink (green dots in Fig. 5a) of this basin. As being terminal is a

410   primary condition, Chabyer Co is considered a saline lake for now. Other lakes in this endorheic

411   basin, such as Qoi'nyi Co (Fig. 5c) draining from the northern shore and Taruo Co (Fig. 5d)

412   draining eastward, are open or flow-through lakes, thus assumed to be freshwater lakes for now.
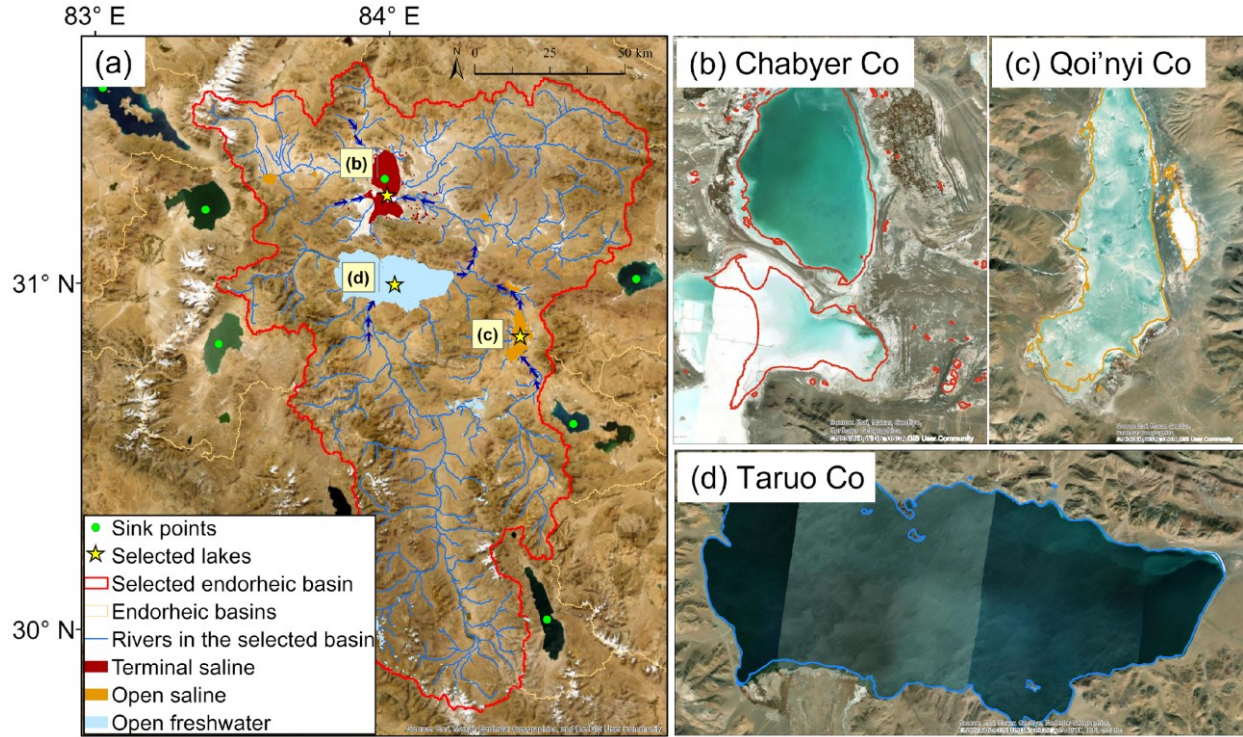
Fig. 5. Lake typology classification in a selected endorheic basin on the Tibetan Plateau. Background is the Esri satellite imagery.

3.4 Climatological evidence

Being terminal is not a necessary condition for the water-solute imbalance. As described in Section 3.2, salinity in a lake can also accumulate if its water loss via Q_{out} and Q_g, both carrying soluble salts, is substantially less than the loss via E carrying only water molecules. Such a disproportional surface evaporation tends to occur in arid climates, where long-term atmospheric demands for water vapor (i.e., potential evapotranspiration) exceed the atmospheric supplies P. Despite a limited recharge from local P, lake water supplies in arid climate can be compensated by more abundant Q_{in} (e.g., glacial meltwater from headwaters). This may lead to lake Q_{out} exceeding E, which is not conducive to solute accumulation. For this reason, we considered high

426   climate aridity a secondary condition to locate the environments favored by saline lakes, which

427   was then used together with additional evidence (Sections 3.5 and 3.6) to determine the lake type.

428   The conventional arid climate zones (i.e., regions with potential evapotranspiration exceeding

429   precipitation) are overall spatially consistent with endorheic basins (Wang et al., 2018; Wang

430   2020), but as described in Section 2.2.3, our defined global arid zones (Fig. 3) are more inclusive,

431   in order to identify saline lakes as thoroughly as possible. These arid zones cover most part of the

432   endorheic Tibetan Plateau, including the example in Fig. 5.

433

434   3.5 Spectral evidence

435   Under intense evaporation or saturated salinity, soluble minerals can precipitate from the

436   water and crystallize on the lake beds or littoral zones, forming evaporites that are indicative of

437   hypersaline environments. Evaporite deposits are usually highly reflective in the visible and

438   infrared spectra, providing another type of primary evidence for saline lakes. In a recent study,

439   Safaee and Wang (2020) applied machine learning on Landsat-8 images to extract salt pans and

440   salt playas across the western United States. While this study demonstrated the potential of

441   multispectral imagery for automated evaporite extraction, the method also implied the challenge

442   of separating evaporites from other high-reflectance substances such as clays, sands, and manmade

443   impervious surfaces. A more accurate classification may be achieved via spectroscopic analysis

444   based on detailed spectral signatures, but this requires hyperspectral images which are not always

445   freely accessible. Along with high spectral reflectance, crystallized evaporites tend to exhibit

446   patchy and crusty textures, which are sometimes discernible in high-resolution multispectral

447   images. Therefore, as a workaround, we combined this unique texture information and the high

448   spectral reflectance of evaporites to define the "spectral evidence" of saline lakes.

449   Specifically, we inspected the existence of the above-defined spectral evidence in the

450   immediate vicinity of each lake. Our focus was lakes in endorheic basins and/or arid climate zones

451   (Section 2; Fig. 3) where evaporites are mostly likely to deposit. We leveraged a variety of image

452   sources, including Landsat-8 source imagery of the circa-2015 lake dataset (see Section 1), Google

453   Earth imagery, Bing Maps imagery, and the Esri World Imagery basemap. Given that the main

454   purpose of this study was to demonstrate the classification framework, our inspection was largely

455   based on expert-based visual interpretation, which was akin to how a human technician conducts

456   an in situ survey based on the surface spectral reflectance and texture surrounding a lake. To assist

457   in visual interpretation, we also followed Safaee and Wang (2020) to flag high-reflectance regions,

458   defined empirically by Landsat-8 pixels where the mean of visible (red, green, and blue)

459   reflectivity exceeds 0.2. The high-reflectance flags, in combination with our meticulous visual

460   inspection, aimed at optimizing the accuracy of evaporite identification. However, our framework

461   allows for the flexibility of potentially replacing this visual method by more automated algorithms

462   which, for example, synthesize both spectral and textural information to effectively identify

463   lacustrine evaporites.

464   In the example of the Tibetan Plateau (Fig. 5), highly reflective brines and evaporites are

465   distributed across Lake Chabyer (Fig. 5b), Lake Qoi'nyi (Fig. 5c), and their littoral zones, showing

466   clear evidence that these two lakes are saline or hypersaline. For Lake Chabyer, the spectral

467   evidence is present on top of the hydrological evidence (i.e., being at the drainage terminal), further

468   confirming this lake is indeed saline. For Lake Qoi'nyi, the spectral evidence complements the

469   climatological evidence (i.e., being in arid climate), suggesting that this lake, although open to

470   surface outflow, has a predominant outflux via evaporation and is therefore saline. In comparison,

471   Lake Taruo (Fig. 5d), although exposed to arid climate, displays no hydrological or spectral

472 evidence and was thus assumed to be freshwater. It is worth mentioning that the use of spectral

473 evidence led to an overall conservative detection of saline lakes because not all saline lakes exhibit

474 evident lacustrine evaporites, at least seen from multispectral imagery.

475

476 3.6 Literature evidence

477   While the lake type might be reasonably inferred from the combination of hydrological,

478 climatological, and spectral evidence, the most authoritative evidence stemmed from literature

479 documentation. Although rarely available and skewed towards larger lakes, literature evidence

480 served an important dual purpose. As shown in Fig. 4 and Table 1, the lake types documented in

481 the literature were used to correct misclassifications from the other set of evidence, therefore

482 determining the final lake type. The literature also provided an independent source to validate the

483 classification accuracy using the other evidence alone. This is especially valuable for

484 benchmarking the fidelity of our lake type classification framework in literature-lacking regions.

485   We considered two types of literature evidence. One is documented nominal lake types

486 (e.g., freshwater, subsaline, and saline) and the other is numeric salinity according to which lake

487 type can be categorized. We followed Hammer (1983) and used a salinity of ~0.05% as the divide

488 between freshwater and saline lakes. When possible, we further labeled the lakes whose salinities

489 fall between 0.05% and 0.3% as subsaline (Hammer 1983; Wang 1993). This intermediate

490 category allows for additional flexibility of lake type classification at the user's discretion. Unless

491 otherwise specified, saline lakes in our study include those that are subsaline.

492   Through a deep search from the literature pool (2,261 lakes with literature evidence, with

493 a total area of 29,703.7 km^2), we collected as much evidence as possible to supplement, confirm,

494   and correct the classification results using hydroclimate and spectral evidence alone. This led to

495   the final leaf nodes of the decision tree (Fig. 4), defining specific scenarios depending on whether

496   the literature opposes or agrees with the classifications based on other sets of evidence. For

497   instance, a terminal lake, which possesses the primary hydrological evidence, was assumed to be

498   saline even though it lacks evident evaporites. However, if the literature opposes this assumption,

499   the lake was reclassified to be freshwater with a scenario label of "F2"; otherwise, the lake type

500   remained to be saline with a scenario label of "S2". An example of such exceptions ("F2" lakes)

501   is Lake Chad, where water remains fresh although the lake has a high evaporation level and is

502   located at the surficial drainage terminal. This is because the local river inflow (Q_{in}) has low

503   salinity and the lake has a high groundwater outflow (Q_g) allowing soluble salts to escape to the

504   aquifers (Isiorho and Matisoff, 1990; Wang, 2020).

505   In the example of the Tibetan Plateau (Fig. 5), we referred to Wang and Dou (1998) to

506   confirm that Chabyer Co is hypersaline with a high salinity of 43.4%. This also proves that our

507   classification for Chabyer Co (label "S1") given both hydroclimate and spectral evidence was

508   reliable (Fig. 4; Table 1). Qoi'nyi Co was classified to be saline due to the presence of visible

509   evaporites. However, we were unable to find any literature reference to verify this classification.

510   As a result, Qoi'nyi Co was labeled "S3", meaning a probable saline lake that has evident evaporite

511   deposits but is open (flow-through). Guo et al (2016) documented a salinity of ~0.05% for Taruo

512   Co, confirming our assumption of a freshwater type was correct. This rendered a label of "F4" for

513   Taruo Co, meaning a literature-validated freshwater lake that is open (flow-through) and has no

514   evident evaporites.

515

516

3.7 Validation

We validated our lake type classification framework in two ways. First, we applied available literature evidence to evaluate the reliability of our classification scheme (as described in Section 3.6) based on hydrological, climatological, and spectral evidence alone (thereafter "non-literature evidence"). This validation was performed for both Tibetan Plateau and Australia. Relative classification error was estimated as the count of lakes where the type determined by non-literature evidence opposes that by the literature, divided by the total count of lakes where literature evidence is available. Specifically, lake scenarios with contradictory literature and non-literature evidence include F2, F3, S4, F5, S6, S7, and S8 (Fig. 4 and Table 1), and these scenarios represent the known classification errors from non-literature evidence alone. It is worth noting that literature evidence was absorbed as part of the typology framework, so any error identified in this aspect has been corrected in the final classification result (see Section 4).

The second validation approach used the external data CNLS (Ma et al., 2010; Zhu et al., 2020) to independently validate the accuracy of the final lake types classified from both non-literature and literature evidence for the Tibetan Plateau. As described in Section 3.6, our classification was based on the lake typology system in Hammer (1983), which used a minimum salinity of 0.05% to define saline lakes, whereas CNLS used a minimal salinity of 0.1% (see Section 2.2.6). A more detailed discrepancy between the two typology systems was visualized in Fig. 6, where the range from 0.05% to 0.1% represents the uncertainty of lake types due to disagreeing salinity thresholds. To remove the impact of this discrepancy, we excluded any lake whose salinity falls in the uncertainty range from validation.
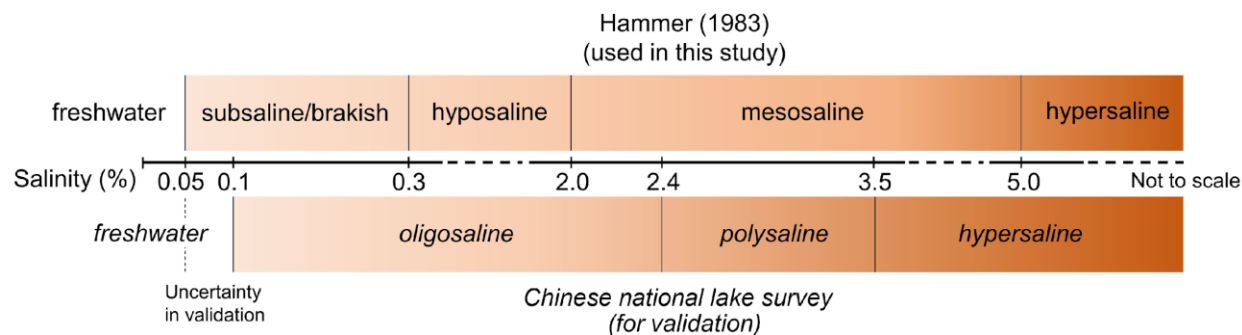
Fig. 6. Lake typology systems adopted in Hammer (1983) and the Chinese national lake survey (CNLS).

4. Results and discussion

4.1 Classified freshwater and saline lake typology on the Tibetan Plateau

Our classification framework comprehensively integrates hydroclimate analysis, spectral remote sensing, and literature evidence and was developed on the Tibetan Plateau using the circa-2015 lake dataset. Our classification approach identified the diversity of lakes on the Tibetan Plateau, including the number, type, size, and location of freshwater and saline lakes. Figure 7 shows the spatial distribution of classified freshwater and saline lakes on the Tibetan Plateau. Freshwater lakes are distributed almost ubiquitously across the entire Tibetan Plateau, whereas saline lakes are concentrated within the endorheic basins, mostly in the northern and northwestern Tibetan Plateau. Figure 8 shows the quantities of the four general lake types, i.e., terminal saline, open saline, terminal freshwater, and open freshwater. Among the 34,723 lakes on the Tibetan Plateau, 4,825 (13.9%) were classified as saline, and the remaining 29,898 (86.1%) were classified to be freshwater. While much fewer in number, the total surface area of saline lakes was much larger. The saline lakes have an aggregate area of 35,490.3 km^2 (82.4% of total lake area), whereas

29

556   the freshwater lakes have a total area of 7,563.4 km^2 (17.6%). Freshwater lakes outnumber saline

557   six to one, but saline lakes account for more than two-thirds of the total lake area, indicating that

558   some of the largest lakes on the Tibetan Plateau are terminal saline lakes.

559   Focusing more narrowly on open lakes, we find that open freshwater lakes (86.0%) make

560   up the largest share of all lakes in the Tibetan Plateau, whereas open saline lakes only account for

561   a small fraction (4.8%) of total lakes. However, these two open lake categories are comparable in

562   area. This is partially because open lakes were classified as saline only when they exhibit clear

563   spectral evidence of surficial and/or littoral evaporites, and such spectral evidence was more likely

564   to be identified for larger lakes given the limitation of image resolution. This contrast also implies

565   that our saline lake detection is conservative. We found little evidence from spectral remote

566   sensing or the literature to counter our assumption that terminal lakes are saline.

567   About 82% of the saline lakes are located on the Changtang Plateau (Fig. 7), the largest

568   cluster of endorheic basins on the Tibetan Plateau (Yao et al., 2018). The Changtang Plateau has

569   an average altitude of ~4800 meters and includes a wide variety of landscapes including plains,

570   hügellands, and mountains, and it is surrounded by the Tanggula Mountains, the Nyainqêntanglha

571   Mountains, and the Kailash Range (Xu et al., 2020). It is cold and dry on the Changtang Plateau

572   because the mountains on the southern side block the warm and humid airflow from the Indian

573   Ocean (Cuo et al., 2014; Tian et al., 2022). Therefore, the climate and hydrography of the

574   Changtang Plateau both result in widespread saline lakes. About 8% of the saline lakes, including

575   Qinghai Lake (37° N, 100.13° E), Hala Lake (38.3° N, 97.6° E), and Chaka Salt Lake (36.7° N,

576   99.11° E), are in the endorheic basins in the northeastern of the Tibetan Plateau. This region

577   encompasses the Hexi basin, the headwater of the Yellow basin, and the Qaidam basin which is

578   one of the three largest endorheic basins in China, and the climate is dry throughout the year and

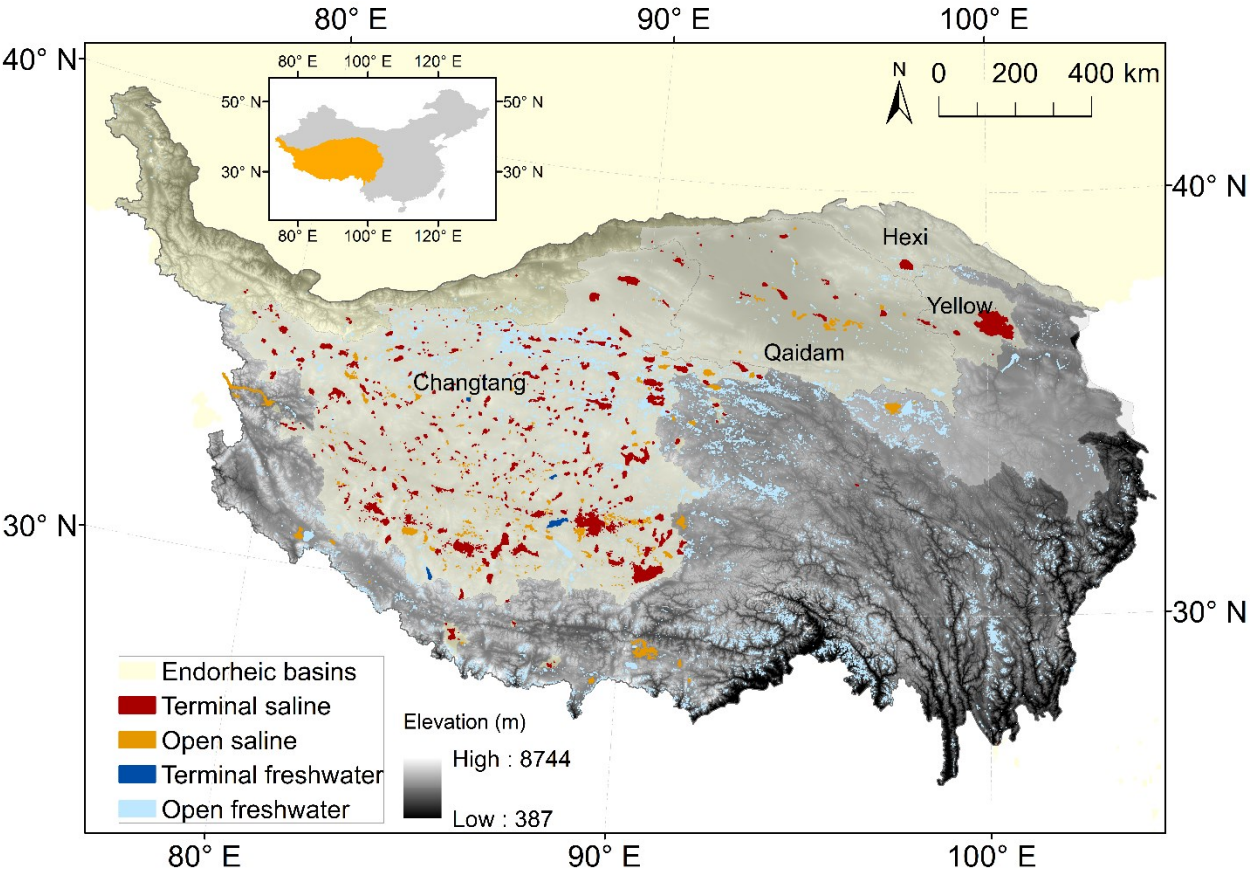579   deserts are widespread (Zhang and Liu, 2020; Wang et al., 2022).

581   **Fig. 7.** Spatial distribution of classified terminal saline, open saline, terminal freshwater, and open

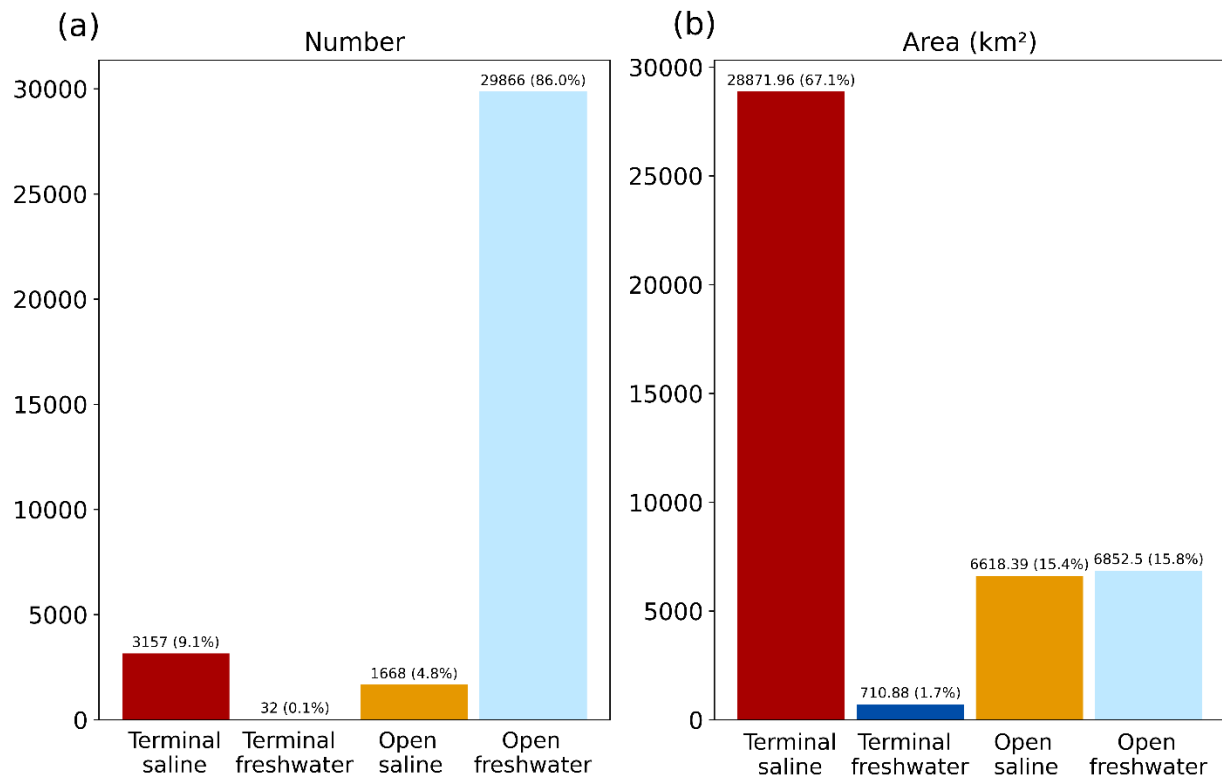582   freshwater lakes on the Tibetan Plateau. The lake mask circa-2015 lake dataset was used to identify

583   lakes.

584

585

Fig. 8. The number of lakes (a) and size of lakes (b) by classified lake typology on the Tibetan

Plateau.

Regardless of typology, lake count (abundance) and size follow a log-log linear

relationship, also termed as Pareto or power-law distribution (Fig. 9). In general, the abundance of

lakes decreases as the lake area increases, and the decay rate remains fairly constant on a

logarithmic scale. There is also a significant difference between the abundance of freshwater lakes

and saline lakes as the lake area increases. When the lake area is less than 1 km^2, the number of

freshwater lakes is nearly an order of magnitude higher than that of saline lakes. However, the

abundance of freshwater and saline lakes begins to converge for medium size lakes (1-10 km^2),

and the count of saline lakes exceeds that of freshwater lakes when lake area is larger than 10 km^2

(Fig. 9). As a result, saline lakes dominate the total lake area (more than 80%) on the Tibetan

32

598 Plateau. As noted previously, our framework tends to be more conservative in identifying saline

599 lakes as the lakes become smaller, while larger lakes are more likely to be appropriately classified.

600 Nonetheless, the classified saline lakes span the entire range of lake size (Fig. 9), including very

601 small lake sizes when supported by multiple lines of evidence. The Pareto relationship weakens

602 when lakes become smaller than 0.015 km^2, probably because very small lakes in the circa-2015

603 lake dataset were mapped incompletely as they approach the minimum mapping unit in Landsat-

604 8 images (0.004 km^2).

605   This explicit classification will facilitate a range of studies on the Tibetan Plateau, from

606 understanding the spatial distribution of lake water resources to attributing lake changes (Zhu et

607 al., 2020). Particularly, there has been a significant expansion of saline lakes across the Changtang

608 Plateau over the past two to three decades, due to increased precipitation as well as warming-

609 induced cryospheric contributions (e.g., glacier melting and permafrost thawing) (Song et al., 2014;

610 Yao et al., 2018; Zhang et al., 2017). Therefore, understanding the time series of Tibetan lake

611 dynamics with consideration of lake typology will be critical to monitor the changes in fresh and

612 saline water budgets, lake salinity, and saline lake ecosystem functions.
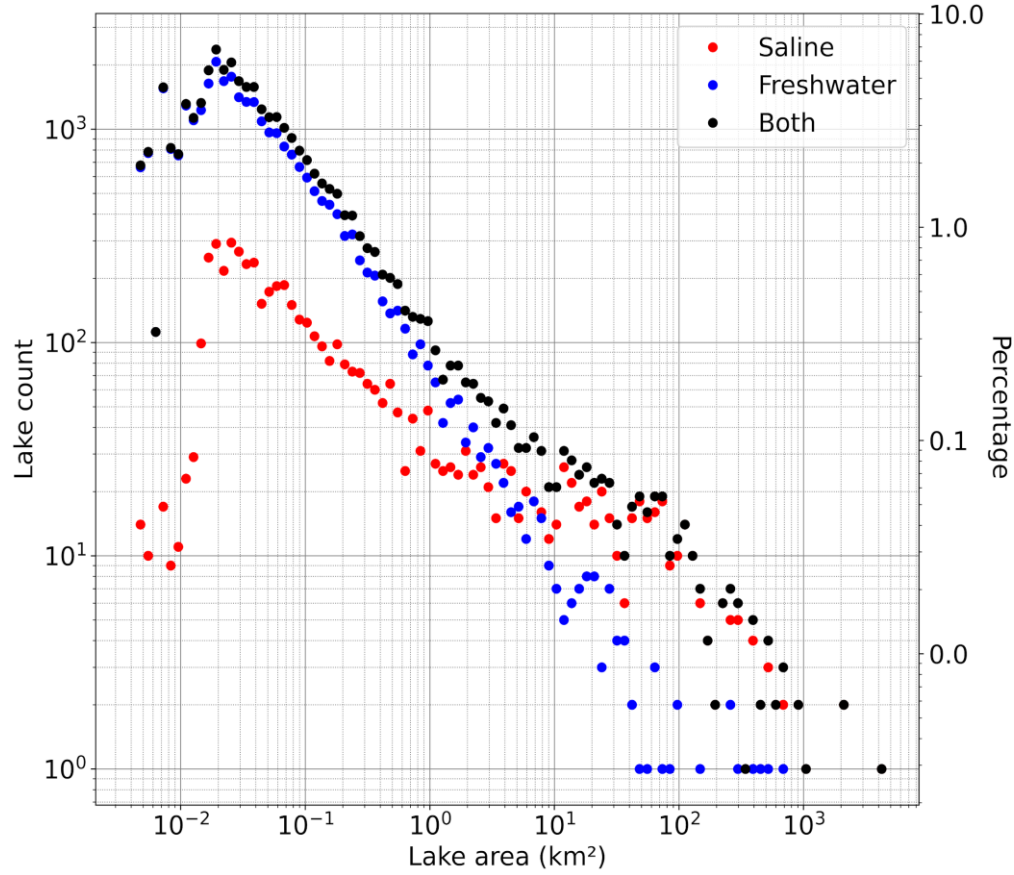
Fig. 9. Log-log relationship between lake area and count (abundance) in the Tibetan Plateau.

4.2 Validation

As described in Section 3.7, our validation first emphasizes the reliability of lake type classification based on non-literature (i.e., hydrological, climatological, and spectral) evidence only. We then benchmarked the accuracy of our final classification result (i.e., with inclusion of literature evidence) on the Tibetan Plateau against CNLS (Ma et al., 2010; Zhu et al., 2020).

4.2.1 Accuracy using hydroclimate and spectral evidence alone

We assessed the classification error by both lake count and lake area by calculating the number and the area of misclassified lakes (where literature evidence disagrees with

624 hydroclimate/spectral evidence) as percentage of the total number and the total area of all classified

625 lakes with literature evidence. Table 2 shows that the number of all classified lakes with literature

626 evidence is 2,261 (94.5% of total lake count), which have a total area of 29,703.7 km^2 (93.2% of

627 total area). Of these lakes, the number of inaccurately classified lakes is 125, with an area of

628 2,020.0 km^2. This means only using hydrological, climatological, and spectral evidence alone, our

629 lake type classification may render an accuracy of up to 94.5% by lake count and 93.2% by lake

630 area.

631 This accuracy assessment is dependent on the literature available for validation. Additional

632 literature evidence would further strengthen validation of our framework. As described in Section

633 3.6, the identified lake type errors were labeled as S4, S6, S7, S8, F2, F3, and F5 depending on

634 their evidence scenarios (Fig. 4) and have been corrected to the corresponding freshwater or saline

635 types in the final classification result.

636

637 **Table 2.** Accuracy of lake type classification for the Tibetan Plateau using hydrological,

638 climatological, and spectral evidence alone. Misclassified lakes fall into the following seven lake

639 categories: i) terminal lakes without visible evaporites in endorheic basins but documented as

640 freshwater lakes (F2); ii) open lakes with visible evaporites in endorheic basins but documented

641 as freshwater lakes (F3); iii) open lakes without visible evaporites in endorheic basins but

642 documented as saline lakes (S4); iv) lakes located in exorheic basins and arid regions and with

643 visible evaporites but documented as freshwater lakes (F5); v) lakes located in exorheic basins and

644 arid regions and without visible evaporites but documented as saline lakes (S6); vi) lakes located

645 in exorheic basins and not in arid regions but documented as saline lakes (S7); vii) lagoons without

646 visible evaporites but documented as saline lakes (S8)

Category	Non-literature evidence	Literature evidence	Count	Area (km^2)
F2	Saline	Freshwater	32	710.9
F3	Saline	Freshwater	1	57.7
S4	Freshwater	Saline	91	1,251.4
F5	Saline	Freshwater	1	0.03
S6	Freshwater	Saline	0	0
S7	Freshwater	Saline	0	0
S8	Freshwater	Saline	0	0
Total	-	-	125	2,020.0
All lakes with literature evidence	-	-	2,261	29,703.7
Accuracy	-	-	94.5%	93.2%

647

648   4.2.2 Accuracy using all types of evidence

649   Our final classification results, which combined both literature and non-literature evidence,

650   were benchmarked against the 1152 Tibetan Plateau lakes - including 270 freshwater lakes and

651   882 saline lakes - documented by CNLS. As described in Section 3.7, we excluded 19 lakes with

652   salinity falling in the uncertainty range (i.e., salinity between 0.05% to 0.1%; Fig. 6) from

653   validation. The results (Fig. 10) are grouped into four scenarios: correctly classified saline lakes,

654   correctly classified freshwater lakes, saline lakes misclassified as freshwater, and freshwater lakes

655   misclassified as saline. Their statistics are summarized in Table 3.

656   Our framework shows high levels of accuracy identifying saline lakes (95.0% by lake count

657   and 98.1% by area) because we only classified a lake as saline if it possesses at least one type of

658   primary evidence (hydrological, spectral, literature, or combined). This conservative strategy

659   means some saline lakes lacking the considered evidence were misclassified to freshwater (i.e.,

660   omission errors), leading to a lower procedure's accuracy for saline lakes (63.3% by lake count).

661   Even so, the procedure's accuracy for saline lakes remains high in terms of lake area (95.3%),

662   suggesting such omission errors tend to occur only for small saline lakes. For the same reasons,

663   problems in the classified freshwater lakes are dominated by commission errors, leading to lower

664   user's accuracies for freshwater lakes (40.7% by lake count and 71.1% by area). The producer's

665   accuracies for freshwater lakes are higher (88.2% by count and 86.4% by area), indicating rarer

666   omission errors where freshwater lakes were misclassified as saline. Combining all scenarios, the

667   overall accuracy of our classified lake typology reaches 68.9% by lake number and 94.3% by area.

668   The classification accuracy increases as the lake size increases due to stronger classification

669   evidence for larger lakes. In general, the conservative nature of our method suggests that our

670   method should not be a complete substitute for in situ surveys, especially for small lakes; however,

671   it does offer a cost-effective way to identify many of the world's saline lakes.

672   To further assess the reliability of using non-literature evidence only, we compared our

673   classification results before literature correction with CNLS. The overall accuracies (67.9% by

674   count and 92.2% by area) are comparable to those after literature correction. In other words, our

675   classification framework based on non-literature evidence alone has correctly classified most of

676   the large lakes, and the inclusion of literature evidence further increased the accuracy but by a

677   limited extent (~1–2%). It is important to note that lake salinity is a dynamic parameter as it is

678   affected by seasonal and interannual variability (Song et al., 2022). For example, the lake types in

679   our literature evidence (mostly from Wang and Dou (1998)) were recorded decades ago whereas

680   the information in CNLS was more recent (i.e., around 2006). Therefore, our mapping error, in

681   theory, has included the uncertainties due to salinity changes between the period of the two
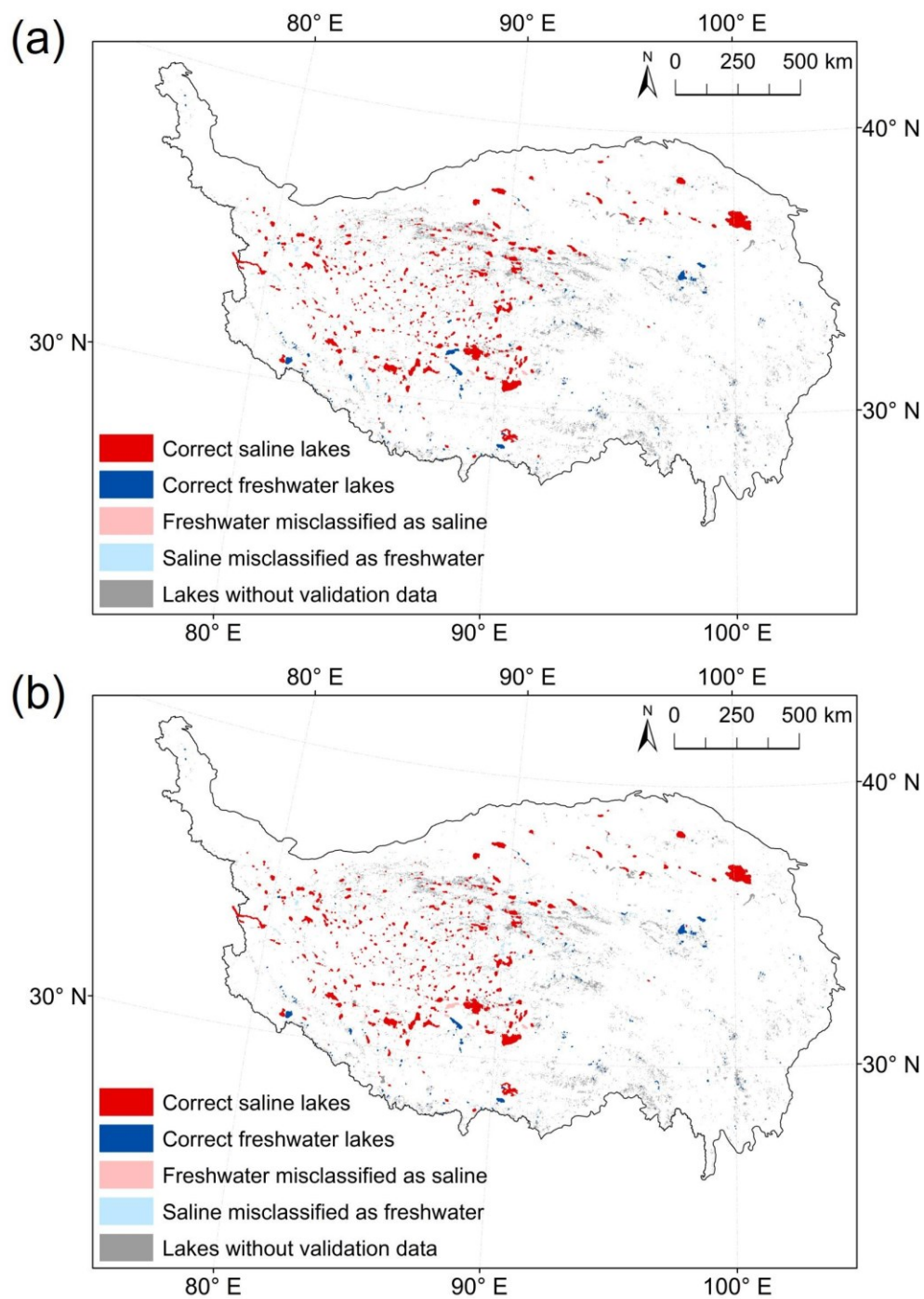
682   datasets.

683

Fig. 10. Validation results for saline and freshwater lake type classification on the Tibetan Plateau

against the Chinese national lake survey. Panel (a) shows the validation of classification results

using all evidence, and (b) shows the validation of classification results using hydrological,

climatological, and spectral (non-literature) evidence only.

38

689 **Table 3.** Comparison between lake typology statistics in this study and those in the Chinese

690 national lake survey.

Validation results	All evidence		Non-literature evidence	
	Count	Area (km^2)	Count	Area (km^2)
Correct saline lakes	506 (49.3%)	30,799.2 (84.1%)	500 (48.7%)	30,635 (83.6%)
Correct freshwater lakes	201 (19.6%)	3,732.8 (10.2%)	197 (19.2%)	3,166.6 (8.6%)
Saline misclassified as freshwater	293 (28.5%)	1,513.6 (4.1%)	299 (29.1%)	1,677.8 (4.6%)
Freshwater misclassified as saline	27 (2.6%)	589.7 (1.6%)	31 (3%)	1,155.9 (3.2%)
Total	1,027 (100%)	36,635.3 (100%)	1,027 (100%)	36,635.3 (100%)
Accuracy summary				
User's accuracy of saline lakes	95.0%	98.1%	94.2%	96.4%
User's accuracy of freshwater lakes	40.7%	71.1%	39.7%	65.4%
Producer's accuracy of saline lakes	63.3%	95.3%	62.6%	94.8%
Producer's accuracy of freshwater lakes	88.2%	86.4%	86.4%	73.3%
Overall accuracy	68.9%	94.3%	67.9%	92.2%

691

692 Table 4 and Table 5 report more detailed accuracy assessments for our classified four lake

693 types (i.e., terminal saline, open saline, terminal freshwater, and open freshwater). There are 104

694 open saline lakes misclassified as open freshwater (Table 4). These errors were attributed to the

695 fact that the literature we collected disagrees with CNLS. We also found that two lakes, Laxiong

696 (34.35° N, 85.23° E) and Jiesa (30.23° N, 84.79° E), were documented to be saline in CNLS but

697 terminal freshwater in the Chinese Lake Catalogue (Wang and Dou, 1998), which we used as

698 literature evidence. In the Chinese Lake Catalogue, Laxiong Lake was reported to have a salinity

699 of less than 0.001%, and Jiesa Lake has no salinity record but is documented to be freshwater in

700 Wikipedia. This situation indicates that discrepancies between the references can indeed occur, so

701 future work may require additional collation among different literature. Some terminal lakes can

702 be freshwater, without literature evidence, this type of lake is easily misclassified, leading to a low

703 producer's accuracy (Table 5). Still, terminal freshwater lakes are rare, accounting for only 0.5%

704 of all terminal lakes in the Tibetan Plateau and about 0.4% of all validated lakes. Improvements

705 also need to be made in finding the "hidden" saline lakes without any of the three kinds of

706 evidence. In the Tibetan Plateau, where saline lakes are very abundant, these hidden saline lakes

707 account for about 14.8% of all validated lakes (104 open freshwater in this study). However, we

708 expect this proportion to reduce in other regions where saline lakes prevail to lesser extents.

709

710 **Table 4.** Confusion matrix for the classified terminal saline lakes, open saline lakes, terminal

711 freshwater lakes, and open freshwater lakes. Numbers in the upper triangle represent the user's

712 accuracies and the numbers in the lower triangle represent the producer's accuracies.

	Chinese national lake survey (CNLS)				
Count (Area in km^2)	Terminal saline	Open saline	Terminal freshwater	Open freshwater	Total
Terminal saline	411 (27,155.8)	0	7 (59.7)	0	418 (27,215.5)
Open saline	0	18 (1,929.2)	0	0	18 (1,929.2)
Terminal freshwater	2 (199.1)	0	3 (508.5)	0	5 (707.6)
Open freshwater	0	104 (430.2)	0	155 (2,099.6)	259 (2,529.8)
Total	413 (27,354.9)	122 (2,359.4)	10 (568.2)	155 (2,099.6)	700 (32,382.1)

This study

713

Table 5. Summary of classification errors and accuracies for each lake type.

Count (Area)	Commission error	Omission error	Producer's accuracy	User's accuracy
Terminal saline	1.7% (0.2%)	0.5% (0.7%)	99.5% (99.3%)	98.3% (99.8%)
Open saline	0% (0%)	85.2% (18.2%)	14.8% (81.8%)	100% (100%)
Terminal freshwater	40.0% (28.1%)	70% (10.5%)	30% (89.5%)	60.0% (71.9%)
Open freshwater	40.2% (17.0%)	0% (0%)	100% (100%)	59.8% (83%)

715

4.3 Application of framework to Australia

Encouraged by the promising accuracy of our classification on the Tibetan Plateau, we then applied it to the continent of Australia using the same circa-2015 lake mask. Figure 11 shows the spatial distribution of our classified terminal saline, open saline, terminal freshwater, and open freshwater lakes in Australia. Most saline lakes are found in endorheic and/or arid regions that account for a large proportion (79%) of the Australian landmass, whereas freshwater lakes are mainly located in the peripheral exorheic basins. This result echoes one of the major climatic characteristics in Australia: a vast arid interior partially caused by the subtropical high-pressure zone. As shown in the latitudinal and longitudinal distributions (Fig. 11), it is clear that saline lakes dominate the continent in terms of lake area. Three large saline lakes, Lake Mackay (22.5° S, 128.58° E) in the Great Sandy Desert, Lake Eyre (28.37° S, 137.37° E) in the Simpson Desert, and Lake Torrens (31.04° S, 137.86° E), contribute a significant proportion (12%) of the total saline lake area (Fig. 11a). Based on the literature evidence, several terminal lakes in Australia are freshwater. Examples include Lake Woods (17.84° S, 133.45° E) and Lake Goyder (26.78° S, 139.13° E), both of which are ephemeral with low salinity (Shipton et al., 2021; Badman and May, 1983). As summarized in Fig. 12, saline and freshwater lakes account for 44.15% and 55.85% of

732   the total lake number, respectively, and the aggregated area of saline lakes is about three times

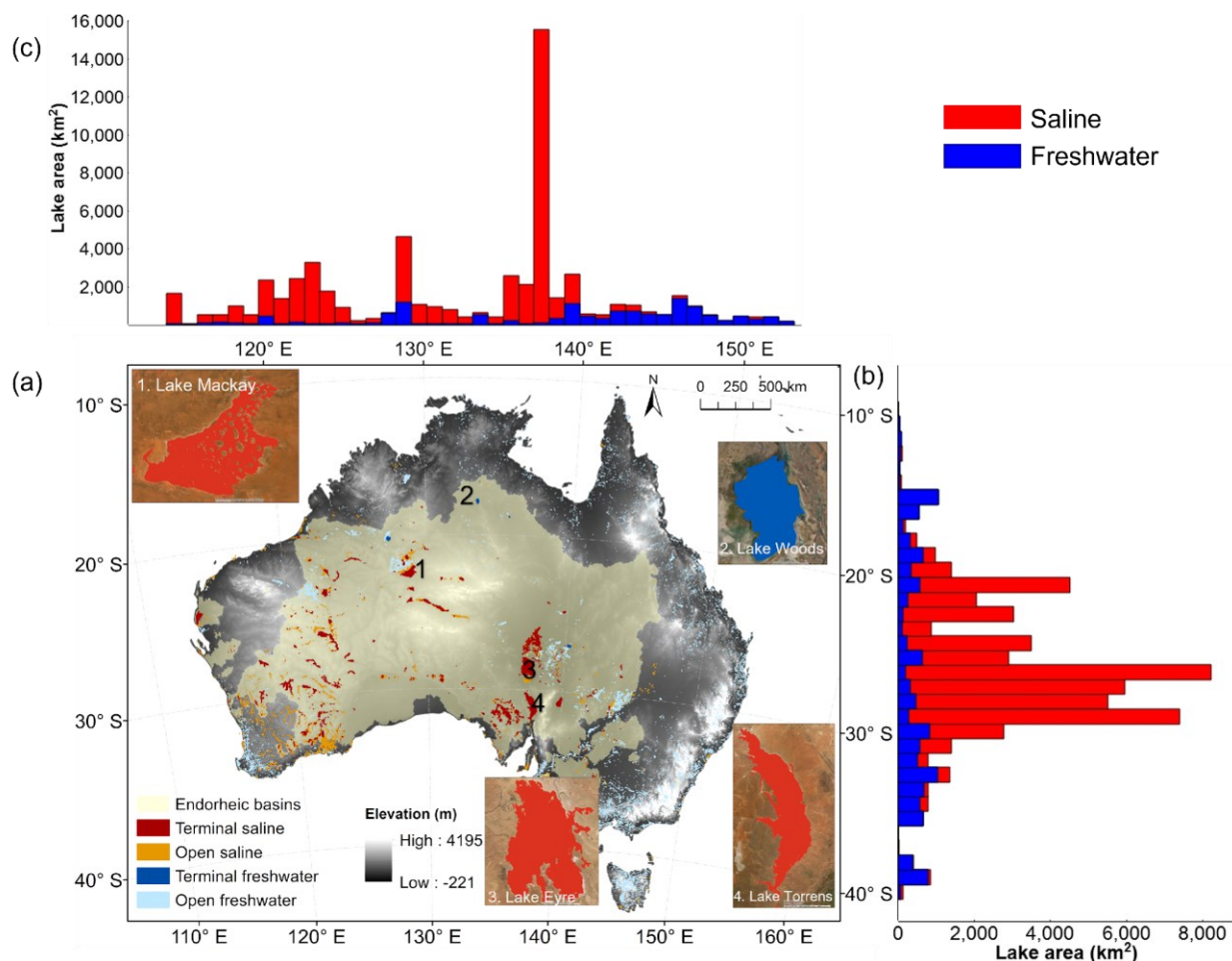733   larger than that of freshwater lakes.

734

735   **Fig. 11.** Classified freshwater and saline lake typology in Australia using the circa-2015 lake

736   dataset. Panel (a): Spatial distribution of terminal saline lakes, open saline lakes, terminal

737   freshwater lakes, and open freshwater lakes. Panels (b) and (c) are latitudinal and longitudinal

738   distributions of the total freshwater lake area and saline lake area, respectively.

739
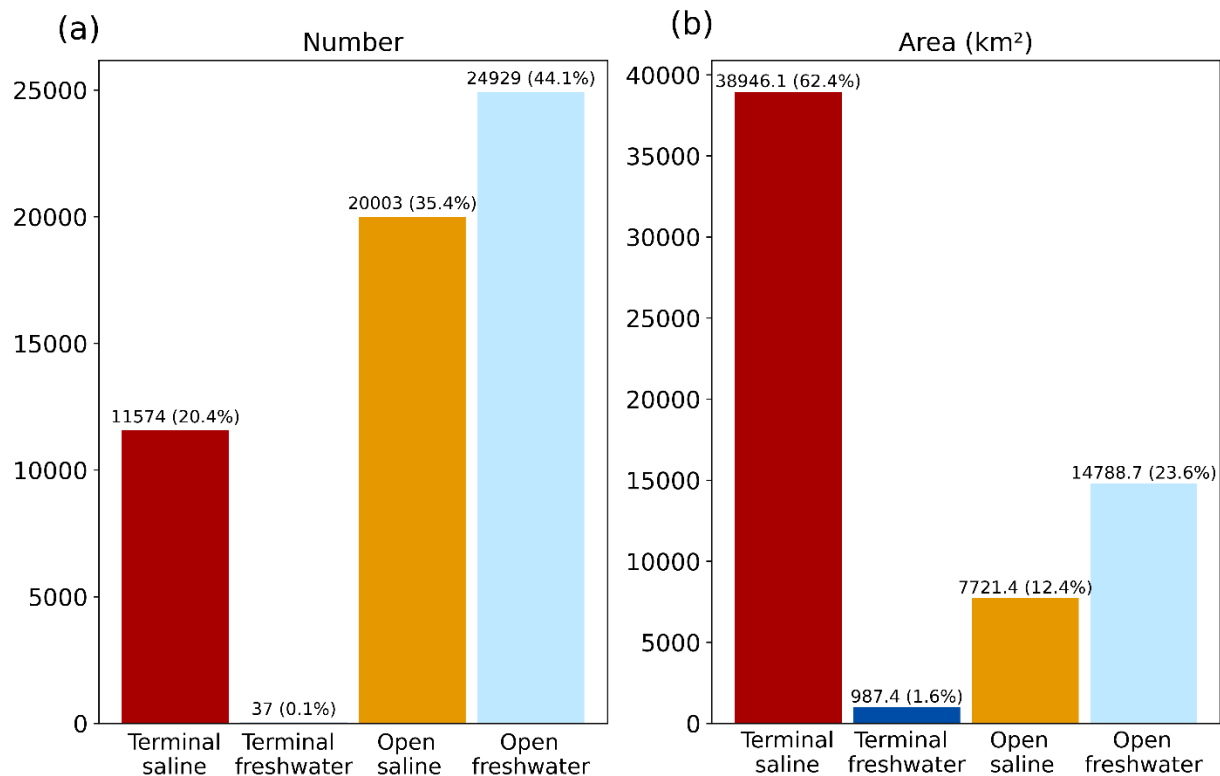
Fig. 12. Statistics of the classified lake typology in Australia. Panel (a) and panel (b) show lake numbers and lake areas, respectively.

Table 6 reports the accuracy of lake type classification based on hydroclimate and spectral evidence alone, validated with reference to our collected literature evidence. The overall accuracies are 99.1% by lake count and 96.9% by lake area, which are generally consistent with, albeit slightly higher than, the accuracies for the Tibetan Plateau. The category F2, terminal freshwater lake, accounts for the largest proportion (66.1% by count and 86.7% by area) of classification errors. Several factors may contribute to terminal lakes being freshwater, including salt decreases due to lake water seepage to the aquifer (Pham-Duc et al., 2020), ephemeral lakes caused by short-term flooding (Whitford and Duval., 2019), and local government protection and

43

management of the lake water environment. However, this type of error constitutes only 0.6% (or

2.7% by area) of all lakes with literature evidence.

Table 6. Accuracy of lake type classification for Australia using hydrological, climatological, and spectral evidence alone. Misclassified lakes fall into the following seven lake categories: i) terminal lakes without visible evaporites in endorheic basins but documented as freshwater lakes (F2); ii) open lakes with visible evaporites in endorheic basins but documented as freshwater lakes (F3); iii) open lakes without visible evaporites in endorheic basins but documented as saline lakes (S4); iv) lakes located in exorheic basins and arid regions and with visible evaporites but documented as freshwater lakes (F5); v) lakes located in exorheic basins and arid regions and without visible evaporites but documented as saline lakes (S6); vi) lakes located in exorheic basins and not in arid regions but documented as saline lakes (S7); vii) lagoons without visible evaporites but documented as saline lakes (S8)

Category	Non-literature evidence	Literature evidence	Count	Area (km^2)
F2	Saline	Freshwater	37	987.4
F3	Saline	Freshwater	0	0
S4	Freshwater	Saline	13	22.8
F5	Saline	Freshwater	6	129.7
S6	Freshwater	Saline	0	0
S7	Freshwater	Saline	0	0
S8	Freshwater	Saline	0	0
Total	-	-	56	1,139.9
All lakes with literature evidence	-	-	6,145	36,649.4
Accuracy	-	-	99.1%	96.9%

766   The relationship between lake count (abundance) and lake area in Australia follows a

767   Pareto distribution (Fig.13), as was the case in the Tibetan Plateau. However, the abundance of

768   saline lakes, as well as the slope of the count-area curve, is comparable to that of freshwater lakes

769   (also shown in Fig. 12), which contrast with what was observed in the Tibetan Plateau. Our

770   classification also captures many small saline lakes, as the power-law relationship still holds when

771   saline lake size decreases. This is partially because under extreme aridity, many small saline lakes

772   in Australia still exhibit clear spectral evidence from high-resolution images, and some of them

773   are clustered as patchy water residuals within large saline lake basins or salt pans. Some of the

774   classified small saline lakes, particularly in the periphery of major fluvial systems, can be highly

775   ephemeral or transitory. During the flood season, some of them can be replenished by freshwater

776   flows, so their salinity may vary significantly within the year. However, we opted to treat them as

777   saline lakes to indicate that these water bodies are located in visibly saline environments and tend

778   to become saltier as they are disconnected from the rivers and their water evaporates during the

779   drier seasons. It is also worth mentioning that saline lagoons also contribute to the saline lake area

780   in Australia. About 3% of the total saline lake area in Australia comes from lagoons, and they were

781   separated from freshwater lagoons using spectral and/or literature evidence (Fig. 4; Table 1).
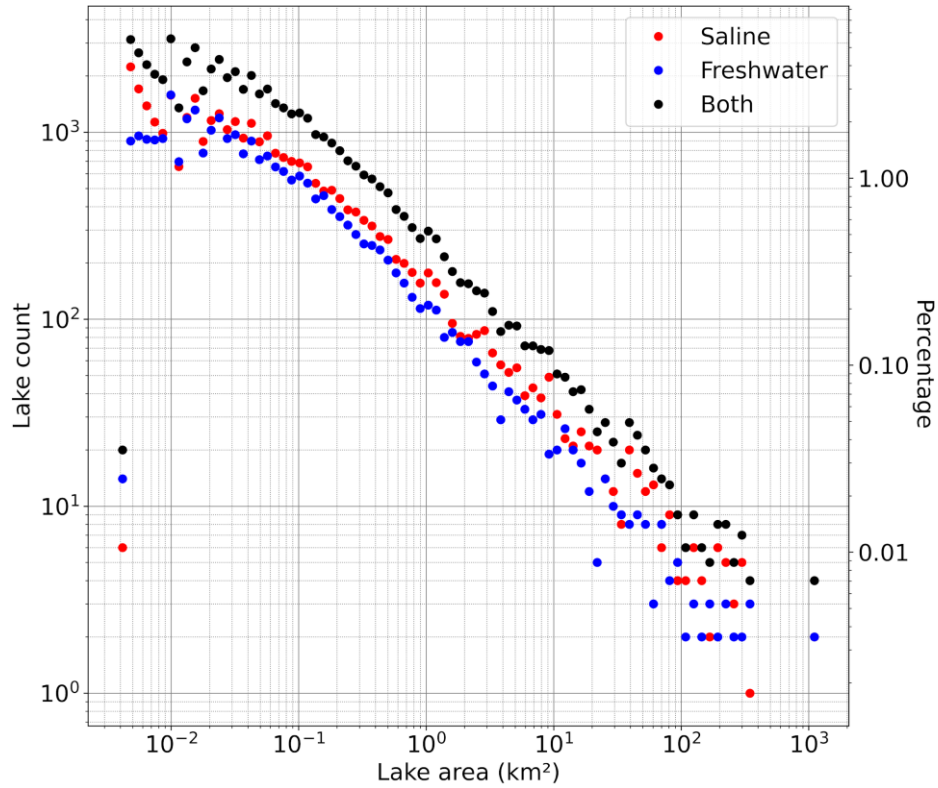
Fig. 13. Log-log relationship between lake area and count (abundance) in Australia.

4.4 Limitations and discussion

Our classification method is overall conservative in extracting saline lakes. As our schematic flowchart shows, only lakes that exhibit sufficient evidence were classified as saline lakes. In this case, our method provides feasibility to identify some of the most evident saline lakes with reasonable accuracies. However, since the evidence for saline lakes tends to weaken as the lake size decreases, the omission error generally increases for smaller saline lakes, leading to an overall conservative recognition of the saline lake number. This was reflected in our validation for the Tibetan Plateau. Although the quantity of saline lakes is underestimated, our method is more successful in capturing the total area of saline lakes, with both user's and producer's accuracies

794 exceeding 95% for the Tibetan Plateau. For this reason, it is important to reiterate that our

795 classification method, with its effectiveness dependent on the presence of remotely sensed

796 evidence, should not be considered a complete substitute for in situ measurement. Furthermore,

797 we also acknowledge that human activities also affect lake salinity (Tang et al. 2022; Williams,

798 2001). For example, agricultural water use can lead to overexploitation of rivers and lakes and thus

799 increase in salinity. The influence of human activities can be further considered when studying

800 changes in lake typology and salinity. The focus of this study is to provide a framework to

801 differentiate between freshwater and saline lakes, and therefore the discussion of the effects of

802 human activities is not involved.

803   Our current identification of spectral evidence relies on visual interpretation. Existing

804 studies related to salt-affected surface extraction applied more automated methods. For example,

805 Safaee and Wang (2020) implemented machine learning to delineate salt pans and playas, but the

806 accuracy of the results is limited to the image spectral and spatial resolutions (Landsat-8

807 multispectral images) and the ability to use multispectral information alone to separate salts from

808 other high-reflectance substance. Wang et al (2020) used satellite hyperspectral images (acquired

809 from China's Huanjing Satellite 1) and the fractional derivatives method to estimate soil salt

810 contents. In another study, Liu et al (2018) analyzed the surface reflectance spectrum from airborne

811 hyperspectral images to construct a salt index and label the salinized soil. Hyperspectral

812 information, although more effective in separating surface substances, is not always freely

813 available. In addition, a common challenge of these studies is that the validity of the methods may

814 be limited by the characteristics of the study area and sample collection, and the accuracy varies

815 from place to place. Therefore, these methods may not always be effective on a global scale. For

816 the purpose of "protocol and framework development", we replaced the automated methods by an

817   expert-based visual interpretation based on high-resolution multispectral imagery. This visual

818   interpretation allowed us to comparatively analyze textural and contextual information so as to

819   optimize the accuracy across heterogeneous surface conditions. However, our framework remains

820   flexible and does not inhibit future inclusion of automated methods.

821   In addition, our current lake type classification framework outputs a binary typology (i.e.,

822   freshwater and saline), although many of the saline lakes we identified were also provided with a

823   numeric salinity value collected from the literature (~7% in Tibetan Plateau, and ~5% in Australia).

824   These records were used to binarize the lake classes, and they were also used (together with other

825   nominal literature records) to verify and assess our classification accuracy based on hydroclimate

826   and spectral evidence alone (see details in Section 4.2). While we made every endeavor to collect

827   as much documentation in the form of published papers and reports, lakes with numeric salinity

828   documentation are still relatively rare given the sheer number of lakes in the study areas. We could

829   have applied the limited numeric salinities to enable a more detailed typology (e.g., including

830   subsaline, polysaline, and hypersaline), but some of the literature only reported nominal lake types

831   which were not always based on a consistent typology system or did not inform specific salinity

832   thresholds. Given these uncertainties, we decided to only keep binary categories (freshwater and

833   saline) for the final lake typology.

834

835   **5. Summary and concluding remarks**

836   Freshwater resources are finite and vital for human activities. As one of the most readily

837   accessible water resources, freshwater lake storage can contribute to human domestic, energy,

838   industrial, and agricultural uses. In addition, both freshwater lakes and saline lakes play important

839   roles in ecological services and climate change adaptation (Vareschi, 1987; Jódar et al., 2020).

840 Therefore, understanding the spatial distribution of freshwater and saline lakes has important

841 ramifications for limnology, ecology, and water security and management. However, classifying

842 freshwater and saline lake typology across large areas is challenging considering the high cost and

843 low efficiency of in situ surveys. Lake classification is further challenged by remote sensing

844 algorithms that are not always transferable among different saline environments. To address these

845 challenges, we composed a systematic lake type classification framework, which followed the

846 "water-solute imbalance" to theorize the conditions where lake salinity tends to accumulate. The

847 conditions were then identified as thoroughly as possible, by leveraging multi-dimensional

848 evidence including drainage terminals (hydrological), aridity (climatological), evaporite deposits

849 (spectral), and existing documentations (literature), which required no additional in situ

850 measurements.

851 When our framework was applied to the Tibetan Plateau, we found that saline lakes, despite

852 constituting less than 15% of the lake population, cover 82.4% of the total lake area across the

853 Tibetan Plateau. Nearly all of the classified saline lakes are distributed in endorheic basins.

854 Freshwater lakes dominate the lake population (86.1%) despite a smaller total area, and most of

855 the freshwater lakes (64.16%) are located in exorheic basins and/or humid regions. Validated by

856 CNLS, our overall classification accuracy reaches nearly 70% in terms of lake count and more

857 than 90% in terms of lake area. Given such promising accuracies, the classification method was

858 replicated in Australia. Our result shows that freshwater and saline lakes in Australia are

859 comparable in count (55.85% for saline lakes and 44.15% for freshwater lakes) but the total area

860 of saline lakes is about three times that of freshwater lakes. The case studies in these two saline

861 lake dense regions suggest the potential of applying our method in classifying lake typology in

862 other regions of the world.

863   We would like to reiterate that our lake type classification was achieved completely based

864   on existing literature and open-source remote sensing, climate, and hydrography datasets.

865   Although the method was proven to be reasonably accurate, there are cases where a saline lake

866   possesses none of the considered evidence, leading to an overall conservative saline lake

867   identification. For this reason, our method should not be considered a substitute for field surveys.

868   Classifying global lakes into freshwater and saline categories on a high-resolution global lake

869   inventory is a difficult task due to the sheer number of lakes and the complex hydroclimate settings.

870   Despite these limitations, particularly a conservative accuracy for identifying saline lakes, our

871   method provides a cost-effective way to provide a first-order separation between freshwater and

872   saline lake systems at broad geographic scales.

873

874   **Authorship contribution statement**

875   **Meng Ding:** Formal analysis, Investigation, Validation, Visualization, Writing - original

876   draft, Writing - review & editing. **Jida Wang:** Conceptualization, Methodology, Formal analysis,

877   Investigation, Validation, Visualization, Resources, Supervision, Project administration, Writing

878   – original draft, Writing - review & editing. **Chunqiao Song:** Methodology, Resources, Writing -

879   review & editing. **Yongwei Sheng:** Resources, Writing - review & editing. **J.M. Shawn**

880   **Hutchinson:** Writing - review & editing. **Abigail L. Langston:** Writing - review & editing.

881   **Landon Marston:** Writing - review & editing.

882

883   **Declaration of competing interest**

50

884   The authors declare that they have no known competing financial interests or personal

885   relationships that could have appeared to influence the work reported in this paper.

886

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