

# Widespread societal and ecological impacts from projected Tibetan Plateau lake expansion

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47 Lakes on the Tibetan Plateau are expanding rapidly in response to climate change. The potential impact 48 on the local environment if lake expansion continues remains uncertain. In this study, we integrate 49 field surveys, remote sensing observations, and numerical modelling to assess future changes in lake 50 surface area, water level, and water volume. In addition, we assess the ensuing risks to critical 51infrastructure, human settlements, and key ecosystem components. Our results suggest that by 2100 52 even under a low emissions scenario the surface area of endorheic lakes on the Tibetan Plateau will 53 increase by over 50% (~20,000 km<sup>2</sup>) and water levels will rise by around 10 m, relative to 2020. This 54 expansion represents approximately a 4-fold increase in water storage compared to 1970s-2020. A 55 shift from lake shrinkage to expansion was projected in the southern plateau around 2021. The expansion is primarily fueled by amplified lake water inputs from increased precipitation and glacier 56 57 meltwater, profoundly reshaping the hydrological connectivity of the lake basins. In the absence of 58 hazard mitigation measures, lake expansion is projected to submerge critical human infrastructure, including more than 1000 km of roads, approximately 500 settlements, and around 10,000 km<sup>2</sup> of 59 60 ecological components such as grasslands, wetlands, and croplands. Our study highlights the urgent 61 need for water hazard mitigation and management across the Tibetan Plateau.

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Lakes store approximately 87% of the Earth's accessible surface freshwater and play a critical role in global hydrological and biogeochemical cycles<sup>1,2</sup> that are important for ecosystem balance and socio-economic development<sup>3,4</sup>. In recent decades, large lakes around the world have experienced widespread declines in total water storage due to a combination of climate warming and anthropogenic disturbance<sup>5</sup>. In contrast, lakes residing on the Tibetan Plateau (TP) have exhibited an exceptionally dramatic expansion in response to the effects of a warmer and wetter climate<sup>6-8</sup>. As such, lake changes within the TP have received considerable attention in studies of global climate change<sup>9,10</sup>.

70 The TP, often referred to as the "Earth's Third Pole", contains vast stores of both solid (glaciers and 71 permafrost) and liquid (lakes) water<sup>11</sup>. It is also one of the most vulnerable regions to climate change, acting as an early warning signal for the wider effects of global warming<sup>12,13</sup>. The TP has experienced a remarkable 72 73 expansion of lakes, and the spatial difference is evident<sup>10,14</sup>. The TP is also witnessing a greener and more 74habitable environment, with a growing population seeking refuge at higher altitudes due to the benefits of 75 warming-induced accessibility to water resources<sup>15,16</sup>. However, the continued expansion of lakes is leading 76 to potential basin mergers or reorganizations, threatening the region's infrastructure and ecological security 77(Fig. 1, Extended Data Fig. 1). Despite the existence of some models to study future changes in the surface 78 area and water storage of the TP's endorheic lakes, their applicability to specific lakes remains uncertain due 79 to the spatio-temporal heterogeneity. Some models have focused on specific large lakes or single case studies but fail to encompass comprehensive future lake changes and their broader impacts on the TP<sup>17-20</sup>. 80

81 In this study, we address these knowledge gaps by developing a generalized data-driven modelling 82 framework that integrates the key drivers (precipitation, glacier meltwater, land surface evapotranspiration, 83 and lake evaporation) (Extended Data Fig. 2) and incorporates field surveys and remote sensing observations. 84 We quantify the annual changes in area, water level, and storage of individual endorheic lakes from 2021 to 85 2100 under Shared Socioeconomic Pathways (SSPs) scenarios. We then assess the magnitude of the impacts 86 on lake basin reorganization, infrastructure, and the ecological environment. We highlight the need to develop 87 effective strategies to mitigate water hazards, while protecting biodiversity and safeguarding the well-being 88 of people living in this ecologically sensitive region.

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#### 90 Future changes in lake area and water storage

91 The future surface area of endorheic lakes on the TP are projected to increase to  $53,657\pm5,068$  (+52% 92 compared to the area in 2020, ~2303 km<sup>2</sup>/dec),  $54,311\pm5,308$  (+54%, ~2385 km<sup>2</sup>/dec), and  $58,716\pm6,681$ 

93 (+67%, ~2936 km<sup>2</sup>/dec) km<sup>2</sup> by 2100 under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively (Fig. 94 2a). Accompanying the expansion of lake surface area, water levels are projected to rise by 10.21±4.14 m 95 (~1.28 m/dec) under SSP1-2.6, 10.64±4.33 m (~1.33 m/dec) under SSP2-4.5, and 13.29±5.18 m (~1.66 m/dec) 96 under SSP5-8.5 scenarios by 2100 (Fig. 2b). The future rates of lake surface area expansion and water level 97 rise are expected to slow down substantially, compared to an increase in lake area of ~11,400 km<sup>2</sup> and a rise in water level of ~5.25 m between 2000 and 2020, respectively<sup>21</sup>. Over the next 80 years, lake water storage is 98 99 estimated to increase by 652.97±211 (~81.50 Gt/dec), 665.32±220 (~83.13 Gt/dec), and 908.44±282 (~113.50 100 Gt/dec) Gt, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, which are ~3.9, ~3.9 and ~5.4 101 times the increase in water storage between 2000 and 2020, respectively (Fig. 2c). However, this change in 102 water storage by 2100 is a staggering ~4-fold increase compared to the 1970s-2020 period.

Our analysis shows a pronounced heterogeneity in the spatial distribution of future lake changes (Fig. 2, Extended Data Figs. 3–4, Supplementary Figs. S1–S2). The most significant change is observed in the northern TP, where the total lake area is projected to increase two-fold by 2100 under the SSP5-8.5 scenario. Albeit to a lesser extent, lakes in the southeastern, central, and northwestern endorheic TP are expected to expand significantly (51–71%). Historically, lake changes in the southern TP have followed a shrinking trend<sup>10,22</sup>. However, our projections indicate a remarkable transition from shrinkage to expansion in ~2021 (Extended Data Fig. 4, Supplementary Figs. S1–S3).

There are notable differences in the evolution of lake surface area, water level, and water storage. During the period 2021–2100, changes in lake storage (level and area) range from about -0.61 Gt (corresponding to -11.89 m and -8 km<sup>2</sup>) to 66 Gt (59 m and 903 km<sup>2</sup>). Most of the increases are between ~0.86 Gt (3.96 m and 7.83 km<sup>2</sup>, 25th percentile) and ~1.29 Gt (14.21 m and 47.14 km<sup>2</sup>, 75th percentile). Notably, Selin Co, the largest lake in Tibet and the second largest lake in the TP, exhibits the largest substantial water gain of ~66 Gt along with corresponding increases in area of ~800 km<sup>2</sup> and level of ~21 m under the SSP2-4.5 scenario.

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#### 117 Changes in the hydrological connectivity of lake basins

Under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, 70 (23%), 70 (23%), and 79 (26%) lake basins will be reorganized into 28, 28, and 31 basins respectively by 2100 (Fig. 3a). New reorganizations will occur mainly in the northern, eastern, and southern endorheic TP (Fig. 3c). In addition, 21, 19, and 23 lakes will merge (i.e., two or more lakes merging into one) under these scenarios, forming 10, 9, and 11 lakes, respectively (Fig. 3b). Lake mergers are predicted to occur mainly in the northeastern and southeastern TP (Fig. 3d). With the 123 anticipated growth of lakes in the future, the reconfiguration of the drainage system, spurred by the 124 interconnected nature of these lakes, is expected to become even more extensive.

125 Seven different types of basin reorganizations are identified, each characterized by distinct processes, 126 quantities, and types of lakes (endorheic and exorheic) (Extended Data Fig. 5). In the future, most basin 127 reorganizations are projected to follow cascading overflow (Type I), and the progression from the 128 amalgamation of endorheic lakes (Type II) to the inflow of lakes into a merged basin (Type III) will occur when 129 merged lakes experience overflow. The outflow of a merged basin into a lake (Type IV) and the convergence 130 of several lakes into a single basin (Type V) are less common, with only one reorganized basin in each case. In 131 addition, future lake expansion can lead to shifts in lake type, such as an endorheic lake becoming exorheic 132 (Type VI). The confluence of endorheic and exorheic lakes (Type VII) shows a particular type of merging, where 133 three endorheic and two exorheic lakes merge into one endorheic lake. Different reorganization types could 134 occur for the same lake over different time periods, given the intricate dynamics of continuous expansion. The 135future evolution of lakes is thus poised to be very complex.

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### 137 Impact of future lake expansion

138 By the end of this century, 1023±281, 959±274 and 1481±421 km of roads will be inundated under the SSP1-139 2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, (Fig. 4a). Under the SSP2-4.5 (SSP1-2.6 and SSP5-8.5) 140 scenarios, ~118 (149 and 136), 215 (264 and 258), and 331 (382 and 390) km of roads are still at risk of flooding 141 in 2030, 2040, and 2050, respectively. The inundated roads are mainly concentrated in the southern endorheic 142 TP. Despite the most significant lake expansion in the northern endorheic TP, the presence of seasonal 143 permafrost limits road construction and human access, resulting in fewer flooded roads. Conversely, although 144 lake expansion is less in the northeastern TP (Fig. 2, Extended Data Fig. 4), a significant number of road 145 segments are expected to be inundated due to increased human activity and the prevalence of roads adjacent 146 to lakes (Extended Data Fig. 6). At the lake scale, 12 lakes including the three largest lakes (Selin Co, Nam Co, 147 and Qinghai Lake) are identified as potentially more vulnerable (Extended Data Fig. 7). Selin Co has the most 148 submerged roads, with the projected length of submerged roadways expected to reach about 84.13–119.08 149 km by 2100. Due to the rapid expansion of Selin Co, the S208 highway was broken by the outflow flood at 150the end of September 2023 (Fig. 5). Nam Co, which is almost surrounded by roads, is expected to have ~73.27, 151 ~34.02, and ~118.91 km of roads submerged under the three scenarios, respectively. Due to the significant 152expansion of Qinghai Lake, some roads in the northwest have been inundated (Fig. 5). Approximately 46.9 km of road is expected to be inundated under the SSP5-8.5 scenario. In summary, a significant number of roads are potentially at risk of being submerged by future lake expansion, which is a serious threat that should be considered in future rail and road planning.

156 Given the importance of water resources and religious culture in the TP, many settlements such as 157 villages, herders' houses, and livestock pens are located around lakes (Fig. 1, Extended Data Fig. 1a). 158Projections indicate that by the year 2100, an estimated 5.66, 7.40 and 5.78 million people will inhabit in the 159 TP under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively<sup>23</sup>. Approximately 462, 458, and 615 160 settlements will be inundated, respectively, and most of them are in the southern endorheic TP (Fig. 4b, 161 Extended Data Fig. 6). Moreover, between 83 and 93 lakes are anticipated to inundate settlements, with Selin 162 Co posing the greatest risk, inundating 64 to 81 settlements across various SSP scenarios. Notably, certain 163 settlements already face inundation or are at heightened risk, such as the village and building near Zhari 164 Namco and Padu Co (Fig. 5), and this impending threat is expected to increase in the future.

165 The future expansion of TP lakes will also inundate many ecological components, including grasslands, 166 wetlands, croplands, forests, and sparse vegetation (Figs. 4-5, Supplementary Fig. S4). By the year 2100, the 167 anticipated inundation areas are projected to reach 8,533, 9,132, and 11,576 km<sup>2</sup> by 2100 under the SSP1-2.6, 168 SSP2-4.5, and SSP5-8.5 scenarios, respectively. More than ~500,000 head of livestock could be disturbed, 169 assuming even distribution of livestock (Supplementary Fig. S5). 4,241±1168, 4,459±1241, and 5,968±1823 170 km<sup>2</sup> of grassland will be inundated by 2100 in the SSP scenarios, respectively (Fig. 4c). This will directly lead 171 to a decline in livestock production, severely affecting the livelihoods of local pastoralists and further 172exacerbating poverty levels. We also identified 291 lakes widely distributed across the plateau, which pose a 173threat to the security of the grasslands (Fig. 4c), such as the large grasslands near Peng Co (Fig. 5). Loss of 174 cropland could disrupt food production, affecting both local food security and the regional agricultural 175 economy.

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# 177 Implications and mechanisms of future lake expansion

As lakes on the TP continue to expand, there is growing concern about increased emissions of greenhouse gases, including carbon dioxide and methane, into the atmosphere<sup>24</sup>. These emissions can further exacerbate global warming, creating a positive feedback loop that amplifies the effects of climate change. In addition, the submergence of grasslands due to flooding can lead to the decomposition of organic matter, releasing additional carbon dioxide into the atmosphere<sup>25</sup>. Furthermore, the interaction between these lakes and the atmosphere, as well as their role in regional hydrological cycles such as extreme rainfall or snowfall events<sup>26,27</sup>,
 is expected to intensify as lakes expand in size in the future.

185 Future increases in lake water volume, with an increase influx of freshwater, can lead to decreases in 186 salinity<sup>28,29</sup>, which could substantially impact the physical environment of lakes<sup>30,31</sup>, alter species richness, 187 composition, and the trophic structure of lake ecosystems<sup>32</sup>. Rising lake surface water temperatures and 188 increasing heatwaves have cascading effects on the physical structure and chemical properties of aquatic 189 systems, threatening lake biodiversity<sup>33,34</sup>. In addition, the overflow water carrying eroded sediments will 190 increase the turbidity and sedimentation in the receiving lakes<sup>35</sup>, which could disrupt the ecological balance 191 of the lakes and lead to species loss. The newly formed channels resulting from lake basin reorganization and 192 lake merging can lead to a cascade of hydrogeomorphic processes along their paths, such as incision, lateral 193 erosion or aggradation, thermal erosion, and increased infiltration, which affect the regional ecological 194 environment and disrupt ecological migration. For example, Zonag Lake in Hoh Xil Nature Reserve burst in 195 September 2011, blocking the Tibetan antelope migration route and affecting their survival and 196 reproduction<sup>36</sup>. The effects of this drainage reorganization can spill over into larger downstream basins.

From a socio-economic perspective, the direct economic loss due to inundated roads by 2100 under the SSP2-4.5 scenario, is estimated at RMB 20 to 50 billion based on investment costs in 2022<sup>37</sup>. The future expansion of lakes can enhance the natural landscapes and increase sustainable tourism development and local income. The Tibet Autonomous Region plans to build ~5,600 km of new highways and three railways<sup>37</sup> (Supplementary Fig. S6). The expanding lakes pose challenges to existing and planned infrastructure and communities and require urgent implementation of effective adaptation and sustainable management strategies to mitigate socio-economic repercussions.

204 Glacier meltwater contributes ~9% to the increase in lake storage from 1995 to 2020<sup>38</sup>, and although the 205 temperature of the TP will continue to rise, the contribution of glacier meltwater is estimated to be only 7 -206 15% by 2100 (Extended Data Fig. 8), due to the limited storage of the remaining glaciers<sup>39,40-42</sup>. Lake 207 evaporation is also an important driver of water loss, and the reduction in lake ice this century is likely to lead to an increase in lake evaporation<sup>43,44</sup>, but the relative contribution is small<sup>19</sup>, with an estimated loss 208 209 contribution of about -34% under SSP2-4.5 and SSP5-8.5 scenarios. Due to future increases in temperature 210 and radiation, precipitation is likely to remain the main controlling factor for evapotranspiration on the TP<sup>45</sup>. Lake expansion on the TP is primarily influenced by net precipitation<sup>7,22,46</sup>, and the significant increase in future 211 212 net precipitation will act as a greater water gain leading to further lake expansion, with an estimated relative 213 contribution of 109 - 116%.

Given the current context of global warming and climate change, it is crucial to comprehensively understand the future changes of the lakes to effectively manage water resources, mitigate hazards, and preserve the ecology of this crucial region. Our study serves as a scientific guide for future planning and provides valuable insights to avoid the devastating consequences of the impending lake expansion.

218

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- 226

# 227 Author contributions

- 228 G.Z. designed the study. F.X. and G.Z. drafted the manuscript. R.I.W., K.Y., Y.W., J.W. and J.F.C. edited the
- 229 manuscript. All authors contributed to the final form of the study.
- 230

### 231 **Competing interests**

- 232 The authors declare no competing interests.
- 233 Figure Legends/Captions:



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### Fig. 1|Schematic diagram illustrating future lake development and impacts over the TP. a, Past lake

236 status. **b**, Future lake development and impacts. Expansion of lake boundaries and changes in the

- 237 hydrological connectivity of lake basins are the result of increased net precipitation and glacier/snow melt.
- 238 Future lake expansion will result in threats to human infrastructure such as roads and settlements, and
- 239 ecological components such as grasslands, wetlands, and croplands, as well as changes to the lake
- ecosystem such as algae, fish, zooplankton, microorganism. Credit: Temperature and evaporation icons in **a**
- and **b**, <u>Flaticon.com</u>.



Fig. 2|The spatial patterns of lake surface area, water level, and storage changes between 2020 and 2100 under the SSP2-4.5 scenario. a, The percentage of lake area change in 2100 relative to 2020. b, The lake level change in 2100 relative to 2020. c, The ratio of lake storage change between 2020 and 2100 relative to the change between 2000 and 2020. The insets in a, b and c show the evolution trends of all lakes under the SSP1-2.6 to SSP5-8.5 scenarios, and the range of the error bands shows the 95% confidence intervals of the estimations of the bootstrap method. d, The changes in lake area, water level, and storage in each subregions. Additional SSP1-2.6 and SSP25-8.5 scenarios are shown in Extended Data Fig. 3.



Fig. 3|Future reorganization of lake basins and lake mergers. a, Number of basins before and after reorganization under different scenarios. b, Number of lakes before and after mergers under different scenarios. c, Spatial distribution of basin reorganization under the SSP2-4.5 scenario. d, Spatial distribution of lake mergers under the SSP2-4.5 scenario. The merged lakes are shown as merged basins because each lake basin has only one endorheic lake.

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Fig. 4|The roads, settlements, and grasslands submerged by expanding lakes by 2100 under the SSP2 4.5 scenario. a, Spatial distribution of the length of submerged roads across the lake basin. b, Spatial distribution and time of submerged settlements. c, Spatial distribution of the extent of submerged grasslands. Insets show annual variations in the length of submerged roads (a), the number of submerged settlements (b), and annual variations in the extent of submerged grasslands (c) under different climate scenarios, with the range of the error bands estimated based on 95% confidence intervals for the lake area. Additional SSP1-2.6 to SSP5-8.5 scenarios are shown in Extended Data Fig. 6.



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Fig. 5|Cases of roads, bridges, settlements, and grasslands threatened by expanded lakes. a, The S208 road was damaged by flooding due to Selin Co expansion on around 25 September 2023. Field photos taken by F. Xu on 2 October, 2023. b, Roads indundated by Qinghai Lake expansion. c, Original S301 road (red) indundated and roads potentially indundated. d, Village at high risk near Zhari Namco. e, Settlement indundated near Padu Co. Photos were taken by R. Zhang. f, High-risk grasslands near Peng Co. The insets show the evolution of lake levels under the SSP1-2.6 scenario. The location of these lakes is indicated in Extended Data Fig. 1.

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### 372 Methods

## 373 Historical lake storage changes

374 Weekly to annual historical changes in lake water storage from five data sources were used to project as many 375 lakes as possible (Supplementary Table S1): (1) Hydroweb (http://hydroweb.theia-land.fr/hydroweb)<sup>47,48</sup>, which 376 contains time series of lake water level, surface area and storage changes, and hypsometric curves, covering 377 42 endorheic lakes in the TP; (2) Annual area and water storage of 976 lakes large than 1 km<sup>2</sup> on the TP for 378 1991–2018<sup>49</sup>; (3) Annual area of ~300 lakes larger than 10 km<sup>2</sup> in the TP for 1991–2018 and hypsometric curve<sup>7</sup>; 379 (4) Water storage changes for 1132 lakes with  $\sim$ 5 year interval and hypsometric curve<sup>21</sup>; (5) Weekly to monthly 380 water level and storage changes for 52 lakes on the TP during 2000–2017 and hypsometric curve<sup>50</sup>. These 381 different types of datasets, that convert area or water level to water storage change by combining hypsometric 382 curves were integrated. In this study, 307 lakes representing ~97% of the total area of endorheic lakes in the 383 TP were selected based on the availability of historical annual lake volume change.

384

#### **385 Precipitation product**

386 The average of two sets of historical precipitation products including ERA5-Land and TPHiPr was used 387 (Supplementary Table S2). ERA5-Land, a state-of-the-art reanalysis precipitation, is an enhanced global 388 dataset for the land component of the fifth generation of European ReAnalysis (ERA5) produced by the 389 European Centre for Medium-Range Weather Forecasts (ECMWF)<sup>51</sup>, spanning 1950 to the present, with hourly 390 to monthly resolution. ERA5-Land data with a spatial resolution of ~9 km is interpolated from the ERA5 data 391 with a spatial resolution of ~31 km, using a linear interpolation method based on a triangular mesh. Although 392 ERA5-Land overestimates the amount of precipitation, it provides a good representation of the spatiotemporal variation patterns over the TP<sup>52</sup>. TPHiPr is a high-precision precipitation dataset for the Third Pole 393 394 region (1/30°, daily), obtained by merging the atmospheric simulation-based ERA5 CNN product with over 395 9000 rain gauges, using the climatologically aided interpolation and random forest methods<sup>53</sup>. This dataset 396 has better accuracy compared to ERA5-Land, IMAGE, MSWEP v2 and AERA5-Asia data, with a Root Mean 397 Square Error (RMSE) of 5.0 mm d<sup>-1</sup>. The comparison of precipitation time series between TPHiPr and ERA5-398 Land (Supplementary Fig. S7), suggested a good agreement. Importantly, the offset between these two 399 datasets did not contribute to uncertainties, as the precipitation anomaly served as the basis for lake 400 modelling. However, we used the average of TPHiPr and ERA5-Land to minimize the uncertainty of the lake 401 projections. For the future precipitation product, the monthly outputs of the 32 CMIP6 ESMs under the SSP12.6, SSP2-4.5 and SSP5-8.5 scenarios were used and calibrated against ERA5-Land and TPHiPr data, respectively, during the overlap period. The top 15 ESMs in each basin were selected using historical references from ERA5-Land and TPHiPr data, respectively, and subsequently the ensemble mean of the 30 ESMs served as future precipitation. Further details on the downscaling and selection for the CMIP6 ESMs method are available in the Supplementary Text1 (Supplementary Figs. S8–9). Detailed information on the evapotranspiration product and glacier mass balance data used in this study can be found in the Supplementary Texts2–3.

409

# 410 Lake evaporation forcing data

411 The forcing variables were used to calculate evaporation include air temperature, specific humidity, pressure, 412 downward shortwave radiation, downward longwave radiation, and wind speed. These variables were 413 obtained from the China Meteorological Forcing Dataset (CMFD) with a 3-hour time step and grid resolution of 0.1°54, and bias-corrected CMIP6 ESM. It should be noted that although CMFD is considered to be the most 414 415 accurate meteorological data for the TP, errors have been identified based on observed data. Therefore, linear 416 corrections were applied to air temperature, specific humidity, air pressure, downward shortwave radiation and wind speed using correction equations from the previous studies<sup>55,56</sup>, which could reduce the bias of the 417 418 CMFD. Details on the corrections equation are available in the Supplementary Text4. The bias-corrected CMFD 419 was then used to correct the CMIP6 15-36 ESMs. For each lake, the area-weighted mean of the forcing data 420 was calculated for the grids intersecting each lake. Further details on the downscaling for CMIP6 ESM method 421 are available in the Supplementary Text1.

422

#### 423 Estimate of lake surface evaporation

During the unfrozen period, the monthly lake evaporation rates were calculated using the Penman-Monteith equation (Eq. 1), which is widely used to estimate open water evaporation<sup>57-59</sup>.

426

$$E_{w} = \frac{\Delta}{\Delta + \gamma} \frac{R_{n}}{\lambda} + \frac{\gamma}{\Delta + \gamma} E_{a}$$
(1)

427 where *Ew* is the daily evaporation rate (mm day<sup>-1</sup>); *Rn* represents the net radiation (W/m<sup>2</sup>); Δ is the slope of 428 the saturated vapour pressure curve (kPa °C<sup>-1</sup>);  $\gamma$  is the psychrometric constant (kPa °C<sup>-1</sup>);  $\lambda$  is the latent heat 429 of vaporization (2.45 MJ kg<sup>-1</sup>).

430 Ea (mm day<sup>-1</sup>) denotes the evaporative component from the turbulent movement of water vapour by

431 eddy diffusion<sup>60</sup> and as follows:

432

$$E_a = 0.26(1 + 0.54u)(e_s - e_a) \tag{2}$$

where *u* is the wind speed at 2 m; es-ea is the vapour pressure deficit (VPD) (KPa). During the freeze period, lake evaporation is in the form of sublimation and is estimated by the equation (Eq. 2)<sup>61</sup>. Further details on the historical and future lake ice phenology are available in the Supplementary Text5.

436 Net radiation (*Rn*) over the lake surface was estimated using (Eq. 3):

437

 $R_n = (1 - \alpha)K^{\downarrow} + L^{\downarrow} - L^{\uparrow}$ (3)

where *a* is the lake surface albedo (0.07);  $K^{\downarrow}$  is the downward shortwave radiation (W/m<sup>2</sup>);  $L^{\downarrow}$  is the downward longwave radiation (W/m<sup>2</sup>);  $L^{\uparrow}$  is the estimated upward longwave radiation (W/m<sup>2</sup>) using  $L^{\uparrow} = \varepsilon_w \sigma (T_a + 273.15)^4$ ; *Ta* denotes air temperature, which ideally should be the lake surface temperature, but due to the unavailability of future data, air temperature is used as a proxy. As we use the relative change in evaporation, the effect of this term on the evaporation is minimal.

443

## 444 **Development of future lake modelling framework**

445 Future lake modelling is limited by the following factors: (1) region-specific methods exist, but individual lakespecific modelling methods for large scales are lacking<sup>19</sup>, (2) the limitation of large-scale application of land 446 447 surface or hydrological models due to the scarcity of runoff inflow observations for lakes (available only for 448 Selin Co and Nam Co)<sup>18</sup>; (3) without considering the topography constraints on future lake changes and 449 hydrological connectivity between lakes; (4) machine or deep learning methods are limited by coarse temporal 450 resolution due to cloud contamination of satellite imagery, and lack of interpretability<sup>17</sup>. The storage changes 451 of endorheic lakes accounted for 95–100% (161.9±14 Gt) of the total lake change observed from the 1970s to 2020, while exorheic lakes remained relatively stable (7.8±5.8 Gt)<sup>21</sup>. Therefore, we developed a data-driven, 452 453 generalized modelling framework specifically for endorheic lakes to model their future annual changes, 454 including lake surface area, water level, and lake water storage (Extended Data Fig. 2). Lake changes are mainly 455controlled by four dominant forcings: precipitation, glacier meltwater (Supplementary Text2), land 456 evapotranspiration (Supplementary Text3), and lake evaporation<sup>7,62</sup>. The framework consists of two main steps: 457(1) projecting future changes in lake storage in response to climate change (Extended Data Fig. 2a), and (2) 458integrating inundation models and digital elevation models (DEMs), considering lake connectivity, to estimate 459 actual surface area, water level, and actual lake storage (Extended Data Fig. 2b).

460 Step 1 of the modelling framework defines the concept of a stable period, where the size of the lake

461 remains relatively constant during the beginning and end years of this period, allowing for fluctuations in lake 462 size during this period (Extended Data Fig. 2a). The stable period can vary for each lake and was determined 463 based on the changes in lake area from 1988 to 2018. Lakes on the TP experienced a contraction from the 464 1970s to 1995, followed by a significant expansion from 1995 to 2020. Most lakes have a stable period around 465 1995, such as the stable period 1989–1995 for Selin co. However, there are also some lakes that have a stable 466 period after 2000, such as Peiku Co for 2008–2015. During the stable period, the lake is in a state of equilibrium, 467 and then the equilibrium states of each factor are calculated as follows:

468

$$\bar{x}^{k} = \sum_{i=t1}^{t2} x_{i}^{k} / n \tag{4}$$

469 where k is the kth variable, including land precipitation ( $P_l$ ), glacier meltwater (G), land evapotranspiration (ET), 470 lake surface precipitation ( $P_w$ ), and lake surface evaporation (E), respectively. t1 and t2 represent the start and 471 end years of the stable period, n is the number of years in the stable period and i represents the years within 472 the stable period. Furthermore, a concept of a change period is defined, which refers to the period outside 473 the stable period for which lake storage data are available, mainly after 1990. The anomaly relative to the 474 equilibrium state is calculated for each contributing factor during the change period as follows:

 $\delta x_i^k = x_i^k - \bar{x}^k$ 475 (5)

476 where *i* represents the years within the change period. Subsequently, the annual cumulative anomalies relative 477 to the equilibrium state (Eq. 4) for each contribution factor were calculated, starting from the first year of the 478 change period as follows:

479

$$X_{i}^{k} = \sum_{i=c1}^{2018} \delta x_{i}^{k} \tag{6}$$

480 where c1 represents the starting years of the change period, the form of each contribution factor can be 481 expressed as land precipitation ( $PL_i^{cum}$ ), glacier meltwater ( $G_i^{cum}$ ), land evapotranspiration ( $ET_i^{cum}$ ), lake surface precipitation ( $PW_i^{cum}$ ), and lake surface evaporation ( $E_i^{cum}$ ), respectively. Furthermore, we also 482 483 calculated the annual cumulative changes in lake storage starting from the first year of the change period as 484 follows:

485

$$V_i^{cum} = \sum_{i=c1}^{2018} (V_i - V_{i-1}) \tag{7}$$

486 By integrating the cumulative changes in lake storage and the cumulative anomalies relative to the 487equilibrium state for each contribution factor calculated from Eq. 6, the lake storage modelling framework can 488 be expressed as:

- 489
- $V_i^{cum} = \alpha(\theta(PL_i^{cum} + G_i^{cum} ET_i^{cum}) + PW_i^{cum} E_i^{cum}) + \beta$ (8)
- 490 Eq. 8 can be decomposed into the following two parts:

491 
$$U_i = \theta(PL_i^{cum} + G_i^{cum} - ET_i^{cum}) + PW_i^{cum} - E_i^{cum}$$

492

 $V_i^{cum} = \alpha(U_i) + \beta \tag{10}$ 

(9)

where  $PL_i^{cum} + G_i^{cum} - ET_i^{cum}$  represents the land component, which includes the combined contributions of surface runoff, soil water, and groundwater to the lake change.  $\theta$  is a land-specific parameter.  $PW_i^{cum} - E_i^{cum}$  represents the lake surface component.  $U_i$  denotes a variable that integrates land surface precipitation, land evapotranspiration, glacier meltwater, lake surface precipitation, and lake surface evaporation, and is considered as net input.

498 The parameters in Eq. 8 were trained for each lake based on historical lake storage changes. Initially, the 499 parameter  $\theta$  was set to a fixed value of 1, and then  $\alpha$  and  $\beta$  were determined using the Theil-Sen 500 nonparametric method. If the  $R^2$  value between  $\alpha$  and  $\beta$  was greater than or equal to 0.60, the constructed 501 model was used to estimate future changes in lake storage. However, if the  $R^2$  value was less than 0.6, the 502 parameter  $\theta$  was adjusted in steps of 0.01 between 0.9 and 1.1, and then the Theil-Sen nonparametric method 503 was used again to determine the  $\alpha$  and  $\beta$  until the  $R^2$  exceeded 0.60. If the  $R^2$  remained consistently below 0.6, 504 the lake was extrapolated based on the ratio of the average storage change of the nearest five lakes. It is worth emphasizing that  $U_i$  and  $V_i^{cum}$  showed a highly robust linear synchronization, which was prevalent 505 506 among endorheic lakes on the TP (Extended Data Fig. 9a, Supplementary Fig. S10). The established model for 507 each lake was then used to project future changes in lake storage in response to climate change by inputting 508 the cumulative anomalies relative to the equilibrium state for each contribution factor from 2021 to 2100.

In step 2 of modelling framework (Extended Data Fig. 2b), the inundation model and DEM were combined, considering the connectivity of lakes<sup>63</sup>, to accurately estimate the actual lake storage, water level, and surface area. If a lake continues to expand in the future until it reaches the lowest point of the basin boundary, it will overflow from its basin and flow into adjacent lakes, resulting in a stable phase. Conversely, lakes that receive overflow recharge from other lakes will experience accelerated expansion. Therefore, the constraint of topography on future lake change is essential.

515 NASADEM (30 m pixel size) was selected to estimate the distribution of the projected lake water volume 516 changes because it was acquired instantaneously (11-day mission in February 2000) and has better accuracy 517 compared to other available 30 m DEMs<sup>64,65</sup>. First, considering that the NASADEM corresponds to the year 518 2000, the average elevation of the lake boundary in 2020 was extracted from the NASADEM and then was 519 used to replace all the elevations within the lake boundary in 2020. Then, using the regional growth algorithm 520 with the center of the lake as the seed point, a growth of 60 m was initiated to determine the corresponding 521 changes in area, water level, and water storage for each step of 1 m growth. Additionally, the maximum 522 storage capacity of the lake basin was determined and compared to the projected water storage from Step 1, 523 to determine whether the lake would overflow from the basin or receive inflows from other lakes. Furthermore, 524 the estimated water storage in Step 1 was also matched with the water storage change corresponding to the 525 1-60 m growth to determine the flow paths of water between adjacent lakes each year, redistributing the 526 water storage and obtaining the actual annual variations in lake storage, as well as the corresponding annual 527 water level and area under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. For lakes experiencing a reduction 528 in size, the approach involves utilizing a robust empirical linear volume-area-level relationship<sup>21</sup>, when the 529 projected water volume change is less than the volume loss recorded between 2000 and 2020. The lake 530 outlines from 2020 were used to conservatively estimate the potential impact of lake inundation. On the 531 contrary, when the projected lake volume change is greater than the recorded volume loss between 2000 and 532 2020, the estimation of the extent is determined through the application of a regional growth algorithm. 533 Further details on the method for analyzing the impacts of lake changes, auxiliary data and the attribution of 534 future lake changes are available in the Supplementary Texts6-8.

535

# 536 Validation and error estimation of future lake modelling

To evaluate the robustness of our approach, the  $R^2$  between U<sub>i</sub> (net input) and  $V_i^{cum}$  (accumulated lake storage) 537 538 was employed to assess the generalizability of the framework (see 'Development of future lake modelling 539 framework' in Method). The modelling framework developed in this study using four drivers performs well, 540 explaining more than 94% of the historical lake storage change in ~70% of the lakes, with a uniform 541 distribution across the TP (Extended Data Fig. 9). Among the 307 endorheic lakes, there were 214, 189, 154, 542 and 91 lakes with  $R^2$  higher than 0.60 (70%), 0.70 (62%), 0.80 (50%), and 0.90 (30%), respectively, which could 543 explain 94%, 92%, 85%, and 61% of the historical lake storage changes, respectively (Extended Data Fig. 9). 544 Furthermore, the performance of the modelling framework varies among lakes of different sizes, with larger 545lakes performing better, leading to a higher proportion of lakes and water storage that can be explained. In 546 addition, the samples for each lake were split in time, with the initial 70% allocated for model training and 547the remaining 30% for validation. The model's performance was assessed using the correlation coefficient (R), 548 Bias, and RMSE. The simulated and observed changes in lake water storage showed good agreement during 549 the validation period, with an overall R of 0.97 and a bias of 0.05 (Extended Data Fig. 10). The correlation 550 coefficients and bias distribution for different lakes also demonstrate good accuracy of the modelling 551 framework.

552 The Bootstrap method, a non-parametric approach to estimating confidence intervals of sample statistics 553 through repeated resampling of the original dataset, was used to assess the uncertainty of projected future 554 lake storage changes. For each lake, the historical data used for parameter training were resampled with 555 replacement 1000 times, with each sample comprising 50% of the total dataset. These 50% samples were used 556 to train 1000 sets of corresponding models, which were then used to estimate 1000 sets of future lake storage 557changes. Finally, the 95% confidence interval of the annual results was taken as the uncertainty of the estimate. 558 Subsequently, the uncertainty of lake storage changes was converted into the uncertainty of water level and 559 area, for example, if the error of lake storage for a given year is ~1 Gt, the uncertainty in water level and area 560 corresponds to the changes in water level and area for that year. The uncertainty of submerged roads and 561 grasslands was estimated based on the lake area. First, the submerged roads and grasslands corresponding 562 to the area changes from 2021 to 2100 were calculated. Then, the uncertainty in area for each year was 563 proportionally converted to the uncertainty in submerged roads and grasslands.

564

#### 565 Limitations and uncertainties of future lake modelling

566 Our model does not account for the effects of thermodynamic changes due to mixing regimes resulting from 567 basin reorganization and lake mergers in future changes. Given the 30 m spatial resolution of NASADEM, 568 changes in lake boundaries within a year are occasionally less than one pixel, in which case the previous year's 569 boundaries were used. Selin Co, which has the largest lake surface area in Tibet and the largest historical 570 extent change on the TP, was selected as a case study to evaluate the impact of DEM accuracy on the projected 571lake water volume distribution. The DEM accuracy could introduce a small uncertainty due to the influence of 572 elevation uncertainty, especially at the lake basin outlet (Supplementary Fig. S11). However, our analysis 573 showed only a small discrepancy in the projected lake volume change from NASADEM compared to the high-574 accuracy AW3D30 DEM<sup>66</sup>. The time series of future volume changes between them are in good agreement 575(R>0.98). Furthermore, the DEM-derived lake volume trends show small errors (R<sup>2</sup>=0.97 and bias=~5%) 576 compared to the altimetry-derived trends for 18 Tibetan lakes<sup>8</sup>. It is important to emphasize that our 577projections are highly dependent on the climate projection used under the CMIP SSP scenarios. However, due 578to differences in the representation of physical processes, parameterization schemes, and the ability to 579 simulate climate systems across climate models, there are discrepancies in projections under the same 580 scenario. To reduce the uncertainty in future projections, the average of multiple models was used.

581 A direct estimate of the groundwater contribution to lake change is limited by the lack of groundwater 582 observations. Basin-wide groundwater change in the inner TP, estimated from decomposed terrestrial water 583 storage based on GRACE observations, suggests a significant but smaller magnitude water mass gain relative 584 to lake change<sup>7</sup>. Our model accounts for groundwater contribution indirectly, with P-ET+G representing the 585 combined contributions of surface runoff, soil water, and groundwater without distinguishing their individual 586 effects on lakes. In addition, our model does not include the influence of permafrost on future lake changes 587 due to the current limited understanding of the freeze-thaw and hydrothermal processes of permafrost on 588 the TP<sup>67</sup>, which could also introduce uncertainties in future lake modelling. However, we consider this to be 589 somewhat limited due to the small contribution of ground ice meltwater to the historical increase in lake water storage<sup>7,68</sup>. 590

591

#### **Data availability**

- 593 The lake boundaries from 2021 to 2100 produced by this study are available at
- 594 <u>https://doi.org/10.6084/m9.figshare.24873747</u>. Precipitation and evapotranspiration from ERA5-Land can be
- accessed at https://www.ecmwf.int/en/era5-land. TPHiPr precipitation dataset is acquired at
- 596 <u>https://doi.org/10.11888/Atmos.tpdc.272763</u>. Noah\_GL can be accessed at
- 597 <u>https://disc.gsfc.nasa.gov/datasets/GLDAS\_NOAH025\_M\_2.0/summary?keywords=GLDAS\_NOAH025\_M\_2.0</u>.
- 598 GLEAM can be accessed at <u>https://www.gleam.eu</u>. CMFD can be accessed at
- 599 http://poles.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49. NASADEM data are
- 600 downloaded from <u>https://search.earthdata.nasa.gov</u>.
- 601 HydroSHED can be accessed at <u>https://www.hydrosheds.org</u>. The outputs of CMIP6 ESMs can be access at
- 602 <u>https://esqf-node.llnl.gov/search/cmip6</u>. OpenStreetMap can be accessed at
- 603 <u>https://www.openstreetmap.org.</u>Settlement data can be accessed at <u>http://www.webmap.cn</u>.
- 604

#### 605 **Code availability**

- 606 The codes associated with this study are available on request from the corresponding authors upon request.
- 607

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# 672 Additional information

673 Supplementary information. The online version contains supplementary material available at

674

- 675 **Correspondence** and requests for materials should be addressed to G. Zhang.
- 676
- 677 **Peer review information**
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![](_page_33_Figure_0.jpeg)

![](_page_34_Figure_0.jpeg)

![](_page_35_Figure_0.jpeg)

![](_page_36_Figure_0.jpeg)

![](_page_37_Figure_0.jpeg)

 2020
 2030
 2040
 2050
 2060
 2070
 2080
 2090
 2100

 Time of lake expansion
 Time of lake expansion
 Time of inundation of the settlement

 Time of inundation of the road
 Time of inundation of the grassland

![](_page_37_Picture_2.jpeg)

![](_page_37_Picture_3.jpeg)

![](_page_37_Picture_4.jpeg)

![](_page_37_Picture_5.jpeg)

![](_page_37_Picture_6.jpeg)

![](_page_37_Picture_7.jpeg)

![](_page_38_Figure_0.jpeg)

![](_page_39_Figure_0.jpeg)

![](_page_39_Figure_1.jpeg)

![](_page_40_Figure_0.jpeg)