

Inland Water Bodies in China: New Features Discovered in the Long-term Satellite Data

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1 Inland Water Bodies in China: New Features Discovered in the

2 Long-term Satellite Data

3

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26 27	

28 Water bodies (WBs) - lakes, ponds, and impoundments, provide essential 29 ecosystem services for human society, yet their characteristics and changes over 30 large areas remain elusive. Here we used unprecedented data layers derived from 31 all Landsat images available between 1984 and 2015 to understand the overall 32 characteristics and changes of WBs between two epochs (i.e., 1984-1999 and 2000-2015) in China. Results show that the abundance estimate of WBs greater 33 34 than 1 km² and the total WB surface area were 0.3-1.5 times and 0.2-0.5 times 35 more than the previous estimates, respectively. The size-abundance and 36 shoreline-area relationships of WBs in China conformed to the classic power 37 scaling law, in contradiction to most previous studies. WB changes with various 38 occurrence probabilities show widespread co-existence of disappearance of 39 existent and emergence of new WBs across China driven primarily by human 40 activities and climate change. Our results highlight the importance of using appropriate long-term satellite data to reveal the true properties and dynamics of 41 42 WBs over large areas, which is essential for developing scaling theories and 43 understanding the relative impacts of human activities and climate change on 44 water resources in the world. 45 Keywords: inland water bodies; size-abundance; fractal dimension; climate

- 10
- 46 change; land use change
- 47

48 Significance Statement

49	Inland water bodies (WBs) provide essential ecosystem services for human society,
50	yet their characteristics and changes over large areas remain elusive. We used
51	unprecedented data layers derived from Landsat imagery to quantify and decipher the
52	spatial distributions and contemporary changes of WBs in China. The results shed new
53	light on the characteristics (e.g., abundance, and size-abundance and shoreline-area
54	relationships) and spatiotemporal dynamics of WBs. This study highlights the
55	importance of using appropriate long-term satellite data to reveal the true properties and
56	dynamics of WBs over large areas, which is essential for developing theories and
57	understanding the predominant impacts of human activities and climate change on
58	water resources not only in China but also in other regions of the world.

59

60 Introduction

The provisioning of freshwater is an essential ecosystem service for humankind, and such services include water supply, biomass and food production regulation, communication and transportation, wildlife habitats, biogeochemical cycles, and climate regulation (1-3). Fresh water bodies (WBs) are under constant change because of the impacts of anthropogenic activities and climate change (4). Monitoring the dynamic changes of WBs and understanding their causes and consequences have important implications to the resilience of social-ecological systems (5, 6).

68 The abundance and area of WBs over large regions are critical information for 69 water resource management but remain highly elusive. For example, the number of lakes larger than 0.1 km² at the global scale was estimated to range from 246,146 to 70 4,123,551 (7, 8), more than one order of magnitude difference among them. The 71 estimated area of lakes larger than 0.1 km² varied from 2,428,100 km² to 4,080,000 km² 72 respectively, and the largest difference was 68%. These huge differences among various 73 74 studies call for innovative investigations to reduce the uncertainties in the number and 75 area of WBs.

76 Biogeochemical processes in WBs represent major components in the cycle of 77 carbon, nutrients, and other materials at the regional to global scales (9, 10). Estimating 78 biogeochemical processes such as greenhouse gas fluxes from WBs from regional to 79 global scales has been challenging because these processes are size dependent (11). 80 Finding the size-abundance relationship therefore has been a persistent effort for over a 81 century to facilitate the scaling of heterogeneous processes across various WBs (12). 82 Although a power law relationship has been reported in many studies, deviations exist, 83 particularly for small WBs (8, 13-15) and in mountainous regions (16) where 84 topographic relief, geology, and complexity of landscapes are thought to affect the 85 goodness of fit to the power scaling law (14). The existence of the power law and its 86 dependence on topography and geology needs to be evaluated more extensively.

87 Water-resource management and planning as well as climate change adaptation
88 rely heavily on the knowledge of long-term trends and spatial dynamics of surface
89 WBs (1) . However, progress on characterizing the dynamics of WBs over large
Page 4 of 19

regions has been hindered by data availability, dynamic nature of WBs, complexity of 90 91 driving forces, and geospatial heterogeneity of environments (8). Most previous studies 92 do not have enough data points in time to capture the temporal changes of WBs, and 93 consequently the overall dynamics and size dimensions of the WBs, particularly the 94 intermittent WBs, are not well represented (17, 18). Recently, an unprecedented effort 95 by Pekel et al. (2016) has generated a global surface water dataset that describes the 96 changes in WBs from 1984 to 2015 at 30 m resolution (19). Although the overall global 97 patterns of WB changes have been analyzed, more detailed and elaborate analyses are 98 sorely needed at regional and continental scales to better understand the spatial and 99 temporal patterns of WB changes and to test the validity of existing theories such as the 100 controversial power scaling law for the size-abundance relationship (12, 20, 21). China 101 represents an ideal place for such as study because of its vast heterogeneous territories, 102 intensified human activities in recent decades, and large uncertainties in the 103 characterization of its dynamic water resources (22).

104 Abundance, area, and scaling of WBs

Our estimate of WB abundance in China exceeds all previous estimates (SI 105 Appendix, Table S1 and Table S2). The abundance of WBs (> 1 km^2) is estimated to be 106 107 6.821 in our study, 1.3 times the previous highest estimate (5.535) and 2.5 times the lowest estimate (2,693) (7, 17, 23, 24). The number of WBs larger than 0.0036 km² in 108 China is 688,617 in this study, much higher than 275,029 estimated previously (24). 109 110 Our estimates of WB area in China are higher than those from previous studies. For example, our estimate of total area of WBs larger than 0.0036 km² in China is 134,158 111 km², 23% higher than 109,102 km² estimated by Yang *et al.* (2014) (24). The total area 112 of WBs larger than 1 km² is estimated to be 123,342 km² in our study, 22-51% larger 113 114 than the previous estimates (7, 17, 23, 24). Similar differences can be found across the 115 regions in China as well. For example, the number of medium and large WBs in the 116 YTR (Yangtze River basin, acronyms for the river basins are listed in SI Appendix, 117 Table S3) is estimated to be 1952 in this study, much higher than 1395 estimated by 118 Yang et al. (2013) (25). The medium and large WBs in the TP amount to 1289 in our 119 study, which is very close to Mao et al. (2018) (1291) (26) but higher than Wan et al. Page 5 of 19

120 (2014) (1055) (27) and Lu *et al.* (2011) (1044) (28). We found that the total area of WBs 121 larger than 0.0036 km² in the YTR is 36,710.83 km², which is 48% higher than Yang *et* 122 *al.* (2013) (24,842 km²) (25). Our estimate of the WBs larger than 1 km² in the TP is 123 56,247.41 km², much higher than Mao *et al.* (2018) (46,264.5 km²) (26) or Wan *et al.* 124 (2014) (41,831 km²) (27).

The overall exceedance of our WB estimates can largely be attributed to the differences in methodology. Conventionally, WBs over large areas are characterized using one or a few snapshots of remotely sensed images, which could not consistently capture intermittent WBs and historical maximum water extents (29). Previous results are therefore contingent to the snapshot-specific climate and hydrological conditions at the time that images were taken.

131 The size-abundance relationships in China conform to the power law with a Pareto 132 coefficient of -0.835 (SI Appendix, Fig. S1F and Table S4), similar to -0.85 reported for 133 the contiguous United States (CONUS) (30), but higher than that for the world in 2004 134 (-0.992) (7) and in 2016 (-1.054) (17). At a regional scale, the Pareto coefficient in the 135 TP is -0.662, the highest among all regions, signifying a higher fraction of large WBs in the TP compared to other regions (SI Appendix, Table S5). In contrast, the scaling 136 137 exponent in the PR is -0.941, the lowest among all regions, representing a relatively 138 higher share of small lakes. Comparatively, the log-transformed WB size-abundance 139 distribution in China presented a shallower slope or Pareto coefficient than those in the 140 world and CONUS, suggesting that small WBs are relatively more abundant in China 141 than in the CONUS and the world (Fig. 1C). Our results showing the power scaling law 142 between abundance and size of WBs in China, despite its complex geography and topographic characteristics, are different from a number of recent studies that have 143 144 found deviations from the power scaling law, particularly for small WBs (8, 13-15). 145 Seekell et al. (2013) show that the size-abundance relationship in a mountainous region 146 (Adirondack, USA) did not follow the power scaling law while it fit well in a flat region 147 (Gotland, Sweden), and argue that the topographic relief, geology, and complexity of 148 the landscapes could impact how well data fits the simple power scaling law (13). It is 149 quite surprising to see that our results fit the power scaling law well in China even 150 though some regions such as the TP, and northwestern and southwestern China are

Page 6 of 19

151 famous for their high topographic relief and steep slopes that are suspected to cause152 deviations from the power scaling law (Fig. 1*B*, *SI Appendix*, Fig. S2).

153 The shoreline fractal dimension (SFD) derived from dimensional analysis (log 154 perimeter-log area analysis) is often used to indicate the influences of human 155 modifications or geology on the shape of WBs (31). The SFD ranges from 1.178 in TP 156 to 1.321 in PR (Fig. 1B, SI Appendix, Fig. S3). Theoretically, the fractal dimension of size-abundance (D) (D = 2 * abs(c), c is the scaling exponent or Pareto coefficient 157 158 mentioned above) is supposed to be similar to the SFD (13, 32). We compared the D 159 and SFD derived from China and found a strong linear relationship between these two fractal dimensions (D = $3.13 \times \text{SFD} - 2.27$, R²=0.73, P<0.05). However, the slope is 160 significantly different from 1, suggesting that our results do not support the theoretical 161 162 equivalency of these two fractal dimensions (Fig. 1D). The deviation of D and SFD 163 from the theoretical equivalency might be caused by increased frequency of smaller 164 WBs and/or effort in shaping WBs more regularly and reducing the sinuosity of WB 165 boundaries. Economic growth and aquaculture intensification have propelled the increase of smaller WBs and geometric regularization of the WBs, particularly in the 166 167 southeastern and coastal parts of China (33).

168 <Fig. 1 roughly here>

169 Various changes between two epochs

170 Overall changes of WBs in China between the two epochs (i.e. 1985-1999 and 171 2000-2015) are shown in Fig. 2, which reveals that 53.9% of the WBs remain unchanged nationwide, and further shows the various degrees of change between the 172 epochs. A total of 5197.09 km^2 or 3.92% of the WB area in China disappeared 173 (absolutely decreased); whereas the very likely (with 75-99% probability), likely (with 174 175 25-74% probability), and unlikely (with 1-24% probability) deceases accounted for 1.6%, 6.23%, and 7% of the total WB area, respectively (Fig. 3, SI Appendix, Table S6). 176 A total of 9040.26 km² were converted from non-water surfaces into WBs (absolutely 177 178 increased), corresponding to 6.81% of the total WB area in China. At the same time, 179 very likely, likely, and unlikely increase occurred on 3.76%, 8.18%, and 5.71% of the

total WB area, respectively. The large WBs (>10 km²) explain most of the very likely, 180 likely, and unlikely increase or decrease, followed by the small WBs ($< 1 \text{ km}^2$) (SI 181 182 Appendix, Fig. S4 and Table S7). The WB changes vary widely across regions (Fig. 2). 183 For example, the highest absolute increases in area in percentage (13.72%, 16.41%, and 184 9.69%) are found in the TP, NWR, and SER, respectively. The region changed the most 185 was the HR since only 11.74% of WBs remained unchanged, and the most stable region 186 is the SWR with 75.99% persistently covered by water. The largest absolute decreases 187 in WB occurrence in percentage are found in the HR, SHR, and YTR account for 14.26%, 7.83% and 5.47% of their total WB areas, respectively. 188

189 <Fig. 2 roughly here>

Our analysis shows a net gain (absolute change) of $3,843 \text{ km}^2$ in WB between the 190 191 two epochs. Although some previous studies have quantified an increase (34, 35), 192 decrease (22, 24) or net change of the WB area in China, they are not comparable to our 193 estimate because of the differences in time span and definitions of change. Our change, 194 following Pekel et al. (2016), is defined as the difference between two epochs or 195 periods while it is defined as the difference between two time points or years in other 196 studies (19). Consequently, our estimate of change likely represents permanent changes 197 whereas the estimate using other definitions would be more likely influenced by the 198 interannual variability in the climate and hydrologic conditions. Starting with a dry year 199 and ending with a wet year would contain false signals of WB increase, for example, 200 when using the second definition.

201 Driving forces of WB changes

WB changes across the country show great divergent trends (Fig. 3), which were most likely driven by multiple compounding drivers such as climate change and direct human land use change activities (22, 35) (Table 1). Climate change has been shown to have a major impact on WB changes, particularly in the TP and NWR regions. Because of the TP's high elevation and sparse population, its WBs are predominantly influenced by climate change. Despite a decline only some areas, the widespread increase of WBs in the TP is primarily entailed by multiple climate-related factors, including the 209 precipitation, temperature, glacier, and permafrost (36, 37). On the one hand, the 210 climate change in the TP is prevalently accelerating, as the mean annual precipitation 211 has increased 20 mm and mean annual air temperature has warmed 1.6°C from 2000 to 212 2014 (26), resulting in the expansion of existing WBs and formation of new WBs by 213 melting glacier and snow in high mountains. On the other hand, permafrost degradation 214 and WB shrinkage have also been observed in some localized areas with drier climate 215 and reduced precipitation, especially in the area between the Himalayas and Tanggula 216 Mountains and in north of the Hengduan Mountains (26). Similarly, increasing WBs are 217 observed in the less populated mountainous areas in the NWR region caused by glacier 218 melting and increase in precipitation (38). The dry climate and drought events in the 219 arid regions (e.g., Inner Mongolia Plateau and part of the Xinjiang Uygur Autonomous 220 Region) have also contributed to WB shrinkage (35, 39).

221 <Fig. 3 roughly here>

222 <Table 1 roughly here>

223 Land use change activities have contributed to the expansion and/or contraction, 224 disappearance, and emergence of WBs at different locations throughout the country. 225 For example, dam constructions can substantially change WB in the upstream and 226 downstream regions (34, 40). Using the YTR basin as an example, both the numbers 227 and surface areas of the reservoirs in the YTR have increased rapidly during past 228 decades, and the impoundment of the great Three Gorges Dam alone formed a new large reservoir with an area of 1.084 km^2 in 2003 when it was put into full operation 229 230 (41). Intensification of agriculture also brings heavy pressure to WBs (40, 42). For 231 example, the northeast region has experienced a rapid increase (319.0%) in irrigated 232 cropland area in the past three decades (22, 43). Aquacultural change affects the 233 dynamics of WBs in China, particularly in the east, south central, and southeast regions 234 where water resources and climate are suitable for aquaculture (33). Land reclamation, 235 or WB impoldering (i.e., conversion of WBs into other land uses), has resulted in the 236 loss or shrinking of WBs (38, 41). Many natural wetlands and WBs have been drained 237 and transformed into croplands, grasslands, and woodlands (22, 43), resulting in the loss of about 50,360 km² or 14.18% of the wetlands across the country from 1990 to 238 239 2000 alone. Many small WBs are infilled in the process of urban expansion (41).

Page 9 of 19

240 Wuhan, the capital city of Hubei province and once known as the city with thousands of 241 lakes, has lost about 70% of its lakes to reclamation and development between 1994 242 and 2014 (44). Various policies are being put forward by Chinese governments to 243 promote wetland conservation and restoration in recent years (45). After joining the 244 Ramsar Convention in 1992, the Chinese government has implemented the National 245 Wetland Conservation Plan, trying to prevent natural wetlands from further loss and 246 degradation (43). The government had funded more than 200 pilot programs with 20.7 247 billion US\$ during 1990-2007 to restore degraded wetlands and create new ones to 248 make amends for lost wetlands (46).

249 Assessing the dynamics of WBs over large regions has been a major challenge 250 because of the constraints in data availability, heterogeneity of environments, and the 251 complexity of driving forces (8). Many studies have mapped WBs with multi-spectral 252 and hyperspectral images and built databases comprising locations, sizes, and 253 distributions of WBs over large regions (17, 47). However, these studies often suffer 254 from two weaknesses. First, they usually do not have enough data points in time to 255 capture the temporal changes of WBs. For instance, results are often generated from 256 subsamples of available remote sensing data at 5-year or longer time intervals (48), representing only snapshots of WB conditions in the sampled years. As a result, the 257 258 overall dynamics and size dimensions of the WBs, particularly the intermittent WBs, 259 are not well represented (17, 18). Second, the minimal detectable WB size, defined by 260 the resolution of remotely sensed data (e.g., Terra /Aqua MODIS), is usually not fine 261 enough to detect the small WBs that are biologically more active than the large ones 262 (49). Our study shows that the use of dense long-term satellite data at appropriate 263 resolution has the potential to overcome some of the difficulties and reveal 264 unprecedented distributional details and dynamics of WBs over large areas. This 265 capability is essential for validating the relevant theories such as the power scaling 266 relationship between size and abundance and for adequately scaling many hydrological 267 and biogeochemical processes (e.g. the carbon cycle) from individual aquatic systems 268 to regional and global scales (50). It is also important to map the details of WB changes 269 and understand their causes and consequences to improve water resource management 270 and planning.

271 Materials and Methods

272 Study area and region boundaries

- 273 China (73°33'-135°2'E and 3°52'-53°33'E) is our study area (Fig. 1A). To
- investigate the regional differences of WBs, we delineated China into 11 large regions,
- 275 primarily following the region boundaries from HydroSHEDS
- 276 (http://www.hydrosheds.org, last accessed in 2018) (51) and National Lake-Watershed

277 Science Data Center (http://lake.geodata.cn). The abbreviations of the regions are listed

in Table S3.

279 Extraction of lakes, ponds, and impoundments

280 The Global Surface Water Dataset (GSWD), published by the European

281 Commission's Joint Research Centre, was the basis for our study

282 (<u>https://global-surface-water.appspot.com</u>, last accessed on December 12 in 2018).

283 GSWD was generated using 3,066,102 (1823 terabytes of data) scenes from Landsat 5,

284 7, and 8 acquired between 16 March 1984 and 31 December 2015 (19). To address the

challenges in separating water from other surfaces on the global scale over multiple

decades, expert systems, visual analytics, and evidential reasoning techniques were

287 exploited. Details about the implementations of these techniques can be found in Pekel

et al. (2016). The resultant maps constitute the long-term water history that show the

289 "when and where" of the water presence during the observation period. At the same

time, the Water Occurrence, Occurrence Change Intensity, Seasonality, Recurrence,

291 Transitions, Maximum water extent are also shown in the dataset. The accuracy of the

292 water maps was assessed by the developers of GSWD in term of errors of omission and

commission at the pixel scale (i.e., 30 m) using a total of 40,124 control points

distributed both geographically (globally), temporally (across the 32 years). Overall,

errors of commission were less than 1% and omission less than 5%.

The data layer showing the maximum water extent (MWE) (all locations ever mapped as water) during the 32 years was used to extract the locations and maximum extents of WBs in our study. GSWD contains three types of waters: artificial paddy fields, rivers, and others (i.e., lakes, ponds, wetlands, and impoundments). As our goal

Page 11 of 19

- 300 was to investigate the characteristics and dynamics of lakes, ponds, wetlands, and
- 301 impoundments, rivers and rice paddy fields were removed from the MWE map using
- 302 the HydroSHEDS data through overlay operation in ArcGIS v10.2 (ESRI, Redlands,
- 303 CA, USA) and manually corrected by visual inspection against Google Earth
- 304 high-resolution images. Consequently, the temporal changes of rivers and streams were
- also effectively excluded from this analysis (SI Appendix, Text S1). Paddy fields in the
- 306 MWE were removed by referring to the Global Land Cover dataset (GLCD)
- 307 (http://www.globallandcover.com, last accessed in 2018).
- 308 WB change between two epochs

309 GSWD provides water occurrence change intensity (OCI) between two epochs 310 (i.e., 1984 to 1999, and 2000 to 2015), which was derived from water occurrence 311 difference between homologous pairs of months (19). Specifically, the water 312 occurrence difference for each homologous pair of month between epochs was 313 calculated, and then differences between all homologous pairs of months were 314 averaged to create the surface water OCI map between the epochs. The OCI map shows 315 where surface water occurrence increased, decreased, or remained invariant, providing 316 a summary of the location and persistence of water in space between the two epochs. 317 The OCI map represents the degree of change as a percentage with values ranging from 318 -100% to 100%; positive values indicate increase in occurrence while negative ones 319 show loss of occurrence, and 0% suggests no change in occurrence between the epochs. 320 To summarize the results, OCI values were grouped into several classes: 75-99% (high 321 OCI), 25-74% (medium OCI), 1-24% (low OCI), 0% (unchanged), and 100% 322 (absolutely changed). In essence, these OCI classes effectively represent the 323 probabilities or likelihoods of conversion from non-water to water (positive OCI) or 324 from water to other surfaces (negative OCI) between two epochs, which resulted in nine 325 generalized probability classes of conversion between water and other land covers: 326 absolutely decreased (OCI= -100%), very likely decreased (OCI= -99% to -75%), 327 likely decreased (OCI= -74% to -25%), unlikely decreased (OCI= -24% to -1%), 328 unchanged (OCI= 0%), unlikely increased (OCI= 1% to 24%), likely increased (OCI= 329 25% to 74%), very likely increased (OCI= 75% to 99%), and absolutely increased 330 (OCI= 100%).

Page 12 of 19

- The minimum water surface area detectable is the pixel size of Landsat (0.0009
- 332 km²). To facilitate comparison with other studies, whenever necessary, WBs were
- classified into three categories of small (< 1 km^2), medium (1-100 km^2), and large (>
- 334 100 km²) following the classification scheme of most previous studies (35, 39). All data
- processing and analysis were performed using ARCGIS 10.2 (ESRI, Redlands, CA,
- USA) and Python 3.6.

337 Data Availability

- All data used in support of this manuscript are available in Figshare
- 339 (https://figshare.com/s/9e931d6db628e3f96689; DOI: 10.6084/m9.figshare.9959516)
- 340

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Figure Legends

Fig. 1. Boundaries of regions, morphological and size-abundance scaling of water bodies in China. (A) locations and boundaries of the 11 regions in China; (B) shoreline fractal dimensions (SFD) of TP. (C) size-abundance distributions of water bodies in China, CONUS, and the world. (D) shoreline fractal dimensions (SFD) and fractal dimension of size-abundance (D) in China and the regions.

Fig. 2. Regional occurrence changes of WBs at various confidence levels. Subsets of four selected cases show WB changes. A, Dongting lake in the YTR, centered at 112.8° E, 29.1°N. B, Hulun lake in the SHR, centered at 117.5°E, 48.9°N. C, Seling Co lake in the TP, centered at 89.1°E, 31.8°N. D, Hongze lake in the HuR, centered at 118.6°E, 33.2°N. E, epochal changes in different regions.

Fig. 3. Epochal changes of water bodies in China and regions at various confidence levels. Changes are classified as Absolutely Decreased (AD), Very Likely Decreased (VLD), Likely Decreased (LD), Unlikely Decreased (ULD), Unchanged (UC), Unlikely Increased (ULI), Likely Increased (LI), Very Likely Increased (VLI), and Absolutely Increased (AI).

Region	Main driving forces	References
TP	variations of precipitation; warming-induced glacier-melting and permafrost degradation	Mao et al. 2018b, Zhang et al. 2017a
PR	land reclamation; waterbody impoldering; urbanization	Li et al., 2018; Guo et al., 2015
YTR	dam constructions; aquacultural change; land reclamation or impoldering; urban expansion; sand mining and illegal sand dredging	Cai et al., 2016; Xie et al., 2003
YR	intensification of agriculture; intensified groundwater exploitation	Shi et al., 2011; Zhang et al., 2003
HR	rapid urbanization; land reclamation or waterbody impoldering	Yang et al., 2011; Tian et al. 2016
HuR	dam and floodgate construction; land reclamation	Hu et al., 2008; Zhang et al., 2009
SHR	intensification of agriculture; irrigation; wetland draining or restoration	Xie et al., 2018; Ma et al., 2010
NWR	persistent drought; intensification of agriculture (irrigation); mining	Fang et al., 2018; Tao et al., 2015
SWR	variations of precipitation; warming-induced glacier-melting	Wu et al. 2007; Mao et al., 2018b
SER	aquacultural change; land reclamation or waterbody impoldering;	Lu et al. 2015; Wu et al., 2018
LR	intensification of agriculture (irrigation); wetland conversion	Xie et al. 2018; Ma et al., 2010

Table 1. Summary of main driving forces in different regions.

Region	Main driving forces	References
TP	variations of precipitation; warming-induced	Mao et al. 2018b, Zhang et al
IP	glacier-melting and permafrost degradation	2017a
PR	land reclamation; waterbody impoldering;	Li et al., 2018; Guo et al.,
ΓK	urbanization	2015
	dam constructions; aquacultural change; land	Coi at al. 2016: Via at al
YTR	reclamation or impoldering; urban expansion;	Cai et al., 2016; Xie et al., 2003
	sand mining and illegal sand dredging	
YR	intensification of agriculture; intensified	Shi et al., 2011; Zhang et al.,
IK	groundwater exploitation	2003
HR	rapid urbanization; land reclamation or	Yang et al., 2011; Tian et al.
IIK	waterbody impoldering	2016
HuR	dam and floodgate construction; land	Hu et al., 2008; Zhang et al.,
TIUK	reclamation	2009
SHR	intensification of agriculture; irrigation;	Xie et al., 2018; Ma et al.,
SIIK	wetland draining or restoration	2010
NWR	persistent drought; intensification of	Fang et al., 2018; Tao et al.,
	agriculture (irrigation); mining	2015
SWR	variations of precipitation; warming-induced	Wu et al. 2007; Mao et al.,
SWK	glacier-melting	2018b
SER	aquacultural change; land reclamation or	Lu et al. 2015; Wu et al.,
SER	waterbody impoldering;	2018
LR	intensification of agriculture (irrigation);	Xie et al. 2018; Ma et al.,
	wetland conversion	2010

Table 1. Summary of main driving forces in different regions.





