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City water stress and industrial water-saving potential in stringent management of China

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1 **City water stress and industrial water-saving potential under stringent management in China**

2

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34 China's industrial water withdrawal soared in the last decades and remained high. Stringent water
35 management policies were set to save water through improving industrial withdrawal efficiency by 20%
36 between 2015 and 2020. Although China has a nation-wide water scarcity, scarcity at city-level has not
37 been fully explored. Thus, it is meaningful to use sectoral data to investigate industrial water saving
38 potential and implication for alleviating scarcity. Here, we account for water withdrawal and scarcity in
39 272 prefectural cities, using a 2015 data benchmark. The top 10% of low-efficiency sectors occupied 46%
40 water use. In scenario analysis of 41 sectors across 146 water scarce cities, we assume a convergence of
41 below-average efficiencies to the national sector-average. Results reveal overall efficiency could be
42 increased by 20%, with 18.9 km³ ($\pm 3.2\%$) water savings, equivalent to annual water demand of Australia
43 or Hebei province in China. A minority of sectors (13%) could contribute to most (43%) water savings
44 whilst minimizing economic perturbations. In contrast, implementing water efficiency measures in the
45 majority of sectors would result in significant economic disruption to achieve identical savings. Water
46 efficiency improvements should be targeted towards this minority of sectors: cloth(ing) supply-chain,
47 chemical manufacturing, and electricity and heat supply.

48

49 Key words: industrial water saving, China, city, stringent management, water scarcity

50 Freshwater is an essential and global resource¹. Over the last 50 years, China's industrial water
51 withdrawal increased in 90% of its cities², and has remained at a high level above 126 km³/yr from 2013
52 to 2018³ largely due to low water-use efficiency. China used to have transnationally low efficiency partly
53 owing to mis-management⁴⁻⁷, specifically poor sectoral controls and water-saving initiatives⁸. China's
54 response to this was to legislate for industrial water withdrawals through the so-called stringent water
55 resources management system ("Three-Redline" regulations), introduced by the Chinese State Council
56 in 2011⁹, and aimed at saving water through improving industrial withdrawal per value-added by 20%
57 between 2015 and 2020. More recently, China established national water-saving demonstration (sponge)
58 cities, but specific control on both industrial water withdrawal intensities and volumes still remains poor¹⁰.

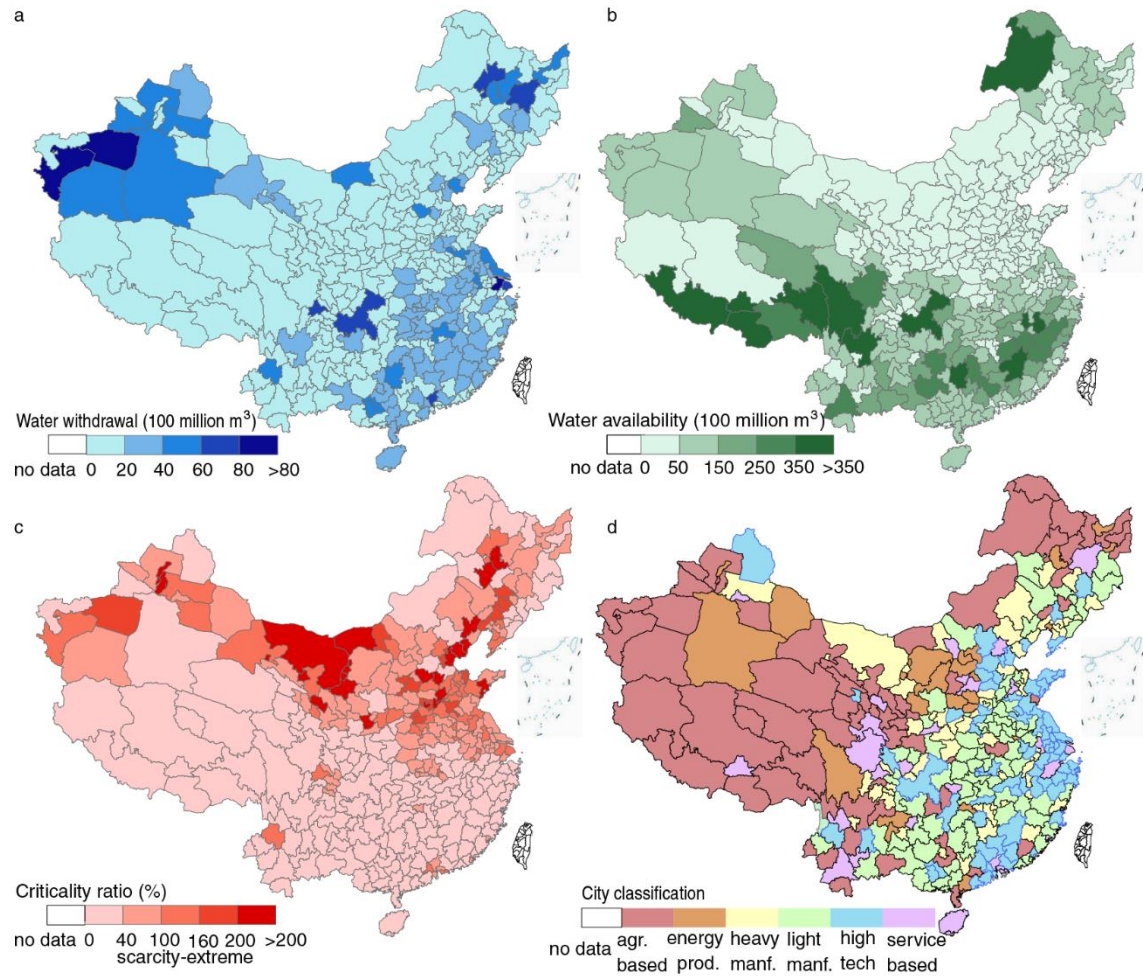
59 Although nation-wide China is deficient in water¹¹, with a wicked problem between water demand
60 and availability^{4,12}, city-level water scarcity has not been fully explored¹³. The science of water scarcity
61 assessment has developed for the past 30 years and, as more spatial geo-data have been available, studies
62 have adopted more integrated and multi-faceted approaches typically based on spatial resolution in grid
63 units at the river basin scale^{14,15} or global levels¹⁶⁻¹⁸, rather than at administrative/territory based units
64 such as the city level. There is only a single city-level based study in 2005 from the Ministry of Water
65 Resources in China, which is not widely available to the public¹⁹. Thus far, to the best of our knowledge,
66 an appraisal of cities and their water scarcity status is unavailable. In terms of measuring scarcity, the
67 criticality ratio (water withdrawal to annual renewable freshwater) is a simple and classical indicator of
68 blue water and quantitative scarcity^{20,21}. It has thus far been applied at the provincial level^{16,22-24}, but not
69 at the city level due to data limitations⁷.

70 Water scarcity is typically exacerbated by unsustainable levels of water withdrawal; hence, society
71 ought to be well placed to mitigate it by improving water use efficiency, especially by reducing water
72 withdrawal intensities. Many studies have focused on agricultural intensification^{25,26} in relation to better
73 water management in land use²⁷ and irrigation²⁸. However, due to lack of measured efficiency data, there
74 remains a dearth of research especially from an industrial and sectoral perspective²⁹, to explore water
75 saving potential and implication on scarcity alleviation³⁰ at the city level.

76 We first accounted for datasets on water withdrawal for 41 industrial sectors in 272 prefecture-level
77 cities (88% of China's population), and water scarcity for all cities (343) in 2015, based on a point-
78 sourced survey in China^{31,32}. We identified cities suffering from water scarcity, and low water efficiency
79 sectors at the city level (compared with the national average). Second, we found the most severely

80 affected city type, and detected water scarcity and differences amongst these city-groups. Finally, in
 81 scenario analysis we assumed a convergence of below-average efficiencies to the national sector-average,
 82 to explore water saving potential amongst 41 industrial sectors and implication on water stress of Chinese
 83 cities under the constraint of the 20%-intensity-reduction. For key sectors and cities, our results help to
 84 identify priorities and optimize efforts for improving water use efficiency and facilitate more effective
 85 water management through enabling distinctive saving strategies.

86 **Water withdrawal and water scarcity datasets at the city level**



116 **Fig. 1.** Prefecture-level cities and their water situation based on 2015 data. (a) total water withdrawal, (b)
 117 water availability, (c) criticality ratio (%), and (d) six groups with predominant sector clustering. Average
 118 size of cities was 2.80 million ha; average population was 4.43 million.

119 We built up datasets using a general accounting framework for Chinese cities, as developed for previous
 120 work^{31,32}. Drawn on the datasets, Fig. 1a represents a map of total water withdrawal at the city level.
 121
 122 Criticality ratio was determined by dividing total water withdrawal (1a) by water availability (1b) for
 123 each city^{23,33,34}. Typically an empirical threshold of 40% is regarded as water scarcity status^{18,35,36}, and

124 over-100% as extreme water scarcity stress, signifying that annual water withdrawal exceeds renewable
125 water resources¹³.

126 Overall, 146 of 272 cities (55% of population) were found to be under water scarce conditions, a
127 result consistent with previous studies¹³. These cities are represented by darker colors in Fig. 1(c):
128 Guangzhou and Shenzhen (south), Shanghai, Suzhou, and Yancheng (east), Harbin (north), and Hotan
129 (west). Notably, in contrast to an earlier study¹³, we also identified some severe water-scarce areas in
130 south China: Shenzhen (south; 108%) and Foshan (southeast; 107%). Water scarcity in China is known
131 to already be serious, thus caution should be exercised when interpreting the south expansion of scarcity.

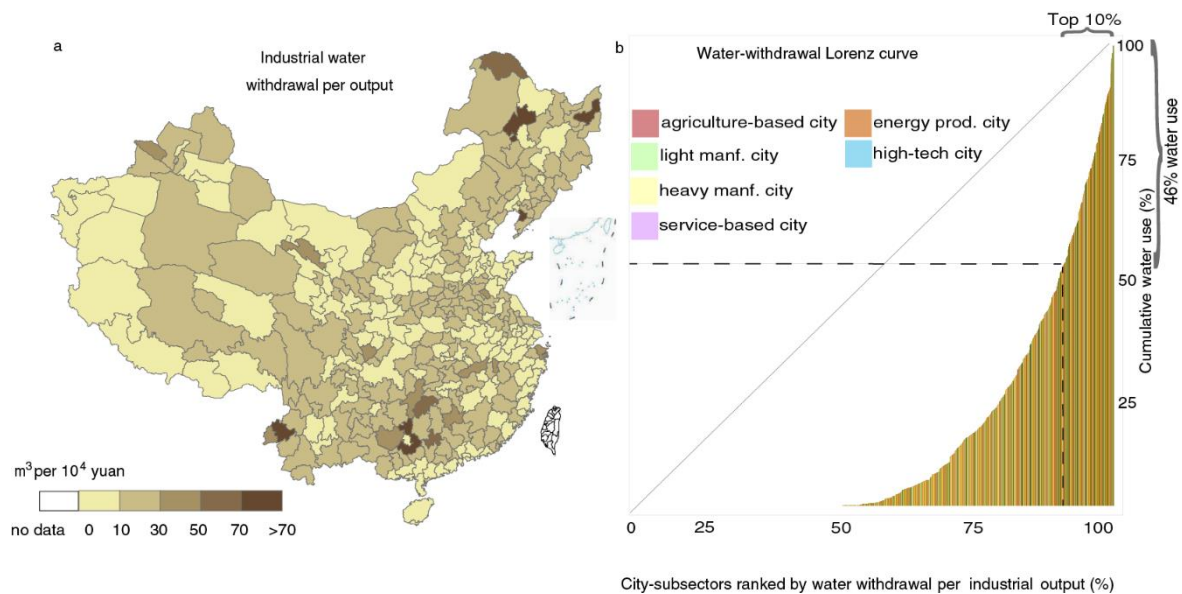
132 Sixty-nine Chinese cities (25%) were found to be under extreme water scarcity. These cities
133 occupied 27% of the population. We identified cities in different regions experiencing extreme scarcity
134 (Fig. 1c), for example Jiayuguan, Kelamayi and Lanzhou (northwest), Panjin (northeast), Puyang and
135 Zhengzhou (central), and Shanghai (east). One of the adverse effects of extreme scarcity was observed
136 in Zhengzhou, where average level of shallow groundwater decreased by 0.5 m in 2015³. Of 13
137 metropolitan areas containing over-ten-million citizens, 11 cities were constrained by water scarcity, and
138 6 by extreme scarcity. Median criticality ratio was 46%, varying between 0.38% in Ganzi (southwest) to
139 over 200% in Jiayuguan (northwest). This median was six percentages exceeding the scarcity threshold
140 of 40%.

141 Fig. 1(a), (b) and (c) show a mismatch in distribution between water use and availability at the city
142 level. This uneven distribution results in water resources being commonly over-exploited in northern
143 China. For example, several hotspots (with large water withdrawals) in northwest China, such as Hotan,
144 Kuerle and Bayannur, have criticality ratios exceeding 100%. This indicates that environmental flow³⁷⁻
145 ³⁹ is largely reduced for natural runoff and ecosystem survival. Fig. 1(d) shows city classifications and
146 their intuitive spatial distribution. We classified cities into six groups, namely: agriculture-based, energy
147 production, heavy manufacturing, light manufacturing, high-tech and service-based cities, using a
148 clustering based methodology⁴⁰.

149 **Discrepancies in water withdrawal and water scarcity between cities**

150 When constrained by severe water scarcity, one might expect industries in water scarce cities to adopt
151 water saving technologies, hence their industrial water withdrawal intensities should be lower than
152 comparable industries in water sufficient areas. In other words, water scarcity should force local
153 industries to be front-runners in water use efficiency. Nevertheless, a few water scarce cities (Fig. 2(a))

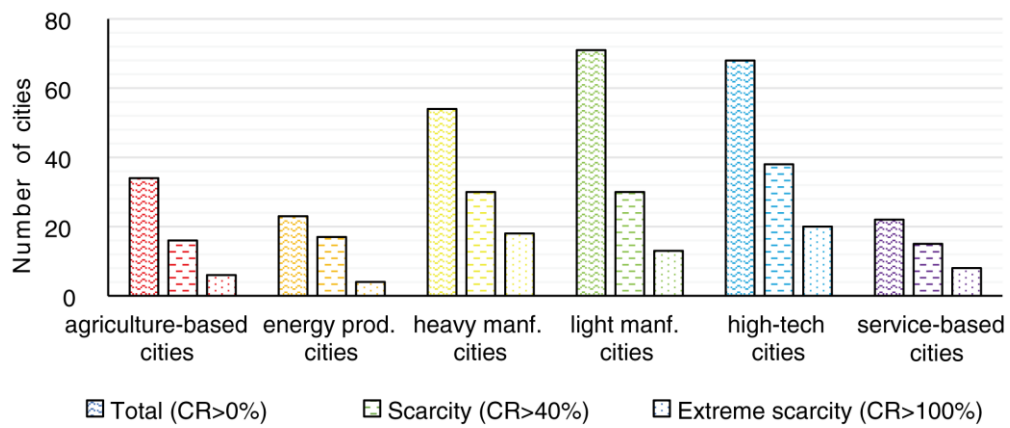
154 such as Qiqihar (north), Yingkou (east), Wuhai (west) and Puyang (central), had water intensities which
 155 were much higher than in cities abundant in water resources. Although China has set intensity reduction
 156 targets in stringent management since 2011, reducing intensities of sectors in water-scarce cities should
 157 therefore be prioritized. Awareness of industrial water savings should be given greater focus in these
 158 sectors in water scarce cities to prevent the situation to get worse. For example, cities such as Wuhai,
 159 Hegang, Puyang, and Qitaihe, had water intensities which were still high, yet they were all included in
 160 the 69 cities known to be over-exploiting resources, as released by the Chinese government in 2018⁴¹.



161
 162
 163 **Fig. 2.** Discrepancies in water withdrawal intensities across cities; (a) spatial distributions of overall
 164 industrial intensities across cities; and (b) water-withdrawal Lorenz curve depicted by different
 165 intensities of a total of $41 \times 272 = 11,152$ city-sector combinations from six groups. (Different city groups
 166 are represented by their corresponding color, as the same below.)
 167

168 A disproportionately small fraction of sectors at the city level contributed to large industrial water
 169 withdrawals. Thus sectors of low-efficiencies across cities should be well targeted to save water. We
 170 ranked a total of $41 \times 272 = 11,152$ city-sector combinations by order of water intensity from low to high
 171 and then calculated share of cumulative water withdrawal accordingly. We depicted these shares relative
 172 to shares of cumulative numbers of sectors and obtained a water-withdrawal Lorenz curve (Fig. 2b). The
 173 curve indicates that the top 10% of high-intensity sectors account for 46% of water withdrawal, as a
 174 disproportionate fraction. Such high-intensity water users were mostly found in small and developing
 175 cities, with representative industries such as papermaking and product manufacturing in Chenzhou
 176 (central), Lincang (southwest) and Qiqihar (northeast); liquor, beverage and tea manufacturing in
 177 Jingdezhen (mid-east), Anqing (mid-south) and Wuzhou (southwest); and electricity and hot water
 178 supply in Changde (mid-south).

179 We compared water scarcity occurrence amongst different city-groups. The most-severely affected
 180 were found in the high-tech group (Fig. 3); 38 cities over the 40% criticality-ratio (water scarce) and 20
 181 above 100% (extremely scarce). These are the highest in their corresponding tier, indicating economic
 182 growth limitations subject to water resources constraints. Notably, population in high-tech cities
 183 accounts for 33% of the total, and are commonly affected from severe water scarcity. Heavy- and light-
 184 manufacturing cities were also ranked, following high-tech cities. These water scarce cities with sectors
 185 of low water withdrawal efficiencies should be targeted.



186

187 **Fig. 3.** Statistics of city numbers in different criticality-ratio categories.

188

189 **Industrial water saving potential based on efficiency improvement**

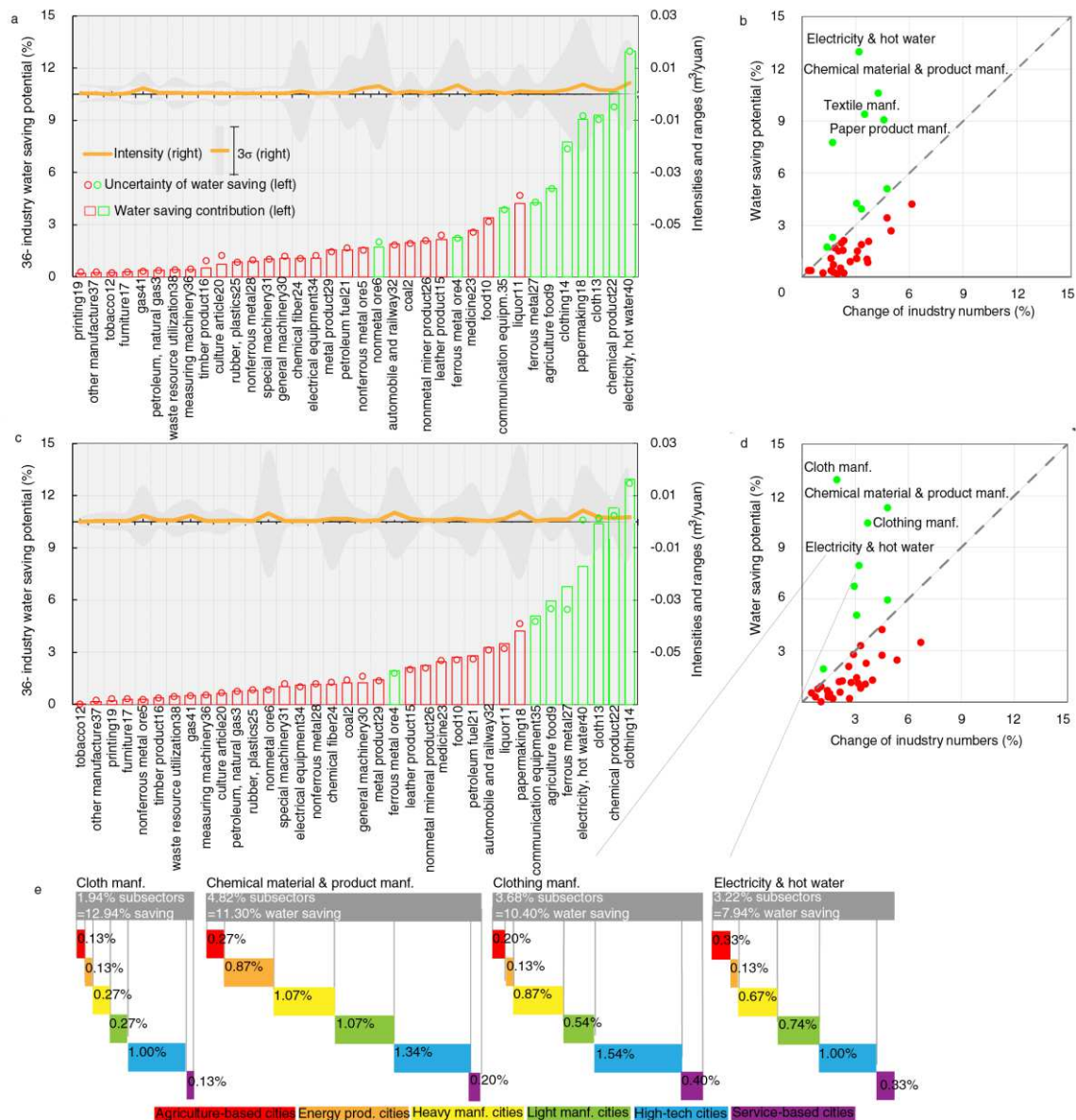
190 Industrial sectors in 272 cities were investigated for two reasons: first, there were special regulations for
 191 industrial water withdrawal intensity in the redline policy; a number of cities were even required to
 192 implement the most up-to-date technologies or regulatory standards for water savings during industrial
 193 production. Second, the 41 industrial sectors we considered in total (see appendix III details) showed
 194 high heterogeneity in water use and saving potential³².

195 For scenario analysis in individual of 41 industrial sectors, we substituted above-average water
 196 intensities with average ones, by assuming technical progress in water use efficiency. Scenario A was
 197 for all 272 cities and B was for the 146 water-stressed cities. Water saving strategies are more stringent
 198 in A than B. If water withdrawal intensity of a sector in a city was lower than the national sector-average,
 199 we left water intensity as it was. This would help maintain a stable technological and economic structure
 200 whilst improving efficiency; If intensity of a sector was higher than the national sector-average, but it
 201 occurred in a city with no water stress (criticality ratio less than 40%), we did not substitute it either;

202 Only for sectors that both had above-average intensities and were located in water-stressed cities, we did
203 substitute intensities with national sector-averages. In fact, technology is a vital factor underpinning
204 different intensities in the same sector. For example, in Suzhou, electricity and hot water supply
205 consumed as much as 5.3 km³ p.a. (64% of total water use) due to once-through cooling technology
206 (water-intensive) accounting for 99% in thermal plants. Conversion of these plants to circulating cooling
207 technologies, would result in large water savings. In contrast, food or general machinery manufacturing
208 in Dongguan and Hanzhong, which stood out as high-efficiency exemplars, should be set as
209 demonstration sites for peers in the same sector.

210 For all 272 cities, we estimated 41.91 km³ ($\pm 4.45\%$) water could be saved. This amount equates to
211 7% of total water use for the whole of China, and is more than total industrial water consumption (31
212 km³), twice the water demand of Australia or Hebei province of China in 2015⁴², and almost 2,000 times
213 the water storage capacity of the West Lake in Hangzhou, China. A relatively small fraction (27%) of
214 11,152 city-sector combinations contributed to large water savings (39%) of total industrial water
215 withdrawals. Fig. 4(a) illustrates sectors towards right-hand side of x-axis could contribute approximately
216 10% water savings, whilst those on the left could contribute a 0.2% reduction.

217 Furthermore, large contributors arose from fewer sectors at the city level, as shown in 4(b) (above
218 the dotted line), whilst it was less effective to tap saving potential for sectors in the lower section (below
219 the dotted line). Typically, there will be more than a single sector affected in most cities. Jiang (2009)⁴³
220 recommended exploration of cost-effective and long-term saving options by considering perturbations
221 caused to economy. Here we hypothesized that the fewer individual sectors substituted, the less economic
222 perturbation would result. Interestingly, a minority of sectors could save most water whilst affecting
223 fewer cities. This seems a win-win opportunity. Instead, most sectors needed to disturb more economy
224 to achieve the same saving. From an industrial water usage perspective, we therefore recommended water
225 saving initiatives in five key sectors which potentially contributed half the available water savings:
226 electricity and hot water supply (13.0%), chemical material and product manufacturing (10.6%), cloth
227 (textile) manufacturing (9.4%), papermaking and products manufacturing (9.0%), and clothing (apparel,
228 footwear and hats) manufacturing (7.8%). Requiring all industrial sectors to improve water efficiency
229 does not therefore represent an optimal policy choice. This finding also applies to



230 Fig. 4. Water saving potential and withdrawal intensity in each sector; (a) and (b) for Scenario A, and
 231 (c), (d) and (e) for B. Grey shading indicates empirical distribution range of intensities in each sector. Upper
 232 and lower boundaries were calculated by the three-standard-deviation method. (e) shows the top four
 233 water-saving sectors and their structure within different city-groups. For brevity, we listed a product and
 234 a code in each sector; 2-8 represent mining and processing, 9-39 are manufacturing, and 40-42 are
 235 production and supply of electricity, gas and hot water. For full names and descriptions please refer to
 236 appendix III. We excluded sectors of small contributions.
 237
 238

239 water scarce cities (Scenario B, Fig. 4(c) and (d)). In 4(a) and (c), uncertainty arose from treatment of
 240 high-intensity sectors during the survey, considering considerable heterogeneity of water use technology
 241 across cities for the same sector. For Jing-Jin-Ji agglomeration 0.96 km³ ($\pm 9.8\%$) water could be saved.

242 In the 146 water scarce cities, reducing high water intensities in a relatively small fraction (13%) of
 243 11,152 city-sector combinations would result in large water saving (18%) of total industrial water
 244 withdrawals. A level of 18.9 km³ ($\pm 3.2\%$) of water would be saved. This equates to annual water demand

245 of Australia or Hebei province of China, and almost 1,000 times the West Lake capacity. For individual
246 city-groups, water savings would reach 7.90 km³ for high-tech cities, 4.17 km³ for heavy manufacturing
247 cities, 3.40 km³ for service-based cities, 2.71 km³ for light manufacturing cities, 0.7 km³ for energy
248 production cities, and 0.62 km³ for agriculture-based cities. For individual cities, water savings ranged
249 from 118,700 m³ in Beijing, to 2.0 km³ in Guangzhou. We hypothesized industrial value-added levels
250 remained unchanged, in which case water withdrawal per value added would decrease by 20%, equating
251 to the 2015-20 efficiency target in the stringent management. At identical water availability levels,
252 criticality-ratio reduction ranged from 0.72% in Dongguan to 62% in Lanzhou. A small number of cities
253 would be alleviated below the scarcity threshold (40%) and shake off water scarcity, for example Jilin
254 city (northeast), Jincheng (northwest), Yulin and Tongchuan (west), and Xiangtan (mid-south). Heavy-
255 manufacturing cities would be alleviated by 11% on average to sub extreme-scarcity level. At the national
256 level, although the situation would remain severe, mean water scarcity level of 146 cities would fall by
257 six percentage points from 95% to 89%.

258 Notably, in contrast to conventional understanding, electricity and hot water supply was not the
259 largest contributor to water savings. Manufacturing of clothing, chemical materials and products, and
260 textile would bring greater savings. The largest potential was in the cloth-clothing supply chain, including
261 from cotton to intermediate products (yarn, cloth and other materials), and from yarn etc. to final clothing
262 products such as apparels, footwears, hats, masks, and trims. This finding is supported by a previous
263 study⁴⁴, and could be useful in water saving management for relevant industrial committees.

264 We also decomposed structure of the important 13% sector fraction into different cities and groups,
265 and identified four sectors (Fig. 4(d)) which contributed to half of total water savings; cloth(ing) supply
266 chain, chemical material and product manufacturing, and electricity and hot water supply. Fig. 4(e) shows
267 proportions of affected sectors from individual city-groups, respectively. For example, cloth
268 manufacturing contributed to 12.94% (~2.37 km³) of water saving in total, yet these sectors accounted
269 for just 1.94% overall at the city level. These subsectors and cities should be prioritized. A list is provided
270 in appendix IV.

271 Most severely scarce city-groups were effectively pinned down, such as high-tech, heavy- and light-
272 manufacturing cities. These city-groups basically hold the top three places for efficiency improvements.
273 For example, proportions of affected cities (sectors) in heavy-manufacturing and high-tech cities were
274 all highest; 78% (37%) and 56% (26%) respectively. Proportions of water-saving contributions from

275 individual city-groups were also checked and consistent (upon request). Thus, we were able to reliably
276 and robustly validate discussion on substitution.

277 Of course, realization of water intensity reductions is likely to be different²⁹ from our rather crude
278 scenario analyses; technologies between sectors and cities vary, and we must consider institutional as
279 well as technical interventions. In fact, China's water saving potential in this regard is significant, with
280 opportunities for factories and enterprises to adopt or advance efficient water-use equipment from their
281 respective sector in the global environment. The main improvements we would recommend are in water
282 recirculation (wet tower) in power generation, for example abstraction per kWh could be improved from
283 168 liters to 5 liters⁴⁵. Alternatively, we would encourage sectoral water abstraction and use rights, and
284 incentives such as trade and other subsidies for water-saving sectors and cities⁴⁶ through water
285 management contracts⁴⁷. Regularly updated indices for leading-edge enterprises and high water
286 efficiency manufactured products should be promoted by water efficiency labels⁴⁸ and national awards.
287 Finally, online/real-time monitoring on water withdrawal of key sectors at the city level through roll-out
288 of smart meters should be considered²².

289 In summary, we have reported water withdrawal and scarcity accounting for 272 Chinese cities,
290 using a 2015 data benchmark. The top 10% of low-efficiency sectors made up 46% industrial water use.
291 In scenario analysis of 41 sectors across 146 water-scarce cities, through efficiency improvements by 20%
292 and satisfying the stringent management policy, 18.9 km³ ($\pm 3.2\%$) water saving would be realized.

293 Yet, here we recommend water saving potential in a handful of sectors, as these sectors identified
294 to contribute to half of total water savings amongst 41 sectors. Focusing on these sectors makes sense in
295 terms of producing water saving returns, whilst minimizing potential economic disruption across the
296 industrial base. China may therefore target key sectors and cities in stringent water management, rather
297 than requiring all industries and cities to be involved in water saving.

298

299 **Methods**

300 **City-level industrial water withdrawal data sources.** Industrial total water withdrawal and water-
301 withdrawal per value added were compiled from water resources bulletins at provincial and city levels.
302 Industrial water withdrawal is a newly withdrawn water amount³. This variable may depict pressure on
303 available water resources from domestic economic activities more accurately since it excludes reused
304 water.

305 Industrial water withdrawal intensities for individual sectors in each city were derived from the
306 China High Resolution Emission Gridded Dataset³¹, in which a key survey of spot-sites covered 162,000
307 enterprises, across 41 industrial sectors for all 343 prefecture-level cities (including leagues, regions and
308 autonomous prefectures) in China. Sectoral industrial outputs were sourced from statistical yearbook for
309 each city.

310 We applied the general accounting framework used in previous work, and built up city-level and
311 territory-based industrial water withdrawal data for individual sector and city, according to IPCC
312 administrative boundary (scope 1)⁴⁹. For method validation please refer to detailed discussion in previous
313 paper³² and Turner et al. (2010)⁵⁰. Of 343 cities, only 272 cities' data were available for sectoral
314 accounting datasets, and 343 were further accounted for total blue-water withdrawal, availability and
315 quantitative blue-water scarcity status.

316

317 **Clusters for city classification.** Cluster analysis usually refers to magnitudes of a series of pre-provision
318 indicators (or variables) for specific datasets⁵¹. In the result, difference within a group would be
319 significantly small, whilst relatively large between groups i.e., clusters represent variables with similar
320 attributes^{52,53}. Beyond administrative or provincial territories, city-level studies^{54,55} concerning resource
321 use across industries have utilized Shan et al. methodology⁴⁰ to classify Chinese cities into different
322 groups (a k-mean cluster analysis). We used a similar treatment (employing proportions of industrial
323 output) and supplemented with an agriculture-based grouping, to Shan et al. method. Agriculture-based
324 cities occupied greater proportions of farming, forestry, animal husbandry, and fisheries in their GDP
325 than other cities. We thought six groups represented different economic development stages by assuming
326 a development time lag. For example, representatives of service-based cities were the so-called first-tier
327 cities, including Beijing, Shanghai, Guangzhou, Shenzhen, as well as provincial capitals such as Wuhan
328 and Nanjing. These were typified as wealthy and industrialized economies, as demonstrated by average

329 per capita GDP of 132,302 Yuan. This ranked 1st in all six groups, and was more than twice that of energy
330 production cities. Service-based cities were assumed to take leading position for industrialization process
331 in all Chinese cities.

332 Fig. 1 in the Appendix shows top-/bottom-ten sectors for water withdrawal efficiency and GDP
333 statistics in six groups. Some low-efficiency and large water-users should be targeted to save water.
334 Examples of energy production cities include Daqing, Panjin, Changzhi and Liupanshui. Although the
335 top and bottom ten for water withdrawal intensity were amongst the smallest, this group appeared
336 vulnerable since some cities such as Wuhai, Panjin, Hegang, Huozhou, and Qitaihe, have exhausted
337 energy and water resources. High-tech cities followed, of which examples included Dalian, Nanchang,
338 and Shaoguan. In heavy manufacturing cities, water withdrawal intensities were complex: these were
339 amongst the largest, for example Panzhihua, Sanmenxia, Anshan and Handan, and most withdrawal
340 efficiency varied across a large range. Service-based city water withdrawal intensities were not high.
341 Furthermore, some cities were featured through cluster sectors with large water-use, such as Changchun
342 (heavy manufacturing: special purpose machinery), Suzhou (high-tech manufacturing: communications
343 equipment), and Yangzhou (heavy manufacturing: chemical materials and products). These sectors could
344 learn from their peers within the same group.

345

346 **Application of criticality ratio as an indicator for water scarcity.** The criticality ratio (%) was applied
347 to measure annual water scarcity²³, i.e.:

$$348 \quad \text{Criticality Ratio}_i = \text{Water withdrawal}_i / \text{Water availability}_i \quad (1)$$

349 where i represents a city (one ratio number for one city); water withdrawal was the total amount from
350 including farming, forestry, animal husbandry, fisheries, industry, construction, service, household, and
351 ecosystem and environment preservation; and water availability included surface water and groundwater.

352 There are mainly three indicators in the current study: net runoff, natural streamflow, and natural
353 streamflow minus consumptive use from upstream human activities¹³. We adopted the natural-
354 streamflow measure and obtained relevant data from water resources bulletins for the cities, referring to
355 Zhao et al. (2019)⁵⁶. Basically produced from domestic precipitation, it is calculated through surface
356 water plus groundwater minus double measurements. In 2015, China's precipitation (and water
357 availability) was 2.8% (0.9%) more than, but close to, its average values through multiple years (1957-
358 2000, with statistics)³. Criticality ratio takes into consideration environmental flows^{39,57} and connects

359 with water quality and biodiversity⁵⁸. The higher the ratio is, the more stress is placed on available water
360 resources from withdrawal, and the greater the probability of water scarcity occurrence³⁵.

361 In addition to Fig. 3, we further found there appeared to be discrepancies in criticality ratio in
362 different city-types, indicating frequency and severity of water scarcity occurrence, referring to
363 Veldkamp et al. (2016)⁵⁹. For energy production cities (Appendix Fig. 2), frequency seemed relatively
364 higher, but not as severe when compared to heavy manufacturing group. Trendline curve peaked at 50%,
365 exceeding the 40% definition for water scarcity. In other words, most cities appeared to be distributed to
366 the right of scarcity threshold. Reassuringly, there appeared to be relatively few instances of cities
367 occurring in the extreme scarcity region (i.e. >100%).

368 In contrast, heavy manufacturing cities had lower frequencies of water scarcity occurrence, but once
369 over the 40% threshold it tended to be more severe. The peak in the frequency trendline appeared at
370 approximately 10-15% i.e., most cities tended to be distributed in a narrow band to the left of scarcity
371 threshold. However, there was a greater, more even spread of samples above the extreme scarcity
372 threshold, with a slight frequency approximately 5% for each distance, so the trendline tended to decrease
373 gradually. Examples were Jiayuguan (3507%, northwest), Shizuishan (962%, northwest), Baiyin (489%,
374 northwest), Tangshan (290%, north), Alashan (287%, northwest), Dongying (200%, east) and Baotou
375 (189%, north). This small subset (approximately 13%) of cities in this group mainly influenced our
376 findings for water scarcity in heavy manufacturing cities.

377 According to discrepancies of scarcity occurrence in different city-types, we also considered distinct
378 water saving strategies. For heavy manufacturing cities, policy focus should therefore be on a small
379 number of scarce cities at this stage. By comparison, for energy production cities, policy makers should
380 focus on a greater number of cities. For agriculture-based and light-manufacturing cities, given their
381 relatively lower GDP per capita, balance between economic development and water saving needs to be
382 better coordinated in decision-making.

383

384 **Uncertainty analysis.** We also clustered cities based on economic shares of GDP for primary, secondary
385 and tertiary industries, then classified cities into three groups for sensitivity analysis. We found only
386 minor differences between ratios of cities at individual water scarcity levels, from the groups using
387 proportions of industrial output. Specifically, for agriculture-based cities, the >40% and >100%
388 criticality ratios accounted for 46% and 17% respectively; for industry-based cities they were 54% and

389 25%; whilst for service-based cities they were 67% and 35%. Although clusters were based on different
390 indexes, we found no significant differences in water-scarcity distribution and status. We also verified
391 water withdrawal per GDP of agriculture-based cities of 211m³ per 10⁴ Yuan, which was close to the
392 magnitude of representative agriculture province such as Heilongjiang at 210 in 2015⁶⁰. Finally, for
393 individual city groups we validated median and average criticality ratios and water intensities; these
394 results as well as significance tests for our group classification are available upon request.

395 Besides, we may over-estimate criticality ratio, considering water withdrawal statistics do include
396 those from reservoirs and upstream rivers, while water availability data do not include these parts. We
397 were unable to incorporate these data into water availability generally due to statistical incongruence
398 between cities. Thus, our results could suffer from an upward bias in some cities. In future, we will
399 supplement these data by combining hydrological simulations^{59,61,62}. In summary, verifications suggest
400 our city clusters are unbiased, and the results are robust and credible.

401 **Limitations and future work**

402 Our study collated and accounted results for a single year and did not consider fluctuations in inter-
403 annual precipitation and withdrawal, due to data availability. Variation of water availability for
404 individual cities should be considered in future work since we have observed significant fluctuation, for
405 example a decrease of approximately 60% in Qingdao, Zaozhuang, Laiwu and Linyi cities in 2016, due
406 to reduced precipitation in dry years. This further work will not only reduce uncertainty of water scarcity
407 status, but also explore temporal insights into understanding of water scarcity and allow for more time-
408 series and statistical-significance testing.

409 Water quality-induced scarcity^{16,63,64} has not been included in this paper due to lack of data for water
410 temperature and salinity, nutrient and other pollutants. Besides, the extent to which water savings could
411 be driven by water stress needs quantitative analysis.

412 At this stage our study is also limited by data availability for agriculture; we do not find sufficient
413 irrigation efficiency data for subdivided crops or lands in individual cities, in order to project water saving
414 potential for agriculture. For industrial sectors, it is better to use value-added to substitute output to assess
415 efficiency, especially when such sectoral value-added data will be accessible in the future.

416 Finally, we only considered direct water savings for isolated sectors. It is only partially feasible to
417 assume a smooth knowledge transfer of water efficiency experience from wealthier cities to poorer ones,

418 for example technology progress for saving water. Consumption-based water accounting considers water
419 saving throughout the entire supply chains, which would be practical in future work.

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