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1 **COVID-19 lockdown improved river water quality in China**

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18 **Capsule summary:** River water quality improved during China's COVID-19
19 lockdown, but returned to normal conditions after the lockdown.

20 **Abstract:** The impacts of COVID-19 lockdowns on air quality around the world have
21 received wide attention. In comparison, assessments of the implications for water
22 quality are relatively rare. As the first country impacted by COVID-19, China
23 implemented local and national lockdowns that shut down industries and
24 businesses between January and May 2020. Based on monthly field measurements
25 ($N = 1693$) and daily automonitoring ($N = 65$), this study analyzed the influence of
26 the COVID-19 lockdown on river water quality in China. The results showed
27 significant improvements in river water quality during the lockdown period but out-
28 of-step improvements for different indicators. Reductions in ammonia nitrogen (NH_4^+ -N)
29 began relatively soon after the lockdown; chemical oxygen demand (COD) and
30 dissolved oxygen (DO) showed improvements beginning in late January/early
31 February and mid-March, respectively, while increases in pH were more temporally
32 concentrated in the period from mid-March to early May. Compared to April 2019,
33 the Water Quality Index increased at 67.4% of the stations in April 2020, with 75.9%
34 of increases being significant. Changes in water quality parameters also varied
35 spatially for different sites and were mainly determined by the locations and levels
36 of economic development. After the lifting of the lockdown in June, all water quality
37 parameters returned to pre-COVID-19 lockdown conditions. Our results clearly
38 demonstrate the impacts of human activities on water quality and the potential for
39 reversing ecosystem degradation by better management of wastewater discharges
40 to replicate the beneficial impacts of the COVID-19 lockdown.

41 **Keywords:** COVID-19; lockdown; water quality; spatiotemporal variations; China

42 1 Introduction

43 The unprecedented severe acute respiratory syndrome coronavirus disease
44 2019 (COVID-19) has impacted ~220 countries or territories around the world
45 (<https://www.worldometers.info/coronavirus/#countries>). According to the WHO
46 COVID-19 Dashboard (<https://covid19.who.int/>), as of 6 August 2021, 199.5 million
47 people have been infected with the coronavirus leading to over 4.2 million deaths
48 worldwide. COVID-19 can spread rapidly via primary modes of transmission that
49 include droplets, direct contact, and faecal-oral pathways (Chen et al., 2020). To slow
50 down the diffusion of the virus, more than 170 countries have implemented localised
51 or national lockdown measures ([https://www.theigc.org/blog/a-policy-trade-off-
52 the-impacts-of-stringent-covid-19-lockdowns/](https://www.theigc.org/blog/a-policy-trade-off-the-impacts-of-stringent-covid-19-lockdowns/)). These included shutting down
53 industries and businesses, closing international and provincial borders, and moving
54 education online (<https://www.bbc.com/news/world-52103747>).

55 COVID-19 lockdowns have had significant impacts on economic activities with
56 implications for national and regional economies. COVID-19 led to an economic
57 recession, with a projected negative global economic growth rate of -4.9% in 2020
58 (<https://www.imf.org/en/Publications/WEO>). The pandemic has also been linked to
59 an increase in some pollutants, in particular those associated with single-use plastic
60 items and equipment (Haque et al., 2021), considerable social tension and confusion,
61 and negative attitudes towards public transportation (Sharifi and Khavarian-
62 Garmsir, 2020). Conversely, positive environmental impacts of COVID-19
63 lockdowns have been reported by numerous studies (Braga et al., 2020; Khan et al.,

64 [2020](#); [Paital, 2020](#); [Saadat et al., 2020](#); [Yunus et al., 2020](#)). In particular, many studies
65 across the world have suggested that COVID-19 lockdowns improved air quality by
66 reducing nitrogen dioxide (NO₂), carbon dioxide (CO₂), and particulate matter (PM_{2.5}
67 or PM₁₀), as well as noise ([Bar, 2020](#); [Khan et al., 2020](#); [Saadat et al., 2020](#); [Tadano et](#)
68 [al., 2021](#); [Tobías et al., 2020](#)). Sudden reductions in human activities also impacted
69 wildlife enabling them to move into normally human-dominated zones ([Bar, 2020](#);
70 [Khan et al., 2020](#); [Yang et al., 2020](#)). [Paital \(2020\)](#) even suggested that the COVID-19
71 lockdown was a self-regenerating nurture strategy of the environment in a global
72 context.

73 Some studies have reported positive impacts of COVID-19 lockdowns on water
74 quality ([Khan et al., 2020](#); [Saadat et al., 2020](#); [Sharifi and Khavarian-Garmsir, 2020](#)).
75 For example, reduced discharges of industrial effluent and vessel traffic improved
76 water transparency in Venice Lagoon, Italy ([Braga et al., 2020](#)). [Yunus et al. \(2020\)](#)
77 reported that within Lake Vembanad, the longest freshwater lake in India, the
78 concentration of suspended particulate matter decreased by an average of 15.9%
79 during a period of lockdown in April 2020. Elsewhere in India, the impacts of
80 lockdown have been identified in both chemical and biological water quality
81 parameters within groundwater samples from the city of Thoothukudi (Tuticorin)
82 ([Selvam et al., 2020](#)). However, to our knowledge, analyses of the impacts of the
83 COVID-19 lockdown on water quality across an entire nation have not been
84 investigated.

85 China was the first country to implement a COVID-19 lockdown beginning in
86 Wuhan City on 23 January 2020 and extending across the whole country on 29
87 January 2020 (Table S1). Human activities, including the rapid pace of urbanization
88 and agricultural intensification, have seriously impacted water quality throughout
89 parts of China (Ho et al., 2019; Huang et al., 2019; Yang et al., 2013; Yu et al., 2019;
90 Zhang et al., 2018). For example, human-induced eutrophication has exacerbated
91 algal bloom conditions in many lakes (Ho et al., 2019) and is clearly reflected in the
92 quantity and composition of organic matter in lakes along the Yangtze River (Liu et
93 al., 2020a). Heavy metal pollution in China's lakes and reservoirs also displayed an
94 increasing trend during the period 2005–2017 (Huang et al., 2019). In tackling the
95 nation's water pollution problems, China implemented "*Detailed Rules for the
96 Prevention and Control of Water Pollution of the People's Republic of China*" in 2000
97 (http://www.gov.cn/flfg/2005-08/06/content_21045.htm). These rules focus mainly
98 on establishing wastewater discharge standards and controlling pollutant discharge
99 to improve the quality of freshwater environments (Qin et al., 2007; Tong et al., 2017).
100 The temporary closure of many sources of these discharges during China's COVID-
101 19 lockdown provides a unique opportunity to investigate both the impacts of
102 pollution reduction on water quality and the potential benefits from more stringent
103 discharge standards.

104 Level I lockdown measures in China were first eased in Shanxi Province on 24
105 February 2020 and ended in Hubei Province, of which Wuhan is the capital, on 2
106 May 2020 (Table S1). Since the end of these Level I restrictions, local soft lockdowns

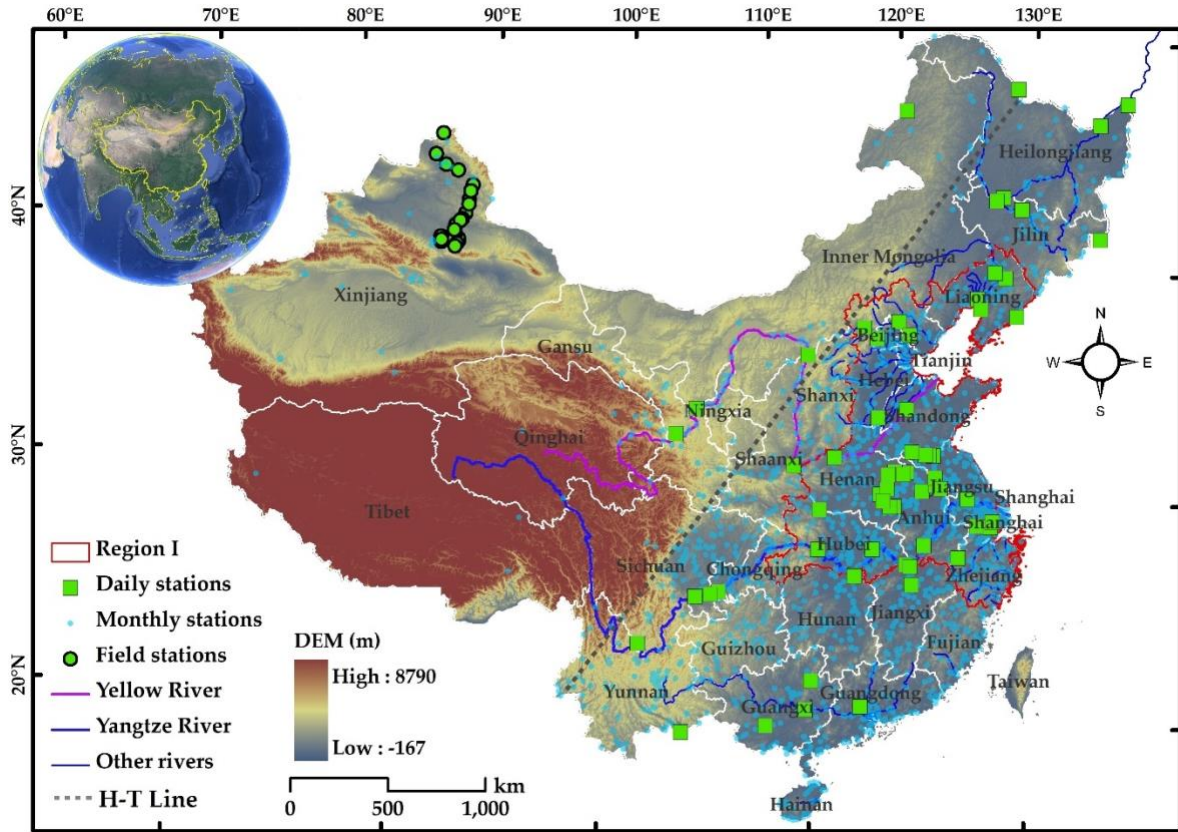
107 have been enforced in response to spikes in COVID-19 cases. Based on
108 environmental monitoring data from January to June of the years 2018–2020, this
109 study quantifies the impacts of the COVID-19 lockdown on river water quality
110 across China with the following specific objectives: (1) to statistically analyse the
111 influence of the lockdown on water quality indicators; (2) to explore the possible
112 reasons for water quality improvements; and (3) to offer policy suggestions to
113 alleviate water pollution in the future. To the best of our knowledge, this is the first
114 study focusing on the impacts of COVID-19 on water quality across an entire nation
115 during and immediately after lockdown.

116 **2 Materials and methods**

117 *2.1 Study area: China*

118 China has a total area of 9.6 million km² and comprises 23 provinces, five
119 autonomous regions, four direct-controlled municipalities, and two special
120 administrative regions (Fig. 1, Table S1). The Heihe-Tengchong Line (or H-T Line)
121 divides China into eastern and western halves (Fig. 1). The region to the east of this
122 line dominates China's economic output; while it accounts for 43% of the country by
123 area, it is home to ~94% of the country's population and contains a large proportion
124 of the nation's cropland. Major urban/industrial conurbations, roads, and railways
125 are also concentrated in this part of China (Yue et al., 2005). The region has been the
126 most heavily impacted by COVID-19. Of China's 121,203 confirmed cases before 6
127 August 2021, more than 99% occurred in eastern China
128 (<http://www.geodata.cn/sari2020/web/index.html>). Especially hard-hit provinces

129 included Hubei, Guangdong, Henan, Zhejiang, and Hunan (Fig. 1). Consequently,
130 China's COVID-19 lockdowns were predominantly in eastern provinces (Table S1).



131
132 **Fig. 1.** The river water quality sampling sites. Region I is a relatively economically developed
133 area in China. National and provincial boundaries were obtained from the National Geomatics
134 Center of China (<http://www.ngcc.cn/ngcc/>). The inset global map was obtained from Google
135 Earth. The Shuttle Radar Topography Mission digital elevation model (DEM) with a spatial
136 resolution of 90 m was obtained from NASA (earthdata.nasa.gov). The H-T Line refers to a
137 demarcation line of China's population density and economic development, with much higher
138 values in the east (Hu, 1935).

139 Based on the spatial distribution of GDP across China, we divided the country
140 into two regions (Fig. 1). Of the two, Region I is relatively economically developed,
141 containing major urban and industrial centres, for example, the Beijing-Tianjin-
142 Hebei Region and the Yangtze River Delta (Fig. 1). In contrast, Region II is generally

143 characterized by relatively lower levels of economic development on the whole, with
144 the exception of Guangdong (Fig. 1).

145 *2.2 Monthly proportions of different water quality levels*

146 Across China, river water quality at 1693 stations was monitored on a monthly
147 basis by the Ministry of Ecology and Environment (Fig. 1). During each sampling
148 period, 21 water quality parameters were collected, including concentrations of
149 hydrogen ions (H^+ or pH), dissolved oxygen (DO), ammonia nitrogen (NH_4^+-N), and
150 chemical oxygen demand (COD) using the potassium permanganate method
151 (MEEPRC, 2002). Based on the values of the 21 elementary items and the
152 environmental quality standards for surface water (Table S2), water quality levels
153 were calculated. For a specific station, the water quality level of the worst indicator
154 was used. In this study, monthly proportions of different water quality levels from
155 January to June (the months immediately before, during, and after the 2020
156 lockdown) in 2018, 2019, and 2020 were sourced from the national surface water
157 quality bulletin (<http://www.mee.gov.cn/hjzl/shj/dbsszyb/>). Data for the first two
158 years were defined as being representative of normal conditions for comparison
159 with those from 2020.

160 *2.3 Daily river water quality data*

161 Whilst 21 water quality variables were measured (Section 2.2), not all are
162 publicly available. This study was only able to acquire daily automatic monitoring
163 data for pH, DO, NH_4^+-N , and COD from 65 stations on rivers in eastern China (Fig.
164 1) from the China National Environmental Monitoring Centre

165 (<http://www.cnemc.cn/>). These variables provide a good representation of water
166 quality because they are the indicators that normally fall below the water quality
167 standards in China. Taking April 2020 as an example, 78.3% of the monitored rivers
168 with poor water quality were placed in this class due to high COD and $\text{NH}_4^+\text{-N}$, low
169 DO, or inappropriate pH. As shown in [Table S2](#), a water body with good ambient
170 water quality (Level I, II, or III) was characterized by pH of 6–9, high DO (≥ 5 mg/L),
171 low $\text{NH}_4^+\text{-N}$ (≤ 1.0 mg/L), and low COD (≤ 6 mg/L) ([MEEPRC, 2002](#)).

172 We employed daily data recorded at 08:00 local time between 23 January and
173 22 June in 2018, 2019, and 2020. These dates cover the extent of the Chinese COVID-
174 19 lockdown in 2020 ([Table S1](#)). The arithmetic mean values across the stations on
175 each day of the period in each of the three years, as well as at a monthly time step,
176 were calculated. It should be noted that missing data from some stations in some
177 months means that inter-year comparisons of water quality parameters were based
178 on different numbers of stations.

179 *2.4 Multi-source data for explaining water quality variations*

180 This study employed daily newly confirmed COVID-19 cases from the National
181 Earth System Science Data Center (<http://www.geodata.cn/>) for 23 January–22 June
182 in 2020 to track the extent of the disease and efficacy of the lockdown. Daily data
183 were available for all of China except Taiwan, Hongkong, and Macao ([Fig. 1](#)). In
184 order to gauge the intensity of the lockdown and explain the spatiotemporal
185 variations in water quality, we also acquired the following multi-source data.

186 (1) From the National Bureau of Statistics of China (<http://data.stats.gov.cn/>), we
187 obtained the total sewage discharge volume from 2000–2019, the provincial
188 population and urban ratio in 2019, the provincial $\text{NH}_4^+\text{-N}$ and COD discharges
189 in 2014 (industrial, domestic, and agricultural), the provincial gross domestic
190 product (GDP) for 2019, and the provincial cumulative growth of industrial
191 added value data at a monthly time step (CGoIAV, %) for February–May 2020.
192 CGoIAV refers to the change in the percent of industrial added value from
193 January to the current month compared with the same period in the previous
194 year (i.e., 2019).

195 (2) From the Ministry of Housing and Urban-Rural Development of the People’s
196 Republic of China (<http://www.mohurd.gov.cn/>), we obtained the daily railway
197 transport passenger volume (persons) from January to June 2020.

198 (3) To explore potential relationships between changes in water quality during the
199 lockdown and levels of economic development, grid-based GDP in 2010, with a
200 spatial resolution of 1000 m, was acquired from the Global Change Research Data
201 Publishing & Repository website (<http://www.geodoi.ac.cn/>).

202 (4) From the European Centre for Medium-Range Weather Forecasts
203 (<https://www.ecmwf.int/>), we obtained total precipitation between February and
204 May in each year between 2018 and 2020, and calculated differences between
205 2020 and each of the two previous years (i.e., 2020 vs. 2018 and 2020 vs. 2019).

206 (5) In addition, we measured $\text{NH}_4^+\text{-N}$ concentrations of snow samples in Xinjiang
207 Province during and before the lockdown ([Fig. 1](#)). Samplings were conducted on

208 20 December 2019 ($N = 7$), between 14 and 17 January 2020 ($N = 30$), and on 29
209 February 2020 ($N = 7$) to collect surface snow samples. After sampling, surface
210 snow samples were melted and stored in a fridge ($-4\text{ }^{\circ}\text{C}$). In the laboratory, NH_4^+
211 -N concentrations were measured using Nesster's reagent and N-(1-Naphthyl)
212 ethylenediamine dihydrochloride spectrophotometry (Crosby, 1968).

213 *2.5 Water Quality Index*

214 The Water Quality Index (WQI), proposed by Pesce and Wunderlin (2000),
215 has been widely applied to comprehensively evaluate water quality (Huang et
216 al., 2019; Wu et al., 2018). In the WQI calculation, measured values of water
217 quality parameters were normalized, and a relative weight was assigned to each
218 environmental parameter based on its potential impact on human health (Pesce
219 and Wunderlin, 2000; Wu et al., 2018). The WQI ranges from 0 to 100, with high
220 values denoting good water quality. In this study, the available pH, DO, NH_4^+ -N,
221 and COD data were applied to calculate the WQI using Eq. (1).

$$222 \quad \text{WQI} = \frac{\sum_{i=1}^n C_i \times P_i}{\sum_{i=1}^n P_i} \quad (1)$$

223 where n is the number of water quality indicators used ($n = 4$); C_i denotes the
224 normalization factor, with a high value for high DO and low values for high NH_4^+ -N
225 and COD; and P_i denotes the relative weight, with different values for input
226 indicators (Refer to Table S3 for more details about on the values of C_i and P_i).

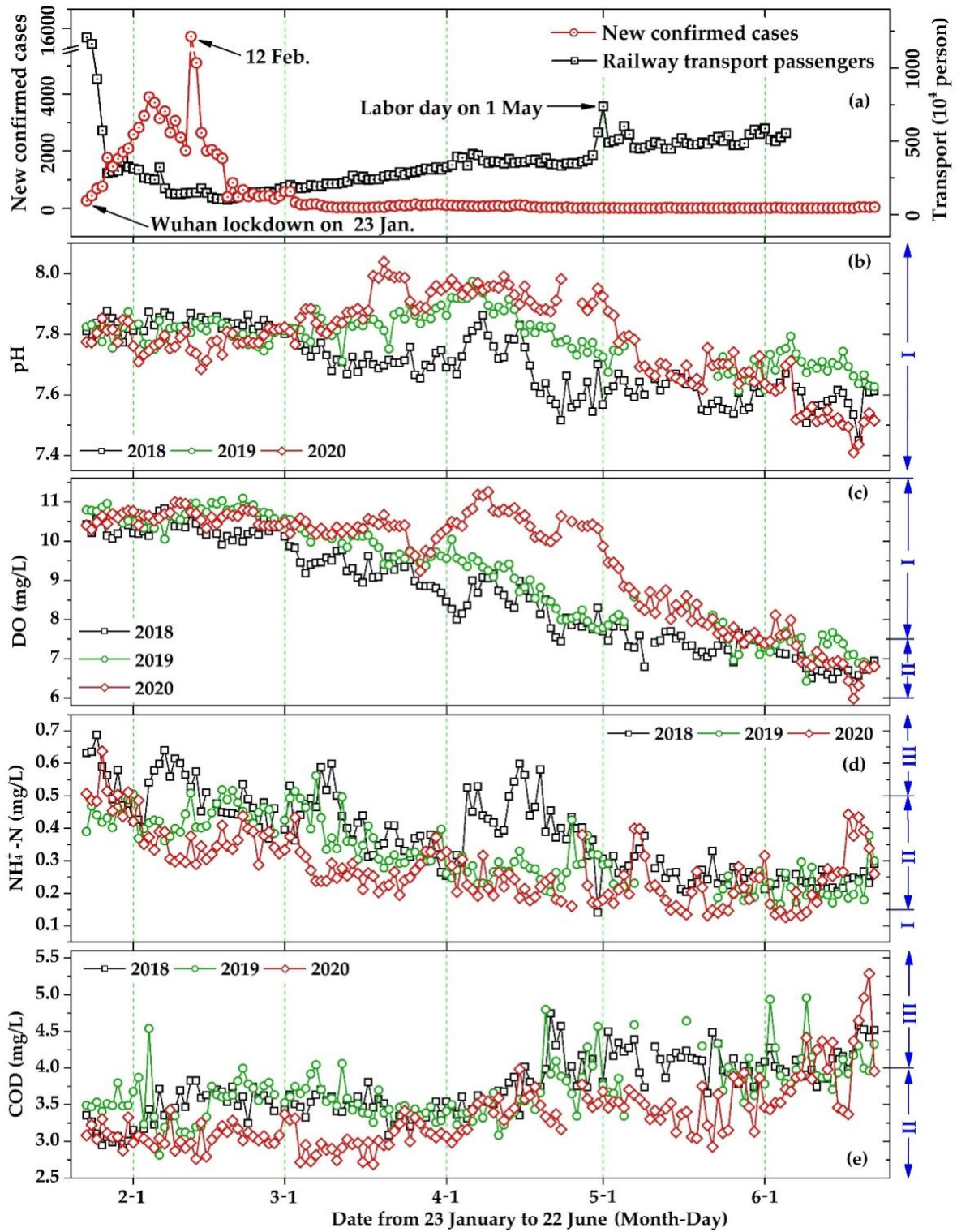
227 *2.6 Statistical analyses*

228 Using SPSS 18.0 (IBM Corp, Armonk, NY, USA), linear regressions were
229 conducted to investigate the relationships among different variables. In addition,
230 independent-samples t-tests were used to determine whether the changes in water
231 quality indicators in different months or years were significant. Correlation analyses
232 with a significance level of $p < 0.05$ (2-tailed test) were reported as significant. The
233 general linear model was used to calculate the contributions of various impact
234 factors on water quality improvements across monitoring stations (Tong et al., 2017).

235 **3 Results**

236 *3.1 The COVID-19 lockdown in China and its economic impacts*

237 The COVID-19 lockdown required that people stay home, so that the daily
238 railway transport passenger volume indicates the lockdown status. After the
239 lockdown began on 23 January 2020, daily railway transport passenger numbers
240 decreased dramatically from 12.08 to 2.83 million over only four days. The numbers
241 continually declined to only 1.04 million on 19 February (Fig. 2a). Subsequently,
242 because of the removal of lockdown restrictions in some provinces (Table S1),
243 passenger numbers increased gradually until the end of the period (Fig. 2a). The
244 beneficial impact of the lockdown on the spread of COVID-19 was evident in the
245 declining numbers of newly confirmed cases in China. After peaking at 15,153 on 12
246 February, the daily number of new cases declined, and by 19 April, it was
247 consistently less than 50 (Fig. 2a). On 2 May, Wuhan's emergency response level was
248 adjusted to Level II, marking the end of COVID-19 lockdowns across China.



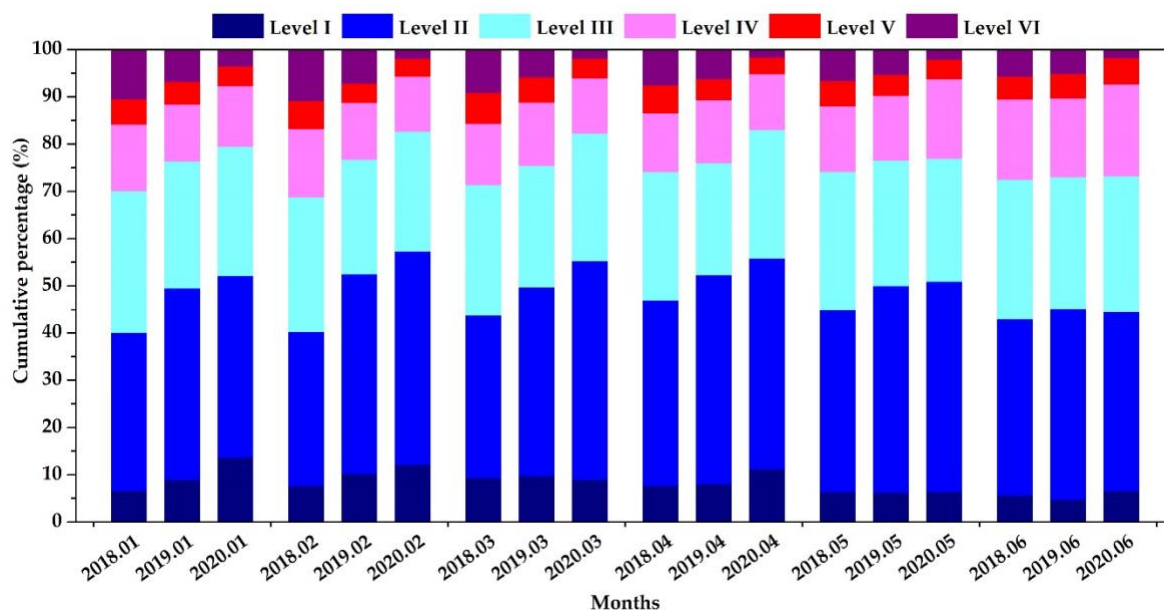
249

250 **Fig. 2.** Daily values of different indicators. (a) New confirmed COVID-19 cases and railway
 251 transport passenger numbers across China between 23 January and 22 June 2020. (b–e) Daily
 252 arithmetic mean values of pH, DO, $\text{NH}_4^+\text{-N}$, and COD derived from data for 65 monitoring sites
 253 (Fig. 1) over the same dates in 2018, 2019, and 2020. Based on the values in Table S2, the water
 254 quality standards are shown on the right axis.

255 The COVID-19 lockdown also shut down many industries. These closures are
256 indicated by the negative CGoIAV values for most provinces between February and
257 May 2020 (Fig. S1). Compared to the industrial added values in 2019 (Section 2.4),
258 all provinces/regions across China had negative CGoIAV values in February 2020,
259 and most were still negative in May; the mean CGoIAV was -13.5% in February,
260 gradually rising to -2.8% in May. Most of the largest declines in CGoIAV were for
261 provinces in eastern China. In Hubei, the province most hard-hit by COVID-19, the
262 CGoIAV was as low as -46.2% in February, increasing to -26.2% in May (Fig. S1).

263 ***3.2 The environmental bulletin results***

264 The environmental bulletin results showed that river water quality improved
265 during the lockdown period in 2020 when compared to both 2018 and 2019 (Fig. 3).
266 Moreover, improvements between February and April were more pronounced than
267 improvements in other months. Water quality levels I, II, and III are classed as good.
268 From 2018 to 2020, the cumulative percentage of good ambient water quality in
269 February was 68.8%, 76.7%, and 82.7%, respectively. The corresponding values for
270 March were 71.4%, 75.4%, and 82.2% and for April 74.1%, 75.9%, and 83.0% (Fig. 3).
271 In contrast, improvements at the beginning (January) and end (May, Section 3.1) of
272 China's lockdown were relatively small. The cumulative percentages of good water
273 quality in June in each year, after the end of the national lockdown in 2020, were
274 72.5%, 73.1%, and 73.3%, respectively (Fig. 3).

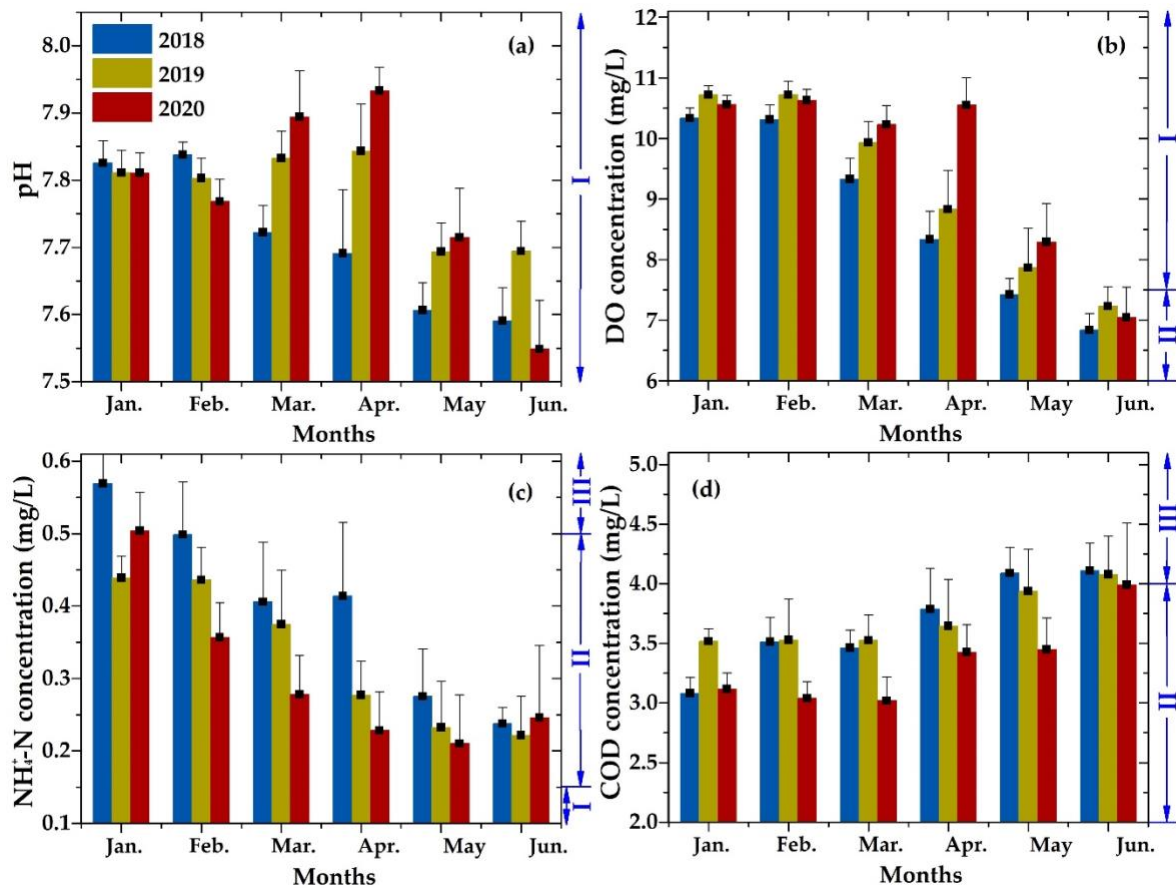


275

276 **Fig. 3.** Proportions of different water quality levels between January and June in 2018, 2019, and
 277 2020. Data were sourced from the Ministry of Ecological Environment, China (Section 2.2).

278 **3.3 Temporal variations in daily water quality**

279 The lockdown of 2020 increased pH. In 2020, the mean pH across the 65
 280 monitoring sites was initially similar to the corresponding values in the two
 281 previous years. It then increased and remained higher throughout March, April, and
 282 May (Figs. 2b and 4a). Compared with the values in 2018, the mean H⁺
 283 concentrations in these three months declined by 32.7%, 42.8%, and 22.1%,
 284 respectively. The corresponding figures for the comparison with 2019 indicated
 285 declines of 13.3%, 18.7%, and 4.8%. Results of the independent-samples t-test
 286 showed that the decreases in the H⁺ concentration in March and April 2020 were
 287 significant, with $p < 0.01$. By the beginning of June 2020, the mean pH reached the
 288 corresponding values of the two earlier years (Fig. 2b).



289

290 **Fig. 4.** Mean values of different water quality parameters in January–June 2018, 2019, and 2020:
 291 (a) pH; (b) DO; (c) NH₄⁺-N; and (d) COD. The error bars indicate the standard deviations. Based
 292 on the values in [Table S2](#), the water quality standards are shown on the right axis.

293 The lockdown had an apparent impact of increasing DO. At the beginning of
 294 February in both 2018 and 2019, DO began to decline, which continued until the end
 295 of June. In contrast, in 2020, DO remained high, albeit with some large fluctuations,
 296 until the end of April ([Fig. 2c](#)). On average, DO was 9.7% and 26.6% higher in March
 297 and April 2020, respectively, compared to the average values in 2018. The
 298 corresponding figures when comparing 2020 with 2019 were 3.0% and 19.5% ([Fig.](#)
 299 [4b](#)). Increases in DO in March, April, and May 2020 were significant, with $p < 0.05$.
 300 From the end of April 2020, DO declined rapidly and reached normal level by June.

301 The lockdown reduced NH_4^+ -N. At the beginning of the lockdown in January
302 2020, NH_4^+ -N was, on average, similar to the mean values in both 2018 and 2019 (Fig.
303 2d). Then, throughout the lockdown from February to April 2020, the mean NH_4^+ -N
304 concentrations fell below those in 2018 (2019) by an average of 28.5%, 31.5%, and
305 44.9% (18.2%, 25.8%, and 17.6%), respectively (Fig. 4c). The decreases in NH_4^+ -N in
306 February, March, and April 2020 were significant, with $p < 0.01$. In May and early
307 June 2020, although the lockdown had ended, the mean NH_4^+ -N was still lower than
308 the averages in 2018 and 2019, and it then increased towards the end of the month
309 (Fig. 2d).

310 The lockdown also appeared to have reduced COD. This was initially evident
311 shortly after the beginning of the lockdown (Fig. 2e). On average, COD during
312 February and March 2020 was 13.4% and 12.8% lower, respectively, compared to the
313 same months in 2018. The corresponding declines from 2019 were 13.8% and 14.4%
314 (Fig. 4d). Although COD increased from the beginning of April, the average values
315 were still lower than in the previous years, especially in May (Fig. 2e). Decreases in
316 COD in February, March, April, and May 2020 were significant, with $p < 0.01$. By late
317 June 2020, after the end of the lockdown, COD was of a similar magnitude to the
318 corresponding values in the two previous years.

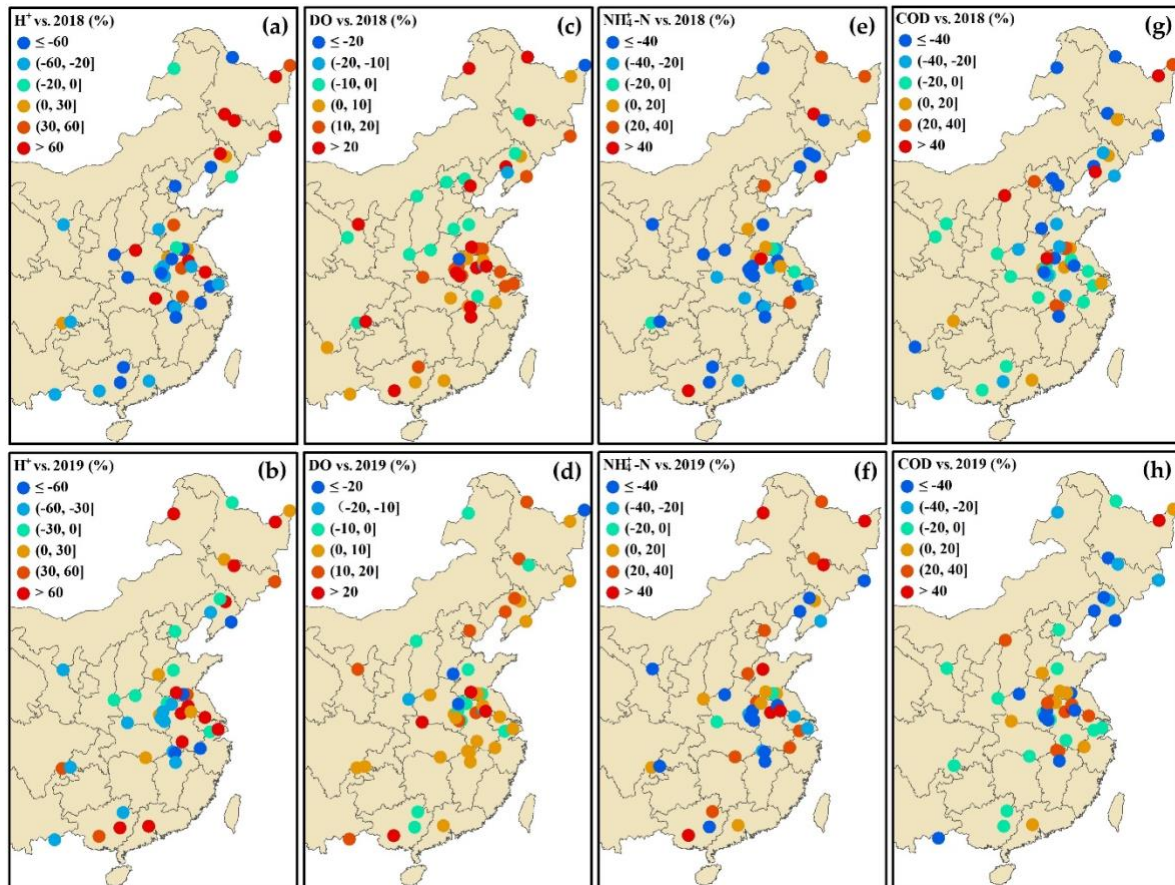
319 In sum, the responses of the different water quality indicators to the COVID-19
320 lockdown were out-of-step. During China's lockdown, DO (NH_4^+ -N, COD) showed
321 improvements beginning in mid-March (early February, late January) (Fig. 2) and

322 ending late May (mid-June, early June), respectively, while changes in pH were
323 more temporally concentrated in the period from mid-March to early May.

324 *3.4 Spatial variations in changes in daily water quality*

325 Changes across the four water quality parameters during China's COVID-19
326 lockdown were concentrated during the period of February–May but were out-of-
327 step (Section 3.3). In order to investigate spatial variations of changes in water
328 quality, the mean values of the four parameters at each of the 65 monitoring sites
329 during different periods (H^+ : March–April; DO: March–May; NH_4^+ -N: February–
330 April; COD: February–May) in 2020 were compared with the corresponding values
331 in 2018 and 2019. This revealed spatial differences in the magnitude of the changes
332 across different monitoring sites, as discussed below.

333 Across the 47 sites with available data, the mean pH in March–April 2020 was
334 higher than that in 2018 at 30 sites and lower at the remaining 17 sites (Fig. 5a).
335 Changes in the H^+ concentration ranged from -91.6% to 322.1%. When compared to
336 2019, the mean March–April pH at the 47 sites with data was higher in 2020 at 25
337 sites (lower at the remaining 22 sites) (Fig. 5b). Both increases and decreases in the
338 H^+ concentration occurred, with an overall range between -96.2% and 419.7%. More
339 sites in northern China experienced large increases in H^+ concentration, and the
340 magnitude of H^+ change showed a significant increase with the latitude of the
341 monitoring site ($p < 0.05$, 2-tailed test); compared to 2018 and 2019, both the Pearson's
342 r values were 0.38 (Fig. S2).



343

344 **Fig. 5.** Mean percentage changes in the four water quality parameters across monitoring sites in
 345 eastern China during different periods of 2020 and the same months in 2018 and 2019,
 346 respectively: (a–b) are for H^+ during March–April; (c–d) are for DO during March–May; (e–f) are
 347 for NH_4^- -N during February–April; (g–h) are for COD during February–May. Base maps show
 348 the province boundaries in China (Fig. 1).

349 Mean March–May DO was higher in 2020 than in 2018 at 41 of the 57 sites with
 350 data (lower at the remaining 16 sites) (Fig. 5c). Most of the sites located in southeast
 351 China experienced increased DO. Overall differences in the DO concentration across
 352 all sites ranged from -30.3% to 54.7%. Compared to 2019, the mean March–May DO
 353 was higher in 2020 at 33 of the 51 sites with data, with differences varying between
 354 -29.3% and 44.6% (Fig. 5d). There was, however, no clear spatial pattern of increases
 355 or decreases across the sites (Table 1).

356 **Table 1** Impact factors on the percentage changes in the four water quality indicators across
 357 monitoring sites (H⁺: March–April; DO: March–May; NH₄⁺-N: February–April; COD: February–
 358 May). *r* denotes the Pearson correlation coefficient, and symbol “*” denotes *p* < 0.05. The
 359 contribution was calculated using the general linear model (Section 2.6).

Index	Factors	2020 vs. 2018 (%)				2020 vs. 2019 (%)			
		H ⁺	DO	NH ₄ ⁺ -N	COD	H ⁺	DO	NH ₄ ⁺ -N	COD
Pearson's <i>r</i>	Longitude	0.38*	-0.06	0.34*	0.20	-0.24	-0.14	0.28	-0.09
	Latitude	0.38*	-0.04	0.09	0.05	0.38*	-0.11	0.25	-0.12
	GDP	0.27	-0.22	0.03	0.04	-0.18	0.08	0.09	-0.07
	DEM	-0.06	0.00	-0.37*	-0.16	0.05	0.07	-0.16	0.10
	Rainfall	-0.13	0.01	0.08	-0.07	0.07	-0.05	0.12	-0.19
Contribution (%)	Longitude	14.12	0.30	28.26	43.33	19.34	0.35	6.83	13.32
	Latitude	1.98	0.24	23.07	13.71	8.54	3.54	16.56	34.80
	GDP	65.17	66.54	5.63	13.54	42.73	13.66	24.46	1.48
	DEM	0.32	0.27	7.21	2.92	6.02	0.01	12.85	26.31
	Rainfall	8.08	1.78	23.34	10.20	15.01	15.67	20.52	6.50
	Others	10.33	30.87	12.49	16.3	8.36	66.77	18.78	17.59

360 The mean NH₄⁺-N concentrations in February–April were lower in 2020 than
 361 those in 2018 at 31 of the 45 sites with data (higher at 14 sites) (Fig. 5e). The
 362 magnitude of the differences ranged between -326.8% and 54.1%. There was a
 363 positive relationship between the change in NH₄⁺-N and site longitude (*r* = 0.34 and
 364 *p* < 0.05) (Table 1), with only one site in southern China experiencing increases (Fig.
 365 5e). of the 44 sites with data, 21 experienced lower February–April mean NH₄⁺-N in
 366 2020 when compared to 2019, with the range of differences equalling -141.7% to 63.3%
 367 (Fig. 5f). The change magnitude in NH₄⁺-N was also correlated with the site longitude,
 368 with *r* = 0.28 and *p* = 0.06 (Table 1).

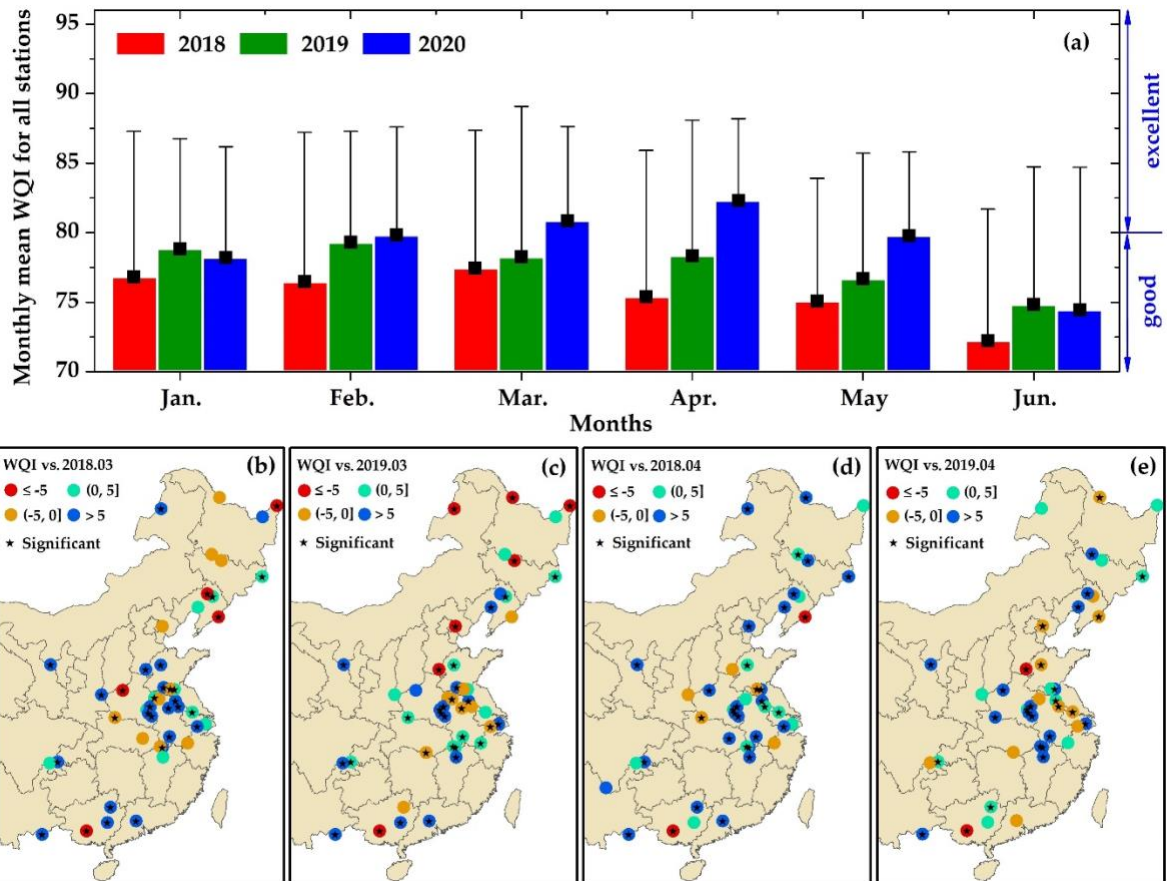
369 Across the 56 sites with data for mean COD in February–May for both 2018 and
 370 2020, reductions in 2020 were recorded at 36 sites (increases at 19 sites) (Fig. 5g). The

371 changes between these two years at different sites ranged between -251.2% and
372 54.0%. Declines between 2019 and 2020 were also dominant (30 of the 49 sites with
373 data in both years; increases at the remaining 19). Across the 49 sites, changes in the
374 mean COD ranged between -140.0% and 47.2% (Fig. 5h). With a majority of sites
375 experiencing declines in 2020 when compared to both 2018 and 2019, those sites with
376 increased COD were concentrated in the developed Region I (Figs. 1 and 5).

377 *3.5 Spatiotemporal variations in WQI*

378 The mean WQI values across all stations also showed that China's lockdown
379 improved river water quality throughout the country (Fig. 6). When compared to
380 2018, monthly mean WQI values were higher in all months from January to June
381 2020 (Fig. 6a). Similarly, comparisons between 2020 and 2019 show higher WQI
382 values in February, and in particular March, April, and May (Fig. 6a).

383 Since pH, DO, $\text{NH}_4^+\text{-N}$, and COD values showed significant improvements in
384 March and April 2020 (Section 3.3), we explored the changes in WQI values across
385 different stations in these two months. Compared to March 2018 (2019), 68.1%
386 (66.0%) of stations had higher WQI values in March 2020, with 78.1% (77.4%) being
387 significant (t-test, Figs. 6b–c). Compared to April 2018 (2019), the WQI values
388 increased at 84.1% (67.4%) stations in April 2020, with 81.1% (75.9%) being
389 significant (t-test, Figs. 6d–e). The comprehensive WQI showed greater
390 improvements in water quality during China's lockdown than the results indicated
391 by a single water quality parameter (Sections 3.3 and 3.4).



392

393 **Fig. 6.** Comparisons of monthly mean WQI in 2020 to those in 2018 and 2019. (a) Monthly mean
 394 WQI values across all stations. The water quality standard is shown on the right axis: $WQI \geq$
 395 80, excellent; 61–80, good; 30–60, acceptable; and $WQI < 30$, poor (Chang et al., 2020). (b–e) are
 396 the comparisons of values in March and April 2020 to the corresponding months in 2018 and
 397 2019, respectively.

398 *3.6 Relationships between precipitation and water quality changes*

399 Precipitation varied from year to year during each of the years between 2018
 400 and 2020. Across the monitoring stations, precipitation from February to May 2020
 401 was generally lower than in 2018 but higher than in 2019. Compared to 2018, the
 402 total precipitation during these months differed by between -66% and 166%, with an
 403 average of -6.42%. When compared to 2019, the differences ranged from -73% to
 404 113%, with an average of 10.06%.

405 Precipitation variations did not show obvious impacts on water quality
406 improvements. When compared to both 2018 and 2019, there were no significant
407 relationships between differences in precipitation and water quality across the
408 different monitoring stations (Table 1). Compared to 2018, precipitation variation
409 explained only 8.1%, 1.8%, 23.3, and 10.2% of the improvements in H^+ , DO, NH_4^+-N ,
410 and COD, respectively. When compared to 2019, the corresponding values were
411 15.0%, 15.7%, 20.5%, and 6.5%, respectively (Table 1).

412 **4 Discussion**

413 *4.1 Possible reasons for water quality improvements*

414 Human activities have had significant impacts on water quality in China. The
415 country's rapid economic development has placed considerable pressure on aquatic
416 environments, with results including widespread deterioration in water quality
417 (Duan et al., 2009; Huang et al., 2019; Tong et al., 2017; Yang et al., 2012). For example,
418 the annual volume of sewage discharged to China's aquatic systems increased from
419 $33.18 \times 10^9 \text{ m}^3$ in 2000 to $55.46 \times 10^9 \text{ m}^3$ in 2019. To improve water quality, the Chinese
420 government has since 2000 implemented major strategies for alleviating water
421 pollution (Huang et al., 2019; Qin et al., 2007; Tong et al., 2017; Yang, 2014). China's
422 COVID-19 lockdown resulted in a unique period during which the intensity of many
423 human activities was reduced, with beneficial implications for water quality.

424 The COVID-19 lockdown improved river water quality by reducing industrial
425 sewage discharges. Industrial activities are important sources of NH_4^+-N and COD
426 to China's rivers (Shon et al., 2006; Zhang et al., 2015); across different provinces,

427 1.2–47.5% of NH_4^+ -N and 3.3–45.6% of COD were sourced from this group of human
428 activities (Fig. S3). The COVID-19 lockdown shut down many industries, as
429 indicated by the negative CGoIAV values, and required people to stay home
430 resulting in the low railway transport passenger volume (Section 3.1). With the
431 exception of Hubei Province, CGoIAV in May was significantly negatively related
432 to COVID-19 cases percent, with $r = -0.53$ and $p < 0.05$ (Fig. S1). In contrast,
433 agricultural discharges to streams and rivers, that include fertiliser and pesticide
434 residues, were less likely to have been impacted by the COVID-19 lockdown.
435 Compared to 2019, agricultural sown area and total output in China in 2020
436 increased, albeit by relatively small amounts (0.6% and 0.9%, respectively;
437 http://www.gov.cn/xinwen/2020-12/10/content_5568623.htm).

438 Improved air quality might also have beneficial impacts on improving water
439 quality. Many studies have suggested that the COVID-19 lockdown reduced
440 atmospheric pollution (Bauwens et al., 2020; Shi and Brasseur, 2020; Wang and Su,
441 2020). Atmospheric deposition is an important source of water nutrients, which can
442 further increase COD by enhancing primary production (Pandey et al., 2014).
443 Although the COVID-19 lockdown had limited impacts on the relatively small
444 economic activities in western China (Xinjiang, Qinghai, and Tibet) (Fig. S1), the
445 available data suggested improving air quality (Wang and Su, 2020) did lead to some
446 improvements in water quality within this part of China. Mean NH_4^+ -N of *in-situ*
447 snow samples in January 2020 (0.9 mg/L) was close to that in December 2019 (0.87
448 mg/L) (Fig. S4a). However, it declined to 0.48 mg/L in February 2020, with

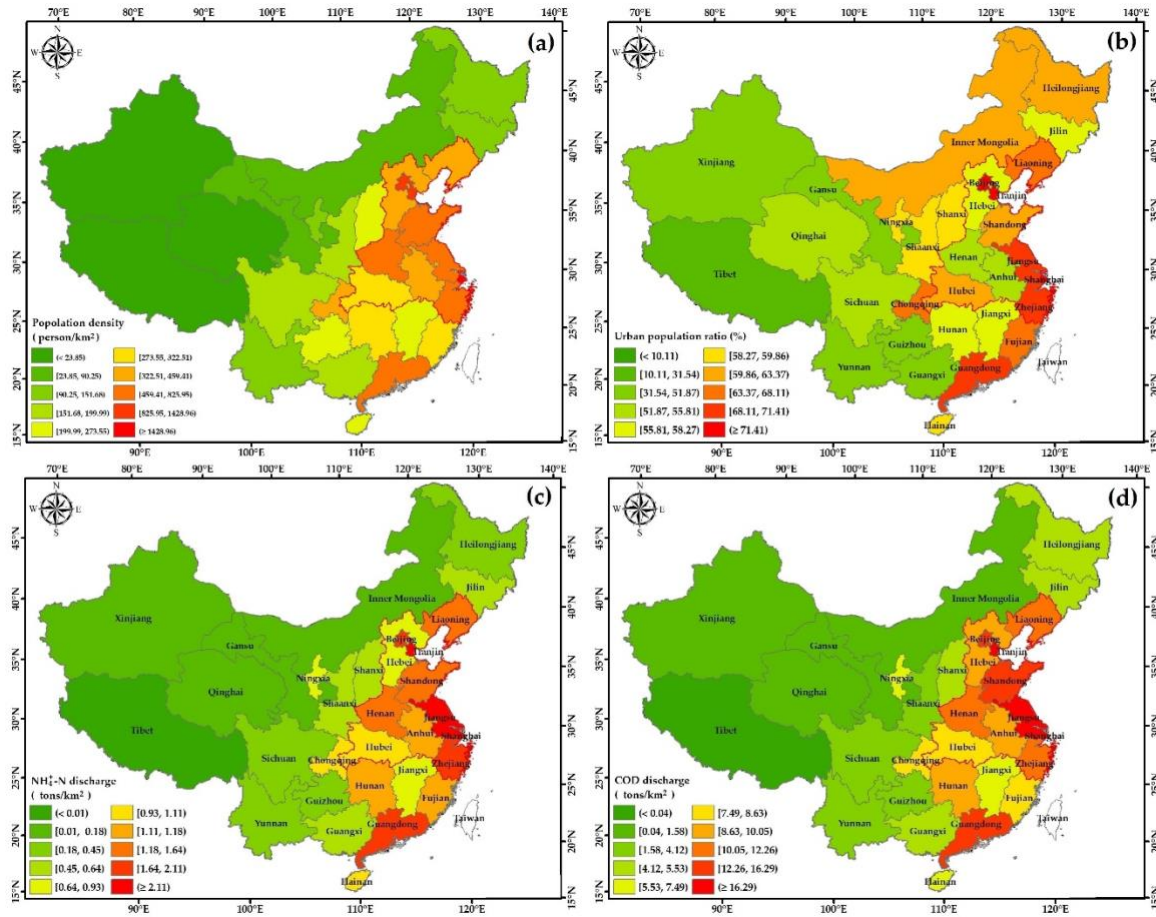
449 reductions of 45.3% and 46.9% from December 2019 and January 2020, respectively.
450 The largest decline at an individual site was 81.4%, and the average across the five
451 sites with lower NH_4^+ -N concentrations was 62.7% (Fig. S4b).

452 The water quality improvements across different monitoring sites were mainly
453 determined by the site locations and the levels of economic development. For
454 example, the longitude, latitude, and GDP together contributed 81.3%, 67.1%, 57.0%,
455 and 70.1% to the changes between 2020 and 2018 in H^+ , DO, NH_4^+ -N, and COD,
456 respectively (Table 1). The severity of COVID-19 lockdown, as indicated by the
457 number of confirmed cases, was mainly located in the east (Fig. S1), whilst the north
458 dominated the area experiencing the largest improvements in air quality (Wang and
459 Su, 2020). Compared to both 2018 and 2019, improvements in water quality between
460 February and April 2020 were generally greater in the developed Region I than those
461 in the undeveloped Region II (Text S1). For example, when compared April 2020 to
462 the same month in 2019, mean improvements in DO, NH_4^+ -N, and COD in Regions I
463 and II were 22.6% vs. 14.8%, 25.1% vs. 3.7%, and 8.4% vs. 4.5%, respectively (Table
464 S4).

465 *4.2 Policy suggestions to alleviate water pollution*

466 The investigation of water quality improvements during China's COVID-19
467 lockdown provides opportunities to review approaches to improve river water
468 quality under both the special circumstances experiences in 2020 and normal socio-
469 economic conditions. Some policy suggestions are given below.

470 First, location-specific pollutant discharge reduction strategies are required to
471 target water quality problems. (1) More attention should be paid to the reduction of
472 pollutant discharges in densely populated areas. Within provinces in Region I,
473 which have a much higher population density (Fig. 7a), river water per unit area
474 received more NH_4^+ -N and COD from human activities compared to other provinces
475 in the less densely population Region II (Fig. 7c–d). Improvements in water quality
476 in Region I were therefore more significant during the lockdown (Text S1). Moreover,
477 an increasing proportion of people across China now live in cities. In Beijing and
478 Shanghai, the urban ratios exceeded 85% in 2019 (Fig. 7b). Therefore, reducing
479 pollutant discharges within rapidly urbanising regions should be a priority. (2)
480 Different provinces should adopt alternative pollution reduction strategies that
481 reflect their levels of development and the magnitude of pollution problems that
482 they face. Although industrial and domestic activities are the major sewage sources,
483 their discharge ratio varies greatly by province: for NH_4^+ -N discharge in 2014, the
484 ratio ranged from 27.5% in Heilongjiang to 86.3% in Yunnan; for COD discharge in
485 2014, the ratio ranged from 55.6% in Shandong to 93.1% in Shanghai (Fig. S3).



486

487 **Fig. 7.** Statistical data from the National Bureau of Statistics. (a) The provincial population
 488 density in 2019; (b) urban population ratio in different provinces in 2019; (c–d) NH₄⁺-N and COD
 489 discharges per square kilometre in different provinces in 2014.

490 Second, pollutant reduction strategies should be sustained. Although the
 491 responses of different water quality indicators to pollutant reduction during the
 492 COVID-19 lockdown were out-of-step, pH, DO, NH₄⁺-N, and COD returned to
 493 normal levels after the lockdown in June 2020 (Section 3.3). Explanations for the
 494 relatively quick return to these levels include the fact that some provinces ended
 495 their lockdowns before May, in some cases as early as late February (Table S1).
 496 Another reason is that the economy rebounded rapidly, leading to the discharge of
 497 large volumes of wastewater as lockdowns were lifted. CGoIAV across China as a

498 whole was -13.5% in February 2020, but increased to -1.3% in June. By December of
499 the same year, CGoIAV was positive at 2.8% (<https://data.stats.gov.cn/>).
500 Government policies aimed at reducing pollutant discharges therefore require
501 sustained, year-round efforts so as to alleviate water pollution in a long term.

502 The different water quality indicators employed in this study are interrelated.
503 For example, from January to June 2020, the daily mean COD across all stations
504 showed a significant negative linear relationship to both DO ($r = -0.51, p < 0.01$) and
505 pH ($r = -0.65, p < 0.01$). Organic matter remineralization under conditions of high
506 COD leads to reductions in DO and increased production of CO₂ (Wang et al., 2018).
507 CO₂ dissolves in water to form carbonic acid, which lowers the water pH. Given
508 these inter-relationships, comprehensive control of the discharges of all pollutants
509 is required.

510 *4.3 Limitations and future work*

511 More water quality monitoring and pollutant reduction data would enable
512 further insights into the impacts of the COVID-19 lockdown on river water quality
513 in China. First, in addition to the 21 elementary items in Table S2, water temperature,
514 total nitrogen, and *E. coli* would have, in particular, been valuable (MEEPRC, 2002).
515 Second, some specific pollutants related to the COVID-19 epidemic were not
516 considered, and data are generally scarce. The pandemic has resulted in the
517 pollution of single-use plastic items and equipment in aquatic environments (Haque
518 et al., 2021), and future research should seek to establish the immediate and longer-
519 term implications of this increasing pollution source. The COVID-19 virus has also

520 been detected in wastewater (Sherchan et al., 2020), and concerns have been raised
521 regarding the potential for transmission of the virus via this source (Carducci et al.,
522 2020; Liu et al., 2020b). Again, this should be considered as a priority research area
523 no least given its potential public health consequences.

524 Accurate investigations that include consideration of the site-scale data and
525 sewage volumes are required to further quantitatively assess the impacts of the
526 COVID-19 lockdown on river water quality at different sites. This is a common
527 limitation of published studies on the impacts of COVID-19 lockdowns on
528 environmental improvement (Braga et al., 2020; Lal et al., 2020; Saadat et al., 2020).
529 First, the mean values of water quality indicators across all stations indicated
530 improvements (Section 3.2), although some stations showed water quality
531 deterioration (COD at a station in Shandong Province for example; Fig. S5). In
532 addition, water quality indicators at some stations fluctuated much more than at
533 others (Figs. S5 and S6), which might reflect the influence of local changes in
534 wastewater discharges or precipitation resulting changes in river discharge. For
535 example, the sudden rise and subsequent decline in COD in June 2020 (Fig. S6) on
536 sites along the Yangtze River is most likely to be the result of summer flooding (Zhou
537 et al., 2021).

538 **5 Conclusions**

539 The COVID-19 lockdown led to a general improvement in river water quality in
540 China. During the lockdown period of February–May 2020, the mean pH and DO in
541 the most of the rivers included within this study increased. Conversely, the

542 dominant trend was for a decline in NH_4^+ -N and COD concentrations. Changes
543 across the four water quality parameters investigated in detail were concentrated
544 during the period of February–May but were out-of-step. Moreover, changes in these
545 water quality parameters at different sites varied according to spatial location and
546 economic development. After China’s lockdown, water quality returned to levels
547 experienced in the two previous years that were not subject to lockdown. These
548 results demonstrate the influence of human activities on China’s water quality and
549 the potential for addressing the nation’s water quality problems by reducing
550 wastewater discharges. Sustained and targeted strategies will, however, be required
551 if the short-term improvements in China’s river water quality exhibited during the
552 unprecedented conditions in 2020 are to be replicated in the long term.

553 **Declaration of competing interest**

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