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# Driving forces and variation in water footprint before and after the COVID-19 lockdown in Fujian Province of China

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## ABSTRACT

The COVID-19 outbreak has injured the global industrial supply chain, especially China as the world's largest manufacturing base. Since 2020, China has implemented a rigorous lockdown policy, which has sternly damaged sectoral trade in export-oriented coastal areas. Fujian Province, which mainly processes imported materials, has a more profound influence. Although the COVID-19 lockdown has had some detrimental consequences on the world economy, it also had some favorable benefits on the global ecology. Previous studies have shown that the lockdown has altered the physical water quantity and quality, but the lack of total, virtual, and physical water research that combines water quantity and water quality simultaneously to pinpoint the subject and responsibility of water resources consumption and pollution. This research quantified the physical, virtual, and total water consumption and water pollution among 30 sectors in Fujian Province based on the theory of water footprint and the Economic Input-Output Life Cycle Assessment model. SDA model was then used to investigate the socioeconomic elements that underpin variations in the water footprint. The results show that after the lockdown, the physical water quantity and the physical grey WF in Fujian Province decreased by 2.6 Gm$^3$ (−6.7%) and 0.4 Gm$^3$ (−1.3%) respectively. The virtual water quantity decreased by 2.3 Gm$^3$ (−4.5%), whereas the virtual grey WF rose by 1.5 Gm$^3$ (4.3%). The total water quantity dropped by 3.3 Gm$^3$ (−4.9%), while the grey WF increased by 1.2 Gm$^3$ (2.5%), i.e. the COVID-19 lockdown decreases physical water quantity and improves local water quality. More than 50% of the water comes from virtual water trade outside the province (virtual water is highly dependent on external), and around 60% of the grey WF comes from physical sewage in the province. The COVID-19 lockdown reduced water outsourcing across the province (paid nonlocally decrease) but increased pollution outsourcing (paid nonlocally increase). And gross capital formation's contribution to the growth in water footprint will continue to rise. As a result, this study suggested that Fujian should take advantage of sectoral trade network to enhance the transaction of green water-intensive intermediate products, reduce the physical water consumption of blue water-intensive sectors, and reduce the external dependence on water consumption. Achieving the shared responsibility of upstream and downstream water consumption and reducing the external dependence on water in water-rich regions is crucial to solving the world's water problems. This research provides empirical evidence for the long-term effects of COVID-19 lockdown on the physical and virtual water environment.

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## 1. Introduction

The disease caused by COVID-19 is affecting most countries and regions worldwide. The vast majority of countries have imposed lockdown measures during the COVID-19 pandemic (Hunter et al., 2021). Although these measures have been effective in containing the COVID-19 spread (Roidt et al., 2020), they have also caused socio-economic impacts (Abdeen et al., 2021; Bazzana et al., 2022; Han et al., 2021; Kang et al., 2021; Kim et al., 2021; Rempel and Gupta, 2021), and environmental responses (Abdeen et al., 2021; Hunter et al., 2021; Liu et al., 2021). For instance, the COVID-19 pandemic has disrupted international supply chains, with world merchandise trade falling by 5.3% in 2020 alone (WTO, 2021). China, the world's largest merchandise trader, has been hit hardest by its international supply chains, falling 6.4% in the first two months of the COVID-19 lockdown alone (January–February 2020) (National Development and Reform Commission, 2021). In response to the impact of the COVID-19 epidemic on China's supply chain, the Chinese government timely proposed a major strategic plan to build a large domestic market, making it possible to focus on the impact of the COVID-19 epidemic on domestic supply chains. As a water-poor country like China, the change of WF in the domestic supply chain during the blockade is an issue worth exploring.

Recent studies analyzed the impact of COVID-19 lockdowns on water consumption and the water environment. Most of the studies conducted on the changes in physical water, mainly at the global level (Chakraborty et al., 2021; Elsaid et al., 2021; Liu et al., 2021; Pant et al., 2021; Tokatli and Varol, 2021; Wetz et al., 2021; Yunus et al., 2020), national level (Liu et al., 2021; Wetz et al., 2021) and basin level (Chakraborty et al., 2021; Pant et al., 2021; Tokatli and Varol, 2021; Yunus et al., 2020). These studies provide evidence for the impact of COVID-19 lockdowns on physical water. But, except for Abulibdeh (2021), who divided the study subjects into six economic sectors, other studies only analyzed aggregate changes in physical water and were unable to quantify water footprint (WF) in the supply chain and its response to COVID-19 lockdowns. Only individual studies describe the collision of the blockade on virtual water (VW), but they are limited to impacts of blue *WF* (Roidt et al., 2020), rare concentration paid to grey and green WF (see Albers et al. (2021) and Li et al. (2021) for the classification of WF and VW), while green and grey WF account for a larger share of the WF (average greater than 60%) (Liu et al., 2020; Mekonnen and Hoekstra, 2011). However, such a conclusion one-sidedly evaluates the impact of the COVID-19 lockdown on the local region, which is not conducive to stakeholders making correct decisions.

To fill the above gaps, we parse out the intermediate product WF (VW) and the final product WF by comparing the production-based direct WF and the consumption-based WF, and further decomposed intermediate WF into internal VW and external VW to explore the impact of the COVID-19 lockdown on water resources in the local supply chain, tracking the underlying causes of water quantity (blue water + green water), water quality changes (grey water), and who is responsible (see Figs. 2 and 8). The specific methods are as follows: investigating the physical, virtual, and total changes in water quality (grey direct WF/VW/*WF*) and quantity (green and blue direct WF/VW/*WF*) in 30 economic sectors of Fujian Province before (2017–2019) and after (2020) the COVID-19 lockdown using the Economic Input-Output Life Cycle Assessment (EIO-LCA) model (Blackhurst et al., 2010; Hendrickson and Horvath, 1998). Varies in WF are further decomposed using the SDA approach(Cai et al., 2020; Zhao et al., 2021b) to identify the key economic factors promoting them. Take Fujian Province, the leading province in the Hercynian region, and an emerging economy fostered by the country as an example. This study provides an annual evidence-based insight into the changes in WF during the pre and post-lockdown period in Fujian Province and China. Not only being able to see the physical, virtual, and total changes and major consumers in the water quantity and water quality before and after the COVID-19 lockdown, but also understanding the differential contributions in drivers, as well as internal and external causes, which is critical for sustainable water management.

## 2. Methodology

### 2.1. Profile of study area

Fujian Province is located on the southeast coast of China (Fig. 1), with many mountains and few fields (the per capita arable land is only one-third of the national average), and a low self-sufficiency rate of food. Nearly 80% of the food comes from outside the province. It is a prominent export-oriented economy and one of the top 10 provinces in China in terms of foreign trade. The COVID-19 containment measures disrupted industrial and supply chains in Fujian, putting pressure on local economic development (Cai, 2020). Such as, from January to March 2020, Fujian Province's trade in goods imports and exports decreased by 3.6% year-on-year ( Exports fell 10.3% ) (Fuzhou Customs, 2020).

Fujian Province is a water-rich area that already faced many water challenges before the lockdown (Ma et al., 2020a; Yu et al., 2020a). For example, although water resources are relatively abundant, they are unevenly distributed in time and space, the water resources do not match the level of economic development, and the contradiction between regional water supply and demand is prominent. For example, the more developed Fuzhou, Quanzhou, Xiamen, Zhangzhou, etc. have only 23% of the water resources but have created more than 70% of the GDP. The water environment quality is not optimistic, more than 90% of the reservoirs are in a state of moderate eutrophication (Fujian Provincial Department of Water Resources, 2017–2020). However, the forest coverage rate is over 60% (the highest in China), and the heterogeneity

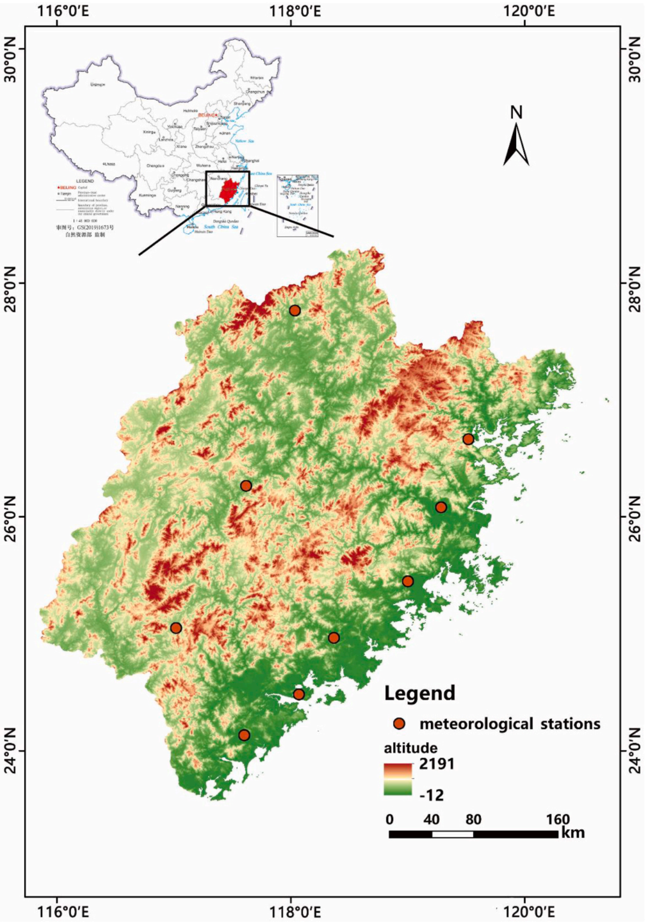

**Fig. 1.** Location of Fujian Province.

of green water resources is unmatched by other regions in China. A joint study on water quantity and water quality is also the implementation of the development concept of " The Golden Mountains and Silver Mountains are lucid waters and lush mountains " advocated by General Secretary Xi Jinping.

Furthermore, Fujian Province is located north to the Yangtze River Economic Belt and south to the Guangdong-Hong Kong-Macao Greater Bay Area. And is a vital node of the Pan-Pearl River Delta Region (Liu and Li, 2021) and the Maritime Silk Road (Xin et al., 2021). The impact of the COVID-19 epidemic on water quantity and water quality in Fujian Province can reveal the general dynamic changes on the southeast coast before and after the epidemic.

### 2.2. Direct WF

This research uses CROPWAT 8.0, as recommended by FAO (2022), to simulate the precipitation and evapotranspiration of water resources directly consumed by agriculture, from 2017 to 2020. Meteorological data from nine major meteorological stations are obtained from China Meteorological Data Network (2017–2020) (Fig. 1), whereas soil and crop data are obtained from CLIMWAT2.0 (FAO, 2022). Subsequently, the direct green *WF* and blue *WF* of agriculture are calculated using standard Penman models (See Equations (1)–(3), Equations (6) and (7). The green and blue WF of forestry, livestock products, and fishery are calculated according to Schyns et al. (2017), Ma et al. (2020b), and Yuan et al. (2017), respectively. The direct blue WF data of service industries related to the primary industry (D5) and sub-sectors of the secondary and tertiary industries are allocated according to the proportion of the added value of each industry in the primary, secondary, and tertiary industries, and then verify by literature research (Zhao et al., 2021b). The direct grey *WF* of the primary, secondary, and tertiary industries is estimated by referring to Hoekstra et al. (2012)(Eq. (8) - (10)). China's "Surface Water Environmental Quality Standard" (GB3838-2002) Class III water is taken as the target water source.

#### 2.2.1. Direct green WF

$DWF_{green\_agr}$ stands for direct green WF of the agricultural sector, which refers to the amount of available precipitation stored in soil consumed during plant growth, and was calculated as follows:

$$DWF_{\mathrm{green\_agr}} = 10ET_{green} / Y \tag{1}$$

$$ET_{green} = \min\left(ET_c, E_{eff}\right) \tag{2}$$

$$ET_c = K_c \cdot ET_0 \tag{3}$$

where 10 is the conversion coefficient (to convert the depth of water from mm to $m^3/hm^2$); $ET_{green}$ is the evapotranspiration of green water (mm); $Y$ is the plant yield ($t/hm^2$); $ET_c$ is the actual plant evapotranspiration (mm); $E_{eff}$ is the effective precipitation simulated by CROPWAT during plant production (mm); $K_c$ is the plant coefficient in CROPWAT simulation results; and $ET_0$ is the evapotranspiration from water resources during the plant growth period simulated by CROPWAT (mm).

The direct green WF of the forestry sector is quantified based on Schyns et al. (2017) and Yu et al. (2020b), and the main formula is as (4):

$$DWF_{green\_for} = \left(W_{green\_con} \cdot P_{con} + W_{green\_bro} \cdot P_{pro}\right) / Z_{\mathrm{log}} \tag{4}$$

$DWF_{green\_for}$ is the direct green *WF* of the forestry sector, $W_{\mathrm{green\_con}}$ and $W_{\mathrm{green\_bro}}$ are the green water per unit of coniferous logs and hardwood logs, respectively, $P_{con}$ and $P_{pro}$ are the annual productions of softwood and hardwood logs, and z is the ratio of logs to wood production.

The direct green WF accounting model for the livestock and fisheries sectors is as follows:

$$DWF_{green\_lf} = \sum_{j}^{n} W_{green\_lf,j} \cdot D_{lf,j} \tag{5}$$

$\mathrm{DWF}_{\mathrm{green\_lf}}$ is the direct green *WF* of livestock or fishery sector, $W_{green\_lf}$ is

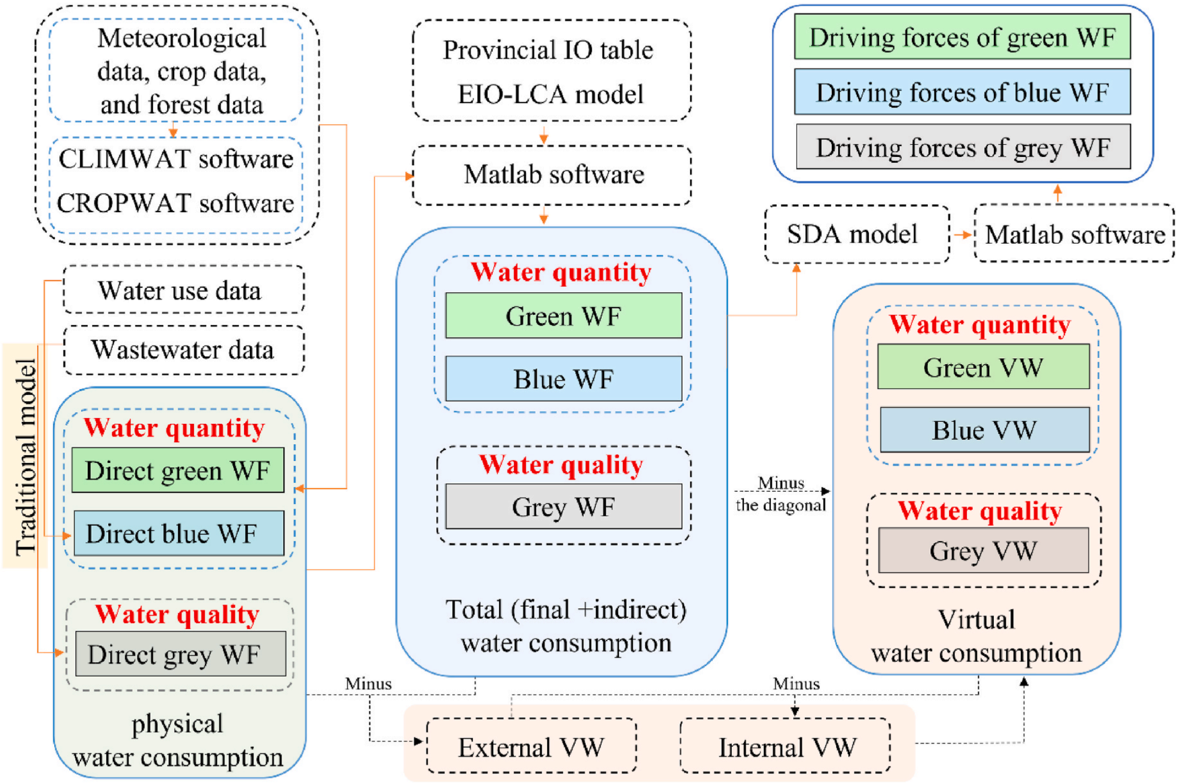

**Fig. 2.** Assessment framework of this study.

the green water consumed by one livestock j at the end of the year or of 1 kg fishery j in one year. $D_{lf,j}$ is the year-end slaughter volume of livestock j or the output of freshwater fishery j, n represents the number of species in the livestock and fisheries sector. The direct green WF of other sectors is 0.

#### 2.2.2. Direct blue WF

$DWF_{blue\_agr}$ is the direct blue WF of the agricultural sector, which refers to the sum of surface and groundwater consumed by agriculture in a given period (unit: y), it was calculated as follows:

$$DWF_{blue\_agr} = 10EF_{blue}/Y \tag{6}$$

$$ET_{blue} = \max\left(0, ET_c - E_{eff}\right) \tag{7}$$

where $ET_{blue}$ is the evapotranspiration of blue water during plant production (mm).

The accounting process for direct blue WF in the forestry, livestock, and fisheries sectors is the same as for direct green WF, see Equations (4) and (5). Due to the availability of data, we use the sector's direct water consumption as the direct blue WF of other sectors.

#### 2.2.3. Direct grey WF

$$DWF_{grey(i,j)\_non} = \frac{f_j \cdot L_{ij}}{C_{\max} - C_{nat}} \tag{8}$$

$$DWF_{grey(i,j)\_poi} = \frac{L_{ij}}{C_{\max} - C_{nat}} \tag{9}$$

$$DWF_{grey(i)} = \max\left(DWF_{i(TN)}, \mathrm{DW}F_{i(\mathrm{TP})}, DWF_{i(COD)}, DWF_{i\left(NH_4^+ - N\right)}, DWF_{i(BOD_5)}\right) \tag{10}$$

where $DWF_{grey(i,j)\_non}$ represents the *direct grey WF* from pollutants *j* in non-point source pollution department *i* ($m^3/a$), $L_{ij}$ is the discharge load of *j* pollutants in the department *i* (kg/a), $f_j$ is the river entry coefficient of pollutant j, $C_{max}$ is the standard concentration of a contaminant under a specified water quality standard (mg/L), and $C_{nat}$ is the natural background concentration of the receiving water body (mg/L). $DWF_{grey(i,j)\_poi}$ represents *the direct grey WF* from pollutants *j* in point source pollution department *i* ($m^3/a$).

### 2.3. WF based on the EIO-LCA model

$$WF = \widehat{E} \cdot (I - A)^{-1} \cdot \widehat{F} = \begin{pmatrix} \mathrm{wf}_{11} & \mathrm{wf}_{12} & \cdots & \mathrm{wf}_{130} \\ \mathrm{wf}_{21} & wf_{22} & \cdots & wf_{230} \\ \cdots & \cdots & \cdots & \cdots \\ wf_{301} & wf_{302} & \cdots & wf_{3030} \end{pmatrix}$$
$$= \begin{pmatrix} 0 & vw_{12} & \cdots & vw_{130} \\ vw_{21} & 0 & \cdots & vw_{230} \\ \cdots & \cdots & 0 & \cdots \\ vw_{301} & vw_{302} & \cdots & 0 \end{pmatrix} + \begin{pmatrix} wf_{11} & 0 & 0 & 0 \\ 0 & wf_{22} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & wf_{3030} \end{pmatrix} \tag{11}$$

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \tag{12}$$

$$E_{ij} = DWF_i / X_i \tag{13}$$

$$A_{ij} = X_{ij} / X_j \tag{14}$$

where *WF* represents the sectoral WF ($m^3$) (30 × 30), wf and vw are the elements in the WF matrix, where the elements on the diagonal represent the WF of the final product, and the elements off the diagonal represent the WF of the intermediate product (aka VW). $E/E_{ij}$ is the WF intensity ($m^3$/10,000 yuan) (30 × 1), $(I - A)^{-1}$ is the Leontief inverse matrix (30 × 30), *Y* is the sectoral final demand (30 × 1), $DWF_{ij}$ represents the direct WF of each sector (30 × 30), $X_i$ is the sectoral output (1 × 30), $X_{ij}$ is the intermediate input matrix (30 × 30), and $A_{ij}$ is the direct consumption coefficient (30 × 30), which represents the input of sector *i* required by sector *j* to increase the unit output. Finally, we remove the values on the diagonal of the WF matrix to get the VW for 30 sectors.

### 2.4. Virtual water trade

#### 2.4.1. Rapid detection of VW in and outside the province

Based on exploring changes in WF, this paper explores for the first time how to use existing data to explore the impact of emergencies on VW trade when data is insufficient. The main methods are: first, a VW matrix based on intermediate products is obtained by removing the diagonal matrix from the consumption-based final product WF matrix; second, a direct WF matrix is subtracted from the consumption-based matrix to generate a VW inflow matrix outside of Fujian Province. Finally, the VW inflow matrix outside the province is subtracted from the VW transaction matrix to obtain the VW matrix in the Fujian province. See Equation (15) - (18).

$$VW = WF - diag(WF) = \begin{pmatrix} 0 & vw_{12} & \cdots & vw_{130} \\ vw_{21} & 0 & \cdots & vw_{230} \\ \cdots & \cdots & 0 & \cdots \\ vw_{301} & vw_{302} & \cdots & 0 \end{pmatrix} \tag{15}$$

$$diag(WF) = \begin{pmatrix} wf_{11} & 0 & 0 & 0 \\ 0 & wf_{22} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & wf_{3030} \end{pmatrix} \tag{16}$$

$$VW_{ext} = WF - DWF \tag{17}$$

$$VW_{\mathrm{int}} = VW - VW_{ext} \tag{18}$$

VW refers to the VW matrix (30 × 30) contained in the intermediate products, vw is the element of the VW matrix. $VW_{ext}$ is the VW flowing into the province (including out-of-province inflows and imports), and $VW_{int}$ is the VW in the province. diag(WF) is the final product WF matrix (30 × 30), wf is the element of the final product WF matrix.

#### 2.4.2. Traditional verification of VW in and outside the province

To validate this research methodology, the VW consumed by trade (including domestic inflow, outflow, and import and export trade) outside Fujian Province is quantified. The formula is as follows:

$$VW_{\mathrm{i}} = \widehat{E}(I - A)^{-1}\mathrm{m}_{\mathrm{i}} \tag{19}$$

$VW_i$ is the extra-provincial trade vector of virtual water in sector i, including domestic inflow, outflow, import, and export, all of which are 30 × 1 vectors, $m_i$ is the domestic inflow, outflow, and import and export of VW, all of which are 30 × 1 vectors. Then, we recalculated the outer VW and the inner VW according to the traditional method to validate our results. See Equation (20) - (21).

$$VW_{ext} = VW_{im} + VW_{dom\_in} \tag{20}$$

$$VW_{\mathrm{int}} = VW - VW_{ex} - VW_{dom\_out} \tag{21}$$

$VW_{ext}$, $VW_{ext}$ represents the outer *VW* and the inner $VW_{im}$, $VW_{ex}$ are the VW of import and export respectively, $VW_{dom\_in}$, $VW_{dom\_out}$ are domestic inflows from other provinces and domestic outflows to other provinces respectively.

### 2.5. SDA analysis

Previous studies have described that the SDA decomposition technology is not unique. Generally, if there are n factors, there are n! decomposition methods. In this study, eight factors including WF intensity (E), industry structure (L), final demand structure (C), per capita final consumption expenditure (FX), per capita gross capital formation

(FZ), per capita domestic and provincial outflow (FS), per capita export (FE), and resident population (P) were selected. To obtain more accurate results, the bipolar decomposition method was selected to obtain the average value of various decomposition methods (Zhao et al., 2021). Equations (22)-(38) represent the two-factor bipolar decomposition.

$$Q = E\cdot(I-A)^{-1}\cdot Y = E\cdot L\cdot(FX+FZ+FS+FE) = E\cdot L\cdot C\cdot P\cdot(FX+FZ+FS+FE) \tag{22}$$

$$\triangle E = E_1 - E_0 \tag{23}$$

$$\triangle L = L_1 - L_0 \tag{24}$$

$$\triangle C = C_1 - C_0 \tag{25}$$

$$\triangle P = P_1 - P_0 \tag{26}$$

$$\triangle FX = FX_1 - FX_0 \tag{27}$$

$$\triangle FZ = FZ_1 - FZ_0 \tag{28}$$

$$\triangle FS = FS_1 - FS_0 \tag{29}$$

$$\triangle FE = FE_1 - FE_0 \tag{30}$$

$$QE = \frac{1}{2}(\triangle E\cdot L_0\cdot C_0\cdot P_0\cdot(FX_0+FZ_0+FS_0+FE_0)+\triangle E\cdot L_1\cdot C_1\cdot P_1\cdot(FX_1+FZ_1+FS_1+FE_1)) \tag{31}$$

$$QL = \frac{1}{2}(E_0\cdot\triangle L\cdot C_0\cdot P_0\cdot(FX_0+FZ_0+FS_0+FE_0)+E_1\cdot\triangle L\cdot C_1\cdot P_1\cdot(FX_1+FZ_1+FS_1+FE_1)) \tag{32}$$

$$QC = \frac{1}{2}(E_0\cdot L_0\cdot\triangle C\cdot P_0\cdot(FX_0+FZ_0+FS_0+FE_0)+E_1\cdot L_1\cdot\triangle C\cdot P_1\cdot(FX_1+FZ_1+FS_1+FE_1)) \tag{33}$$

$$QP = \frac{1}{2}(E_0\cdot L_0\cdot C_0\cdot\triangle P\cdot(FX_0+FZ_0+FS_0+FE_0)+E_1\cdot L_1\cdot C_1\cdot\triangle P\cdot(FX_1+FZ_1+FS_1+FE_1)) \tag{34}$$

$$QFX = \frac{1}{2}(E_0\cdot L_0\cdot C_0\cdot P_0\cdot\triangle FX+E_1\cdot L_1\cdot C_1\cdot P_1\cdot\triangle FX) \tag{35}$$

$$QFZ = \frac{1}{2}(E_0\cdot L_0\cdot C_0\cdot P_0\cdot\triangle FZ+E_1\cdot L_1\cdot C_1\cdot P_1\cdot\triangle FZ) \tag{36}$$

$$QFS = \frac{1}{2}(E_0\cdot L_0\cdot C_0\cdot P_0\cdot\triangle FS+E_1\cdot L_1\cdot C_1\cdot P_1\cdot\triangle FS) \tag{37}$$

$$QFE = \frac{1}{2}(E_0\cdot L_0\cdot C_0\cdot P_0\cdot\triangle FE+E_1\cdot L_1\cdot C_1\cdot P_1\cdot\triangle FE) \tag{38}$$

In these equations, $\triangle E$, $\triangle L$, $\triangle C$, $\triangle P$, $\triangle FX$, $\triangle FZ$, $\triangle FS$, and $\triangle FE$ represent the change of each factor from the beginning of year 0 to the end of year 1, and *QE, QL, QC, QP, QFX, QFZ, QFS,* and *QFE* represent the results after the two-stage decomposition, that is, the contribution of the driving factors to the WF change.

### 2.6. Data and variables

According to the national industry classification standard GB/T4754-2017, the 142 sectors from the 2017 input-output table were merged into 30 sectors (Supplement Table 1). Subsequently, GAMS software was used to compile the input-output tables for 2018–2020. Concretely: according to the technical coefficient in 2017 and the total output in 2018–2020, constructed a temporary intermediate input-output table, and then used RAS technology to iterate until it matches the actual value (Jackson and Murray, 2010). Considering the impact of technology and COVID-19 containment on the structure of intermediate inputs, the intermediate input ratio of the primary industry sector, the secondary industry sector, and the tertiary industry sector at current prices caused to correct by row, and the intermediate input ratio comes from China Statistics Press (2019–2021), Fujian Provincial Bureau of Statistics (2019–2021), National Bureau of Statistics of China (2019–2021). Finally, the price index of each department from 2017 to 2019 was obtained, and the input-output table of comparable prices was constructed using 2020 as the base year (Yu et al., 2022). The water consumption data for 2017–2020 were obtained mainly from the Fujian Provincial Water Resources Bulletin (Fujian Provincial Department of Water Resources, 2017–2020). The water consumption of "service products of agriculture, forest, livestock, and fishery" was captured by subtracting the water consumption of the primary industry from that of agriculture, forestry products, livestock, and fishery. Sewage data was collected from the Fujian Statistical Yearbook (2018–2021) (Fujian Provincial Bureau of Statistics, 2019–2021) and China Environmental Statistical Yearbook (2018–2020) (National Bureau of Statistics of China, 2019–2021), and they included five major pollutants: total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), ammonia nitrogen ($NH_4^+$-N), 5-day biological oxygen demand ($BOD_5$). This paper is based on three assumptions: (1) All economic sectors are assumed to produce pollution; (2) The price index of all goods produced in the same sector is the same; (3) Water intensity per unit currency outside the province (both domestic and foreign) is the same as that of Fujian Province. The main framework of this paper is shown in Fig. 2.

## 3. Results and discussion

Through different mathematical model tests, field investigations, and literature comparisons, it is shown that these research methods are stable and the results are more consistent with the water consumption reality in Fujian Province (Zhang et al., 2019; China Statistics Press, 2017).

### 3.1. The COVID-19 lockdown makes the consumption of green and blue WF paid outside the province more unsustainable

Before the COVID-19 lockdown (2017–2019), the direct *green* and *blue* WF show a fluctuating decrease (0.87 Gm$^3$,- 2.3%), indicating that the local physical water consumption decreased (Supplementary Table 2 and Fig. 3A). The green and blue VW swelled by 1.1 Gm$^3$ (2.1%). The green and blue WF indicate a fluctuating upward (0.1 Gm$^3$, 0.2%) (Fig. 4B). Figs. 3 and 4 depict the local physical water consumption is decreasing, but the VW consumption is increasing, leading to an increase in total water consumption. This is consistent with the study by Zhao et al. (2021b) and Xiong et al. (2020). The decrease in physical water consumption is closely related to the reduction of agricultural water consumption (Fig. 3) and the increase of VW consumption in the secondary industry (Fig. 4G1-G2). First, the primary industry is the sector with the largest water consumption, accounting for more than 80% on average (Fig. 3C), and agriculture is the sector with the largest water consumption (Fig. 3B–D). However, with the rapid development of urbanization, the encroachment of non-agricultural land on agricultural land and the reduction of the area of high water-consuming crops lead to a decrease in local physical water use (Cao et al., 2007). Second, with the formation of supply chain globalization, Fujian Province has given full play to the strategic advantages of the Maritime Silk Road and the Hercynian Economic Zone, featuring logistics outsourcing and product processing outsourcing, actively developing the secondary industry, and participating in global supply chain cooperation, leading to an increase in dependence on water resources outside the province. For instance,

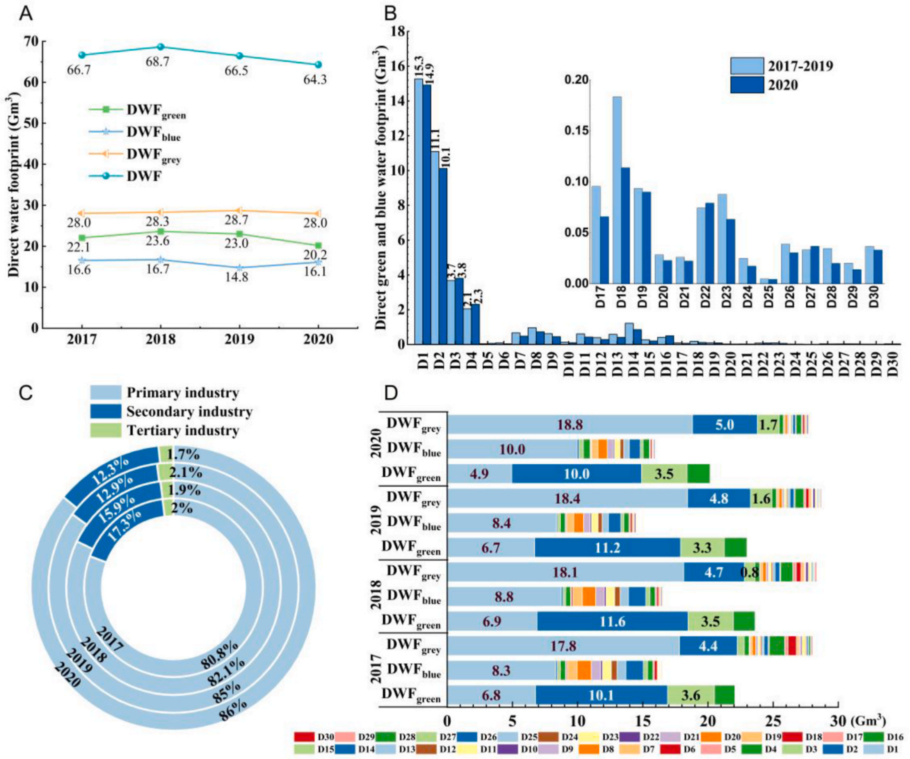

**Fig. 3.** Direct Water footprint (WF) dynamics before and after COVID-19.

From 2017 to 2019, about 41.9% (28.1 Gm$^3$) of VW (green + blue) in the WF (green + blue) comes from outside Fujian Province (external VW) (Zhao et al., 2019b), VW from out-of-province payments up 3.4% over three years.

In contrast, after the lockdown, the direct WF (green + blue) dropped by 2.6 Gm$^3$ (−6.7%), similarly, the *green* and *blue WF* decreased (3.3 Gm$^3$, -4.9%), blue and green VW down by 2.3 Gm$^3$ (−4.5%). This illustrates that the total, virtual, and physical water consumption fell. That said, the lockdown resulted in a reduction in local physical and virtual water consumption. By further comparing direct WF, VW, and WF (Figs. 3–4 and Supplement Tables 2-3), we discover that while both external and internal VW and local end product consumption declined, by 2.5%, 6.9%, and 6.4% respectively, the share of external VW in total WF was higher (1.1%) than before the lockdown. Therefore, increased external dependence on water consumption is considered a consequence of the blockade. On the one hand, the blockade hit the international supply chain hard, but it stimulated a strong domestic supply chain (i.e., domestic inflow after the blockade was 2.3 times that of imports, an increase of 10% compared with before). This is also supported by evidence from the Fuzhou Bureau of Statistics in 2020, as imports of goods trade in Fujian fell by 0.7%. On the other hand, the lockdown restricts the production activities of most sectors of the secondary and tertiary industries (especially "Transportation, warehousing, and postal services", whose proportion has decreased by more than doubled) (Fig. 4E–F), but encourages some sectors to switch to the production of masks. And the raw materials of the masks are mainly from Jiangsu Province, which has greatly increased the proportion of VW in the "Timber, paper, sports, and cultural and educational supplies" department (Fujian Provincial Development and Reform Commission, 2020). In addition, the lockdown has fewer restrictions on the production of daily necessities, resulting in a 3% increase in VW in the proportion of "Food and tobacco". Although the fact that the dependence of agriculture on foreign countries is increasing year by year cannot be changed, the industries most affected are mainly concentrated in the secondary industry with the longest industrial chain and strong export orientation. Switching to mask production is bound to increase Fujian's dependence on external water resources.

Such a trade model resulted in a year-on-year decrease in local physical water consumption before the COVID-19 lockdown, while external VW consumption increased year-on-year. After the COVID-19 blockade, the consumption pattern of a long-term dependence on external water resources has been exacerbated. This trading pattern is both beneficial and detrimental to Fujian Province. For example, such a pattern protects green and blue water resources in Fujian Province to a certain extent but increases water security risks. At the same time, it also raises the pressure on China's water resources. Such as, more than 50% of Fujian's VW originates from other regions (Hua et al., 2021), e.g. Northwest regions (Zhang and Anadon, 2014) especially in Xinjiang (Xin et al., 2022; Zhao et al., 2019b), and central regions (Zhao et al., 2015).

Although this trade model lessens the physical water consumption in Fujian Province (Dong et al., 2019), at the same time, because more than half of the VW comes from water-deficient areas, it will undoubtedly enlarge the pressure on China's water resources, which is not conducive to the sustainable development of China's water resources. It can be hypothesized that by taking full advantage of the intra-provincial sectoral trade, which accounts for roughly 50%, Fujian's external VW may be shortened through it. For example, energetically expand green water-intensive sectors in the province, and reduce the physical water consumption of blue water-intensive sectors by boosting the intermediate input of green water-intensive products (Zhao et al., 2021b). However, the green water-intensive sectors are mainly concentrated in the primary industry, and the economic rewards are not high, so they need government bolster (Dong et al., 2019). Furthermore, it must be noted that the blockade increased the proportion of blue VW and blue WF, while decreasing the proportion of green VW and green WF (Fig. 4C–D). However, blue water resources are currently the most scarce water resources, which undoubtedly increases the water pressure on China's blue water resources.

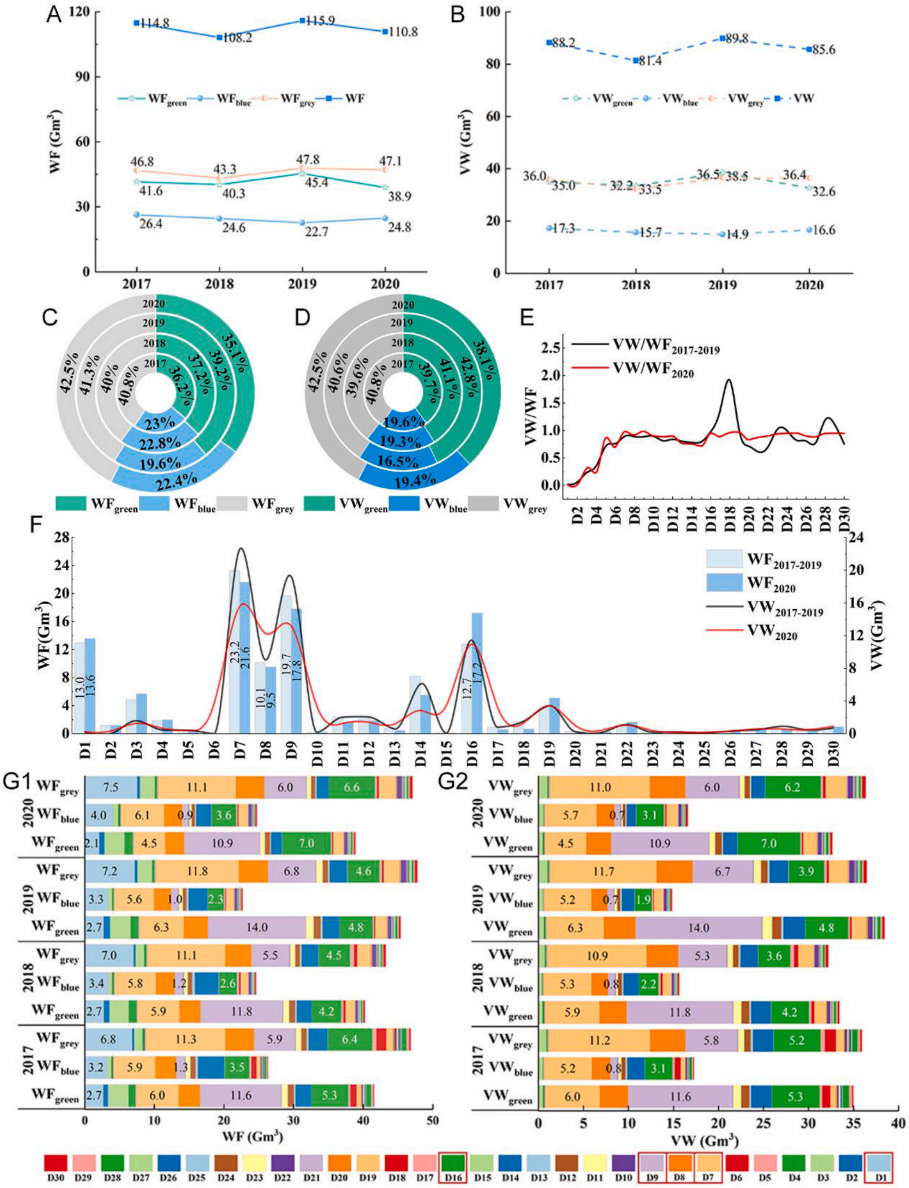

**Fig. 4.** Changes in water footprint and virtual water.

### 3.2. The COVID-19 lockdown promotes a shift in grey WF consumption patterns for local payments

Similarly, before the blockade, the direct *grey WF* show a fluctuating increase (0.7 $Gm^3$, 2.4%), indicating that the physical water quality deteriorates (Fig. 3A). The grey VW increased by 1.6 $Gm^3$ (1.8%). And *grey* WF indicates a fluctuating upward (9.8 $Gm^3$, 2.1%) (Supplement Table 2 and Fig. 2A). In a word, physical water pollution increased, virtual pollution increased, and the total water quality decreased. This is consistent with the conclusions of Ma et al. (2020a), who generally believe that there is serious water pollution in Fujian Province. The main reason for the decline in the quality of the local water environment was the increase in the amount of sewage discharged by the two major polluters, agriculture and forestry. From 2017 to 2019, the three-year pollutant discharge increased by 3.4%, and 9.1% respectively. This change is not unrelated to the adjustment of dietary structure brought about by rapid economic development (Yu et al., 2022).

After the lockdown, compared with 2019, the direct grey WF, grey VW, and grey WF all decreased slightly by 0.7 $Gm^3$, 0.1 $Gm^3$, and 0.7 $Gm^3$, respectively. Contrary to the pre-containment, the physical, total, and virtual water quality slightly improve, this is confirmed by the Fujian Provincial Department of Water Resources (2017–2020). But compared with the three-year (2017–2019) average, the direct grey WF decreased significantly (0.4 $Gm^3$, -1.3%), and grey VW (1.5 $Gm^3$, 4.3%) and grey WF (1.2 $Gm^3$, 2.5%) showed an upward trend. It shows that reducing human activities can rapidly advance water quality and provide an idea for future water resources management. As studied by Graham et al. (2020), economies around the world are increasingly relying on the import of VW, and the epidemic has accelerated the outsourcing of virtual pollution in Fujian Province, which is of great help for Fujian Province to improve its water quality. The pollution pattern that most of the pollution in Fujian has to be paid for by itself (about 60%) is about to change.

like Liao et al. (2019) and Zhao et al. (2021a), the authors find that the primary industry is the industry with the largest direct discharge of sewage (average of 60% of the total WF) in Fujian Province (Supplement Table 2, Fig. 3). While the tertiary industry is generally an industry that consumes physical water, and most of the sewage it discharges (more than 90%) is local (Supplementary Table 2 and Fig. 3), which has been greatly affected by the blockade. For example, online teaching brought

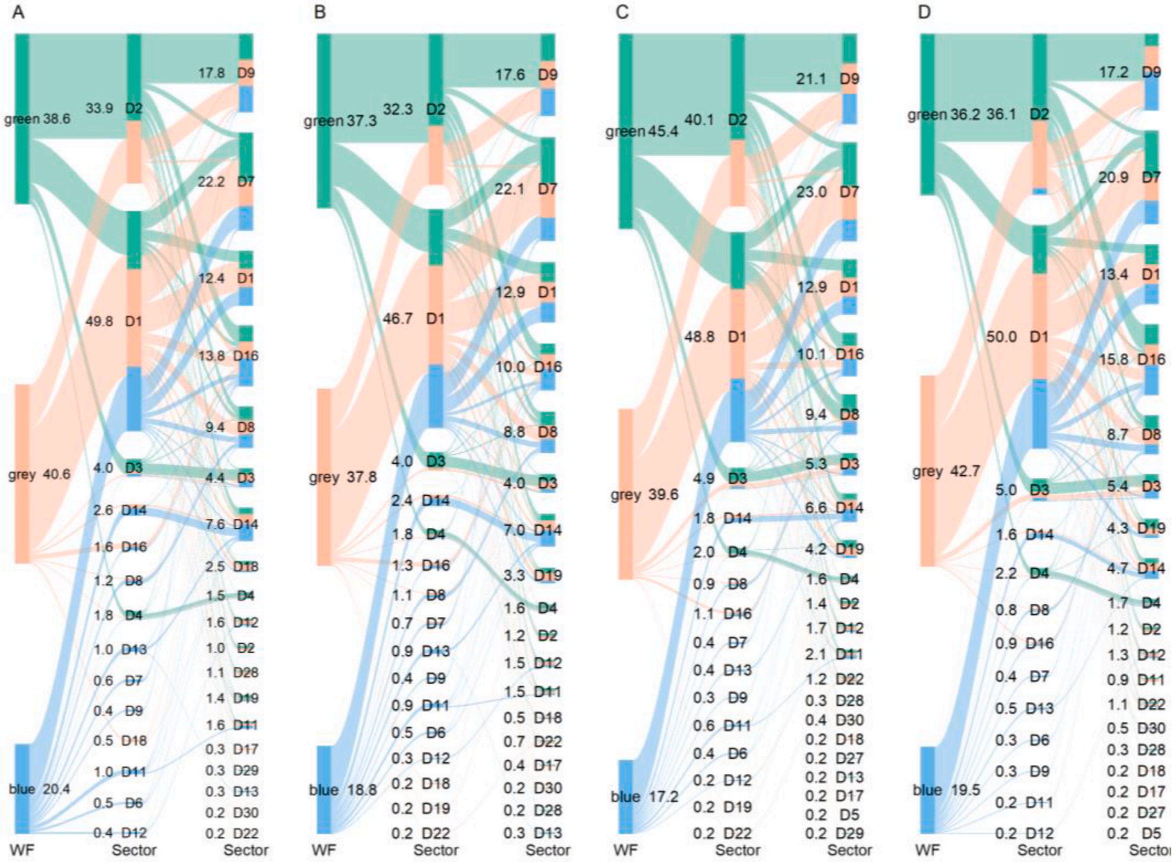

**Fig. 5.** Sectoral flow of water footprint in Fujian Province (unit: $Gm^3$).

about by the lockdown has reduced the education sector's direct grey WF by more than 30%. In addition, as various sectors of the secondary industry are closely integrated with the supply chain (Xin et al., 2022), the grey VW is rather substantial (80% of the total grey WF on average) (Fig. 5). Further, under strict emission restrictions, the direct grey WF is generally small (5.4% on average) (Supplementary Table 2 and Fig. 3). Therefore, secondary sectors in Fujian have modest contributions to local water pollution, and the agriculture, forestry, and animal husbandry sectors of the primary industry have become the main physical source of pollution. Fig. 5 demonstrates that the crucial direct source of grey *WF* in the four years is "Timber, paper, sports, and cultural and educational supplies", "Food and tobacco" and "agriculture", "Construction". Control measures have the greatest impact on the grey WF of the "Timber, paper, sports, and cultural and educational supplies". This is a key measure for the rapid improvement of physical and total water quality after containment. It can be seen that the COVID-19 lockdown has rapidly improved water quality. Therefore, the government should focus on the physical discharge of grey WF in these sectors, formulate corresponding standards and rules for direct sewage discharge, and conduct human intervention to quickly control pollution.

Additionally, it should see that the consumption pattern of locally paid grey WF makes water pollution in Fujian Province increasingly worse (Cai et al., 2020; Ma et al., 2020a). After a short period of water quality improvement, Fujian will face a continuous decline in water quality. Physical water quality management is still the focus of sustainable implementation of water resources in the province.

### 3.3. *Water management in the post-epidemic era requires more technological improvements*

Although obtaining the supply of WF through sectoral trade is the most common way to reduce physical water consumption at present, a serious consequence of this is the high degree of external dependence, which cannot guarantee the security of regional water resources. Therefore, it is crucial to explore the socio-economic drivers of regional WF changes from the region and within the industry. Before the COVID-19 lockdown, Fig. 6 exhibits that, technology (QE) is the main driver of increasing green WF and decreasing blue and grey WF. After the lockdown, technologies (QE) are the key drivers for increasing total blue, and grey WF (2.1 $Gm^3$, 1.7 $Gm^3$, 3.5 $Gm^3$) and decreasing green WF (−4 $Gm^3$). The influence of technology on reducing WF is not significant. Increasing investment in technology remains an important measure for reducing physical WF in Fujian(Cai et al., 2020). The final demand structure (QC) is an important driving force for the surge of total and grey WF before the epidemic and the reduction after the epidemic. Moreover, the effect of the final demand structure (QC) on WF reduction has surpassed technological progress and has become the main driver of water footprint reduction after the lockdown. This is likely to be related to changes in the consumption structure during the lockdown period. Lockdowns have reduced the out-of-province demand for water-intensive meat, dairy, and other foods. Zhao et al. (2021b) also believe that with the improvement of living standards, the demand for services and high-tech products that require less water will increase.

Per capita gross capital formation (QFZ) has been the main positive driver for the increase in green WF, blue WF, grey WF, and total WF. It shows that the local economy is in a stage of rapid development, and WF consumption will continue to increase in the future. Per capita domestic and provincial outflow (QFS), per capita final consumption expenditure (QFX) are all the pivotal drivers of the growth in the WF before the blockade and the shrink after the blockade (Fig. 6). This is related to Fujian's position in the global supply chain and its industrial structure.

For instance, Fig. 7 displays that, before the lockdown, per capita

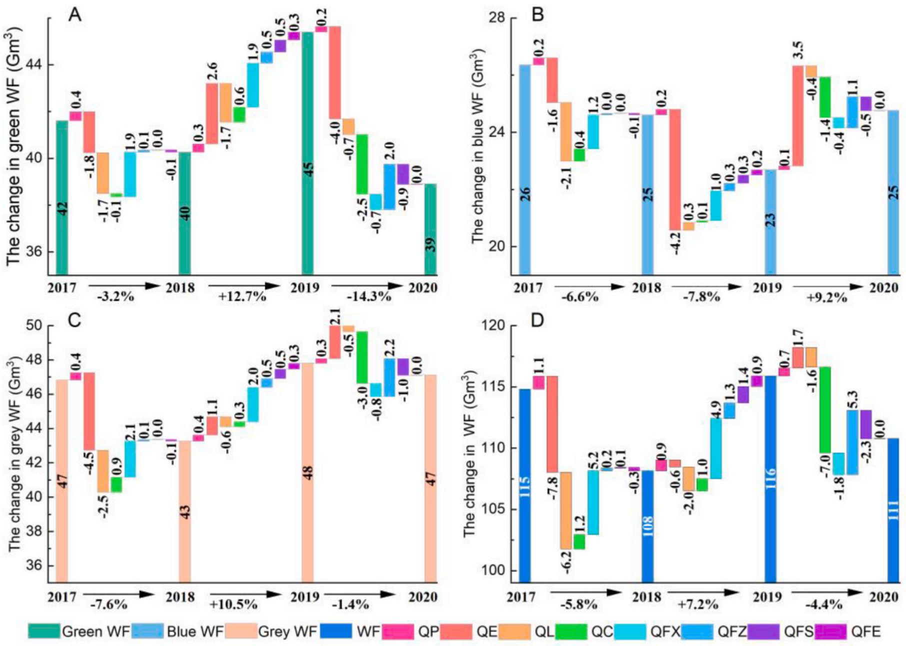

**Fig. 6.** Changes in *green*, *blue*, and *grey* WF in 2017, 2018, 2019, and 2020(*QP* = population; *QE* = direct water footprint intensity; *QL* = industry structure; *QC* = final demand structure; *QFX* = per capita final consumption expenditure; *QFZ* = per capita gross capital formation; *QFS* = per capita domestic and provincial outflow; *QFE* = per capita export).

export (QFE) is a positive driver for increasing “Food and tobacco”, “Textile, clothing, and shoes”, “Timber, paper, sports, and cultural and educational supplies” sectoral WF, and after the epidemic, has become a negative driver of WF growth. However, the water consumption and physical pollution discharge of the output per unit of “Textile, clothing, and shoes” is far greater than that of “Machinery and equipment manufacturing”. Before the epidemic, a large number of water-intensive and pollution-intensive products such as “Textile, clothing, and shoes” are exported, resulting in more physical water pollution discharge. The blockade has disrupted global supply chains, changed the structure of trade, and the heightened export of low-water-consumption, low-pollution products has greatly reduced physical water pollution. For example, after the lockdown, the number of mask manufacturers in Fujian Province rapidly expanded from 9 to 280, becoming the main force in China’s mask supply market (Fujian Provincial Development and Reform Commission, 2020).

Before the lockdown, per capital gross capital formation is a positive driver for the increase in “Real estate” WF, and after the lockdown, it is a positive driver for the increase in “Construction” WF. This suggests that before the outbreak, basic living needs are no longer the main driver of the increase in Fujian’s WF. Higher-level demand for “Real estate” has become a positive driving force for the increase of WF in Fujian Province. This is inseparable from Fujian’s status as a hometown of overseas Chinese and the development of an export-oriented economy. Certainly, the prosperity of the real estate sector has led to the rapid development of “Construction”. Lockdown accelerates the contribution of the “Construction” to the increase in WF, making it the sector with the fastest growth in VW post-lockdown (Figs. 3 and 4). The construction sector is a sector with small physical water consumption and sewage discharge, but a large VW consumption and sewage discharge (Supplementary Table 2, Figs. 3, 4 and 6). Traditional physical water quantity and quality monitoring cannot accurately define responsibilities for water use and water pollution in such sectors. Moreover, physical water pollution control also cannot reduce the total pollution caused by the sector at the source (Yu et al., 2022). Therefore, Water management in the post-pandemic era will face more challenges. It requires changing the traditional water resources technology (Galanakis et al., 2021), letting water technology penetrate all sectors of the supply chain, affording more technical uphold to upstream sectors (Wang et al., 2021), realizing the shared responsibility of water resources consumption and pollution, and reducing the WF from the stem. In addition, if the physical WF cannot be reduced through technology, adjusting the industrial structure to reduce the physical WF is also an effective method. Specifically, comparative advantages among departments should continue to play a vital role in future water conservation practices in Fujian and China (Zhao et al., 2021b). Sectoral production needs to be regulated through comparative synergy, controlling the physical WF of upstream sectors with longer supply chains in order to provide sustainable water resources.

### 3.4. *The COVID-19 lockdowns highlight heterogeneity and imbalances in sectoral water consumption*

Fig. 5 demonstrates that the industry chain involved in the “Food and tobacco” is relatively complex, with a large income of grey VW from the agriculture sectors (Li et al., 2021). Agriculture is the largest outsourced sector, producing a large number of pollution-intensive products for the food and tobacco sector, increasing pollution in the sector and reducing wastewater discharge from the “Food and tobacco”. For industries with a long industrial chain, the impact of the COVID-19 blockade on them is very significant. For example, as shown in Fig. 4E–F, the lockdown tends to have the greatest impact on VW in the “Transportation, warehousing, and postal services”, “Food and tobacco”, “Timber, paper, sports, and cultural and educational supplies”, and “Construction”. Before the lockdown, “Construction” was already the third largest water user after “Timber, paper, sports, and cultural and educational supplies” and “Food and tobacco” water consumers (Xin et al., 2022), although with a comparatively minor quantity of sewage discharge. After the lockdown, physical water consumption increased by 21% and direct grey WF decreased by 57%, while the total WF and VW consumption increased (40%, 47%) and grey WF and VW increased (26%, 46%). The lockdown has increased the construction industry’s water volume by 41% and its grey WF by 30%. Undoubtedly, this may have been a general result of the rapid urbanization and economic development of Fujian province (Zhao et al., 2021b), but the lockdown has accelerated the shift. In addition, more than 80% of the VW comes from its upstream sector

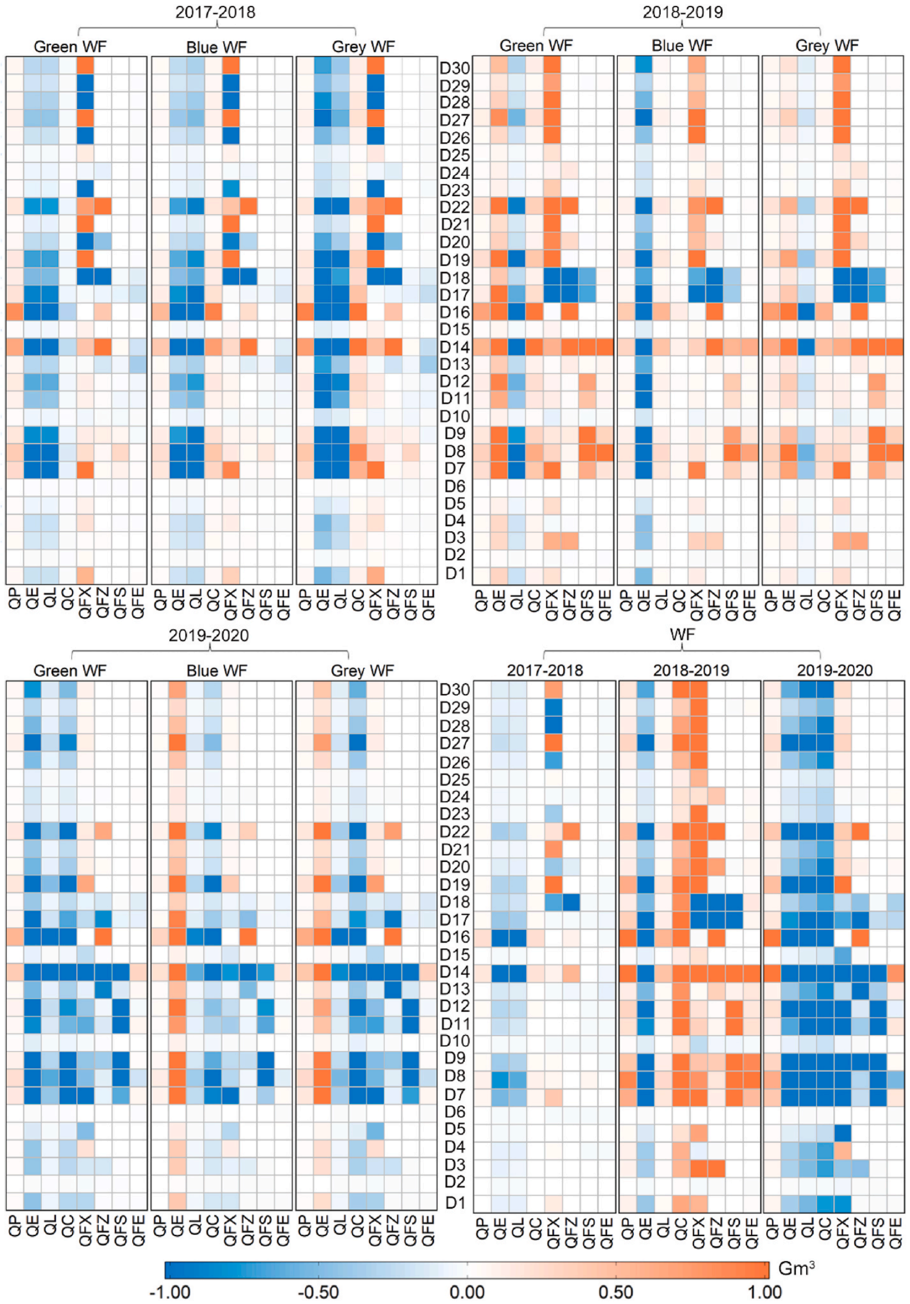

**Fig. 7.** Contribution of driving forces for WF changes in 30 sectors from 2019 to 2020 (The specific meaning of QP, QE, QL, QC, QFX, QFZ, QFS, QFE is the same as Fig. 6).

(Figs. 4 and 5), which will gain the water use pressure on the upstream sector (Yu et al., 2022). Finally, and more importantly, the "Construction" in Fujian Province is highly dependent on other regions, and nearly 50% of its output value comes from outside the province, so the lockdown has little impact on it (Fujian Provincial Department of Housing and Urban-Rural Development, 2021).

Fig. 6 shows that the socioeconomic drivers of WF change weakened by containment, but the contribution of per capita gross capital formation (QFZ) to WF increase become stronger. This also confirms that China is in a stage of economic growth driven by capital investment (Du et al., 2022). The regional economy is developing rapidly, and water consumption will increase in the future (Xiong et al., 2020). It means that if the COVID-19 epidemic continues, physical pollution in the agricultural sector may continue to increase, virtual water use and pollution in the "Construction" sector continue to rise, and the heterogeneity and imbalance in sectoral water use and sewage discharge will strengthen (See Fig. 8A).

Fig. 8A demonstrates that if the lockdown continues, the number of sectors with high water consumption will gradually increase, and the dominance of the two sectors ("Agricultural products", and "Food and tobacco") will change (the upper curve in Fig. 8A), and sectors with pollution heterogeneity will become more dispersed, and their proportion in the total number of sectors will gradually up more than 5% (The dextral curve in Fig. 8A). Fig. 8A also tells that both anthropogenic policy interventions and VW trade make increases in total water quantity increasingly correlated with deterioration in total water quality. Considering physical water use or pollution, or VW use and pollution alone does not fundamentally clarify the problem of water scarcity and water pollution. A comprehensive discussion of the quantity and quality of physical and VW is the fundamental way to fix the water problem.

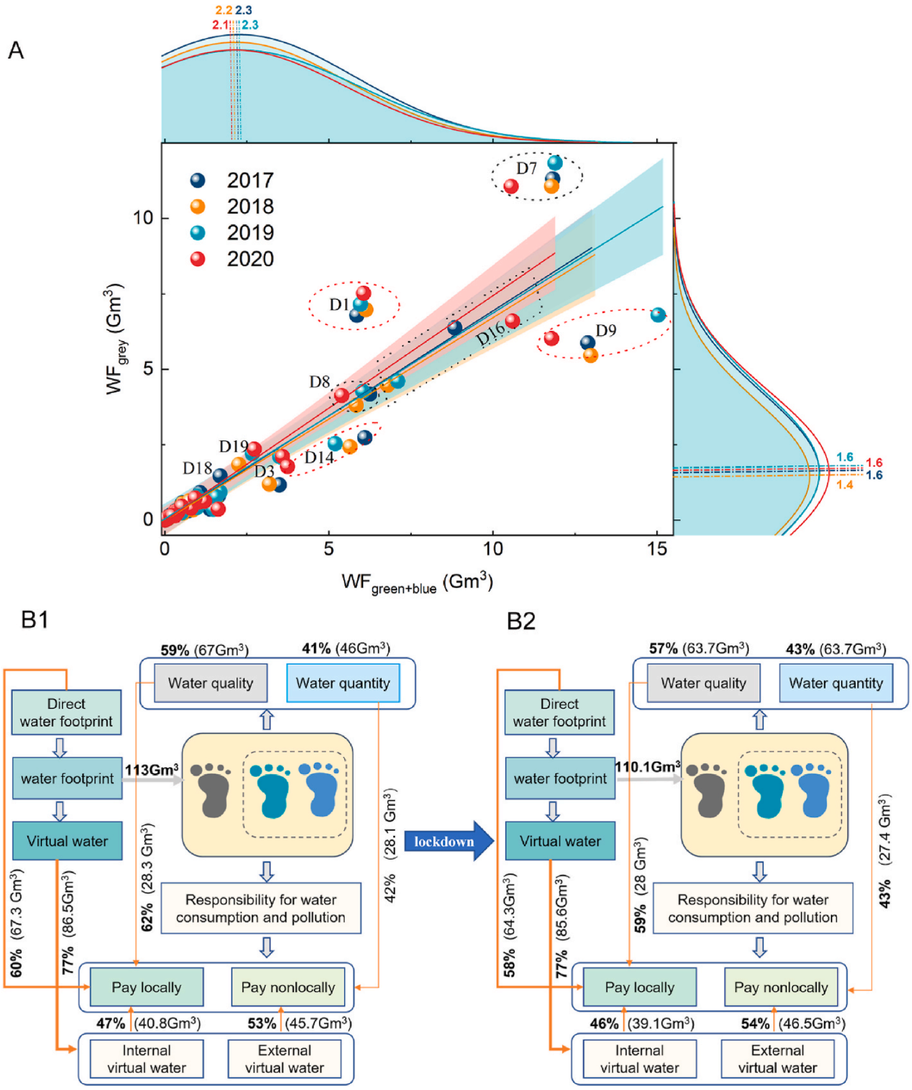

**Fig. 8.** Impact of the COVID-19 blockade on production-based and consumption-based water footprint.

From Fig. 8B1-B2, it can be seen that Fujian Province is very dependent on the external public (more than 50% before and after the closure). However, its water pollution model is still dominated by local pollution (that is, local payment, accounting for nearly 60%), which may have a lot to do with agriculture being a polluting outsourced sector. In addition, the lockdown resulted in a 4.5% drop in production-based direct WF, a 2.6% drop in consumption-based WF, and a 10.4% drop in VW. In a word, the lockdown reduces physical water use, grey WF, and improves the potential and local water quality. This gives us a message that the impact of government policy on physical, virtual, and total water consumption is huge. Therefore, it is recommended that the government should incorporate the "three red lines" and "water-saving society" into the water resources management policy and strictly implement it, to deal with the impact of extreme public events on water use and sewage discharge.

### *3.5. Strengths and limitations*

To scrutinize changes in sector total, virtual, and physical WF in response to the COVID-19 lockdown by adopting EIO-LCA and SDA model. Key sectors for water pollution ("Agriculture products", "Food and tobacco", and "Construction") and the chief sector-by-sector trade flows ("Agriculture products" to "Food and tobacco") before and after the COVID-19 pandemic are identified. Most of the pollution in Fujian Province comes from the direct discharge of sewage from the primary in the province, while most of the water consumption originates from green and blue VW outside the province. Furthermore, the socio-economic drivers behind these changes are explored. This research speculates that the province's construction and real estate sector development is highly mismatched with economic development, and gross capital formation will remain the main driver of Fujian's WF rise for a long time. Exotic green and grey VW will continue to grow. The single region input-output, could not directly display the changes in WF and VW trade between different provinces in China. But can measure external and internal VW by comparing total, virtual, and physical WF, this is a very handy algorithm (Fig. 2).

The limitations of this work should also be addressed when interpreting our findings. First, although the double-proportion balance method (RAS) is relatively mature in updating the input-output table, the intermediate input matrix is also corrected by using the proportion of intermediate input in the current year, after all, this article is an input-output table rebuilt based on the statistical yearbook data, and its data quality may affect the IO table in 2018–2020. Second, owing to the lack of data on services related to the primary industry, using the entire data of the primary industry minus the data of agriculture, forestry, animal husbandry, and fishery to compute its sector data. Existing available data may misrepresent the genuine image of the industry. Although Chinese statistics are often questioned, they are by far the most credible source of data (Zhao et al., 2019a).

With the ease of the COVID-19 era and the unblocking of international and domestic supply chains, researchers should focus on the following two aspects in the future: one is to unify the accounting standards of WF and VW, and establish a global WF and VW database to explore the impact of physical and virtual water flow on water scarcity. The second is to employ a multi-regional input-output model to explore the impact of changes in public health habits on global physical and virtual water resource consumption and transfer in the post-epidemic era, and to decompose global water security responsibilities to national, provincial, and regional industrial sectors.

## 4. Conclusion

This study presents a novel analytical perspective to explore changes and causes of the total, virtual, and physical sectoral WF caused by public emergencies such as the COVID-19 pandemic. The research demonstrates that the COVID-19 lockdown has had a significant collision on total, virtual and physical water quantity and quality. Three main conclusions may be derived from the findings:

1. The COVID-19 lockdown has greatly increased total, virtual, and physical water quality across the economy. Nonetheless, this sheds new light on improving water quality by reducing the influence of human activities on the environment. But this is an unsustainable mechanical change after all. To accomplish long-term sustainable water quality improvements, it is vital to identify the heterogeneous sectors that affect water quantity and quality, classify their total, virtual, and physical WF, and eventually build targeted strategies.
2. The COVID-19 lockdown reduced total and physical water consumption in Fujian Province, and increased the share of VW consumption, especially inflows from outside the province. A considerable amount of virtual foreign water is used in water-rich areas, which is highly unfavorable for the sustainable development of water-scarce China's water resources. From the perspective of China's water security, suggesting that the Fujian Provincial Government should increase technological investment in green water and improve its utilization efficiency, vigorously supports green water-intensive industries, and introduces policies to protect these industries so that they can be transformed into intermediate products of blue water-intensive industries through intra-provincial trade. To achieve sectoral water savings and curtail dependence on external WFs.
3. The sharing of water responsibilities between upstream and downstream sectors and reducing the external dependence on water resources in water-rich areas is vital to clarify the world's water resources problems. But this requires a lot of soft technology support, for instance, the cultivation of scientific research talents related to the water supply chain. And the simple algorithm this research proposes will be easier to grasp and generalize.
4. Vigorously promote the construction of water-saving colleges and universities, on the one hand, reduce the direct water consumption of the education sector, and on the other hand, help to drive and enhance the water-saving awareness of the people.

As the global epidemic eases, it becomes increasingly important to consider the interdependence and externalities of VW in different regions and industries. Regions and industries that import VW should take responsibility for the water environment of exporting regions and industries. The results suggest that realizing cleaner production technology should not be limited to improving water treatment technology but should also focus on reducing global water consumption and water pollution.

To achieve this, increasing the cost of water for importers and improving the management of water pollution technology in the supply chain could help to divert and consume water resources more efficiently, thereby reducing the world's water stress.

These considerations are critical since the global water crisis is becoming increasingly severe, and demand is expected to exceed the available supply in the coming decades. The use of VW can have significant impacts on water resources in different regions.

Therefore, it is crucial to adopt a holistic approach to managing water resources, taking into account the social, economic, and environmental impacts of water consumption. This can be achieved through policies and regulations that incentivize the adoption of cleaner production technologies and cooperation between regions and industries to reduce the negative externalities of water consumption.

## CRediT authorship contribution statement

**Fan Yu:** designed the study, complied the SRIO table, conducted the calculation, Formal analysis, conducted the analysis, drew the figures, all authors have participated the writing of the paper. **Yuan Wang:** designed the study, conducted the calculation, conducted the analysis, Formal analysis, all authors have participated the writing of the paper. **Xin Liu:** Formal analysis, conducted the analysis, all authors have participated the writing of the paper. **Jinru Yu:** conducted the calculation, all authors have participated the writing of the paper. **Dandan Zhao:** complied the SRIO table, Formal analysis, conducted the analysis, all authors have participated the writing of the paper. **Haijun Deng:** Formal analysis, conducted the analysis, all authors have participated the writing of the paper. **Bin Guo:** Formal analysis, conducted the analysis. **Rui Shi:** Formal analysis, conducted the analysis, all authors have participated the writing of the paper. **Bowei Wu:** drew the figures, all authors have participated the writing of the paper. **Huayang Chen:** drew the figures, all authors have participated the writing of the paper.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136696.

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