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Public perceptions of physical and virtual water in China

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HIGHLIGHTS

- Public perceptions of water use in China was investigated through online surveys.
- Most participants underestimated water use needed for varied activities.
- The public generally lacks knowledge of virtual water in daily consumed products.
- Factors impacting individual perceptions of water use are identified.
- We highlight a need of strengthening public knowledge of water use.

GRAPHICAL ABSTRACT

Public underestimated water use in China

Actual water use	2L	4L	6.5L	65L	70L	85L	115L	250L	$2500m^3$
Median of Perceived water use	2L	8L	3L	13L	20L	13L	12L	30L	$100m^3$

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ABSTRACT

Ensuring access to water is one of the United Nations' Sustainable Development Goals. Water demand management, which has emerged as an important approach to secure water supply, should be underpinned by a good understanding of how the public perceive their use of water. In this study, we investigated public perceptions of physical and virtual water in China through online surveys using the multi-level regression models (two-level models). Based on 3262 responses, we found that overall, participants underestimated water uses and differences between water uses (daily potable water of an adult, shower, toilet flushing, etc.). Most participants did not possess the knowledge of virtual water embedded in their daily consumed products. Individuals showed rather different perceptions in water use, which were affected by gender, age, education, resource and environmental attitude, water saving behaviors, water price and residential water source. In combination with previous findings in the United States, we concluded that despite different natural water endowment and socio-economic and cultural conditions, underestimation of water use is commonly shared by Chinese and Americans. This highlights a need of strengthening public knowledge of water use. The results are useful in informing policies to enhance the public's awareness of water use towards improved water demand management.

1. Introduction

Water resources are under increasing pressure in China due to population growth and socio-economic development (Zhao et al., 2015; Ma et al., 2020). Decades of economic growth in China have been enabled by increasing natural resources use including water. As per capita water resource of China is only about 1/4 of the global average

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(i.e., ~2300 m^3), water scarcity has become a major challenge to sustainable development. Much attention has been paid to agricultural water use, which comprises the largest share of total water use by far; however, given projected population growth in relatively water scarce urban areas, the Intergovernmental Panel on Climate Change (IPCC) suggested that domestic sector is the most vulnerable to water shortage among all the sectors (Bates et al., 2008). Securing domestic water supply (i.e., meeting dramatic increasing water demands from households and private and public services) is increasingly concerned because of the high social and economic impacts from unmet demands.

Between 2000 and 2019, China's domestic water use increased by 51.6%, which was much higher than the total water use (9.5%, MWRC, 2000–2019). Domestic water use accounted for 14.5% of the total water use of the nation nationally by 2019 (Fig. 1), and this share of domestic water use was much greater in large cities. For instance, domestic water use in Beijing and Tianjin represents 45% and 26% of the total water use, respectively. Nearly 300 of 655 cities in China have suffered from insufficient water supplies, and 110 have been subject to severe water shortages (Jiang, 2009). Recognizing that natural water availability is not always able to meet ever increasing demands, demand management has emerged as an important approach that complements traditional supply-driven management (Savenije, 2002; Rogers et al., 2002). Because poor water resources management often leads to inefficient water use and allocation, water conflict may be intensified by poor management (Jiang, 2009). This underlines the role of using different technological and management measures to reduce water demand in sustainable water management.

Water demand management offers the cheapest form of water availability, particularly in regions where water resources exploitation has already stretched to its limit (Sharma and Vairavamoorthy, 2009). Effective water demand management should be underpinned by a good understanding of how public perceive and use water (Beal et al., 2013; Jones et al., 2010; Jorgensen et al., 2009; Benhangi et al., 2020). Previous studies showed that communities with water meters generally use less water than those without meters (Vugt, 1999), revealing that one of the major barriers of conserving water is lack of understanding how much water that customers use. Because water-saving attitudes and behaviors depend on public awareness of water availability, use and crisis (Hassell and Cary, 2014), improving public perceptions of water use may drive water conservation (Vugt, 1999; Corral-Verdugo et al., 2002; Attari, 2014; Fan et al., 2014). However, public perceptions of water use often mismatched with actual water use (Beal et al., 2013). For instance, Fan et al. (2014) found that a majority of people had misperceptions on water use. A previous study has provided valuable information about perceptions of water use and their determinants in the United States (Attari, 2014), but there is still a lack of understanding of how people perceive water use in China, given rather different natural water endowment and socio-economic and cultural conditions from the United States.

The water used throughout the production process of a good is referred to as virtual water (Allan, 1993, 1994; Hoekstra and Mekonnen, 2012). Virtual water provides a basis for assessing the impact of a good on freshwater systems and thus is an important concept that can be useful in formulating strategies to reduce those impacts (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2007; Konar et al., 2016; Sun et al., 2017). Virtual water embedded in food consumed by one person in China was estimated over 17 times the household direct water use (Liu and Savenije, 2008). The increasing food demand due to population growth and shift in dietary patterns is predicted to further intensify pressure on water resources (Yang and Cui, 2014). Consumers may contribute to capping human water use in a sustainable limit by reducing their water footprint (i.e., virtual water embedded in all the products that they choose to consume). Lacking awareness of direct and indirect water uses in the production of varied goods will lead to failure to conserve water from perspectives of traders and end consumers. Nonetheless, the public seems to know little about virtual water constituting the food and other products that they rely on in their daily lives (Vanham et al., 2017). Attari (2014) made a first attempt to examine the public's perceptions of virtual water, and found that American citizens were unable to correctly rank the magnitude of virtual water embedded in different foods. Thus far, it has not been studied to what extent Chinese people have knowledge of virtual water in the supply chain.

To bridge the above gaps, we explore public perceptions of water use in China through online surveys. The concern with public perceptions encompass the physical and virtual water, and we seek to address the three questions: i) To what extent do Chinese people over- or underestimate water uses that are common in their daily life? ii) To what extent are people aware of virtual water embedded in their daily consumed food? iii) What are the key factors influencing perceptions of physical and virtual water? In comparison to an American study, our findings reveal the difference or similarity in perceptions of water use in societies of rather different natural, socio-economic and cultural backgrounds. The results are useful in informing water demand management policies to encourage wise use of water by public.

2. Materials, data and methodology

2.1. Survey materials

A survey aiming at understanding Chinese people's perception of water use and virtual water content was distributed online. In the

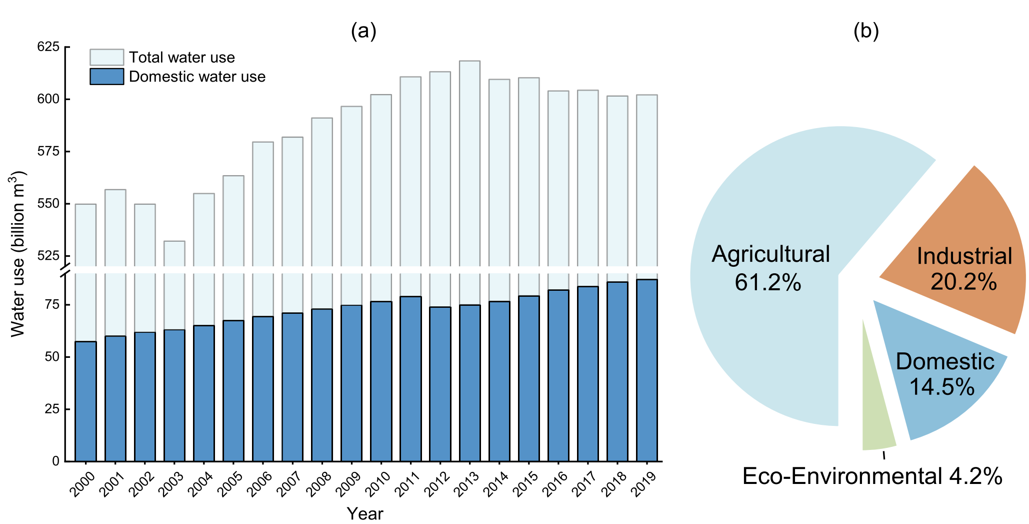

Fig. 1. China's water use trends and structure: (a) water use between 2000 and 2019; and (b) water use structure in 2019.

survey, the participants were asked to estimate 9 end uses of water in their common life (i.e., one-day potable water of an adult, 10-minute shower, bath, leakage from a leaking faucet, standard-flow toilet flushing, washing one load of clothes with standard and efficient washing machines, car washing, and filling an Olympic-sized swimming pool). Estimates of most water uses were given in liters except the last one in cubic meters. Next, participants were asked to rank virtual water embedded in 6 agricultural and livestock products that they consume daily (i.e., 1 kg of rice, wheat, beef, chicken, tea and milk). These 9 water end uses and 6 products in this survey were selected based on a previous study in the United States (Attari, 2014). In the meantime, we considered dissimilar water end uses and dietary habits of Chinese and Americans in the selection. For instance, here we excluded garden hose water use in the American study, as this is not a common practice in households of China. Because most middle-aged and elderly Chinese people are not used to drink coffee, we replaced coffee with tea, which is a traditional, popular beverage in China. China is the largest producer and consumer of tea in the world, with the production and consumption of tea comprising ~43% and ~39% of the world total (FAO, 2018); in contrast, production and consumption of coffee in China account for only ~1% and ~2% of the world total (USDA, 2021). The survey also included questions on socio-demographics, environmental attitudes and other relevant information that may impact water use perceptions. These questions were mostly based on stated choices. The quality of responses to the survey was controlled by asking participants one simple arithmetic test question (i.e., 25–7 = ___?). On completion, each participant received 0.1–10 RMB in random. Informed consent of all the participants was received. The complete survey can be found in Supplementary Information.

2.2. Participants

We distributed the survey on a commercial survey platform (www.wjx.com) that is freely accessible. Between 2nd December 2020 and 28th January 2021, we collected 3448 completed surveys, but 186 of them failed to provide a correct answer to the question for quality control (i.e., 25–7 = ___?). After excluding the surveys that failed in quality control, effective responses from 3262 Chinese citizens were considered for analysis of perceptions of physical and virtual water. Among these participants in our final samples, 59.3% were female (in comparison to 48.8% females of the Chinese population). The median age of the participants was 28 years, in comparison to the median age of 37 years in China. The median family income was between 10,000–20,000 RMB, and the median education level was college degree. The median family size was three people, which was the most common family size when the "one child policy" was implemented between 1980s–2000s in China. The samples covered all age groups (between 18 and 70), education levels, household income ranges and occupations. All the provincial-level administrative regions in the mainland of China were covered by the respondents (Supplementary Information Fig. S1). The samples are therefore considered overall representative here. Tap water was reported as the main residential water source (93.7%, in comparison to private wells 18.4%, and rivers or lakes 8.6%, noting that water may come from more than one sources, Fig. 2). 15.8% participants were not aware of how much they pay for per unit water use. Domestic water price in China was mostly between 2.0 and 5.0 RMB/m^3 (Supplementary Information Fig. S2). Participants were asked a few questions on their resource and environmental attitude and water-saving behaviors. The answer to each question was scaled to a score in a range between 0 and 1, and the mean of the scores corresponding to different questions is used to quantify participants' resource and environmental attitude and water-saving behaviors (see Supplementary Information for more details).

2.3. Multi-level regression model

The multi-level regression model is an extension of regression in which data are structured in groups (Gelman and Hill, 2007). By allowing regression coefficients to vary by group (estimates of 9 end water uses from each participant are considered as a group here), the multi-level regression model is able to address differences in the accuracy of perceptions by individuals in this study. A multi-level regression model was used in this study to examine the relationship between participants' perceptions of water use and actual water use, following a

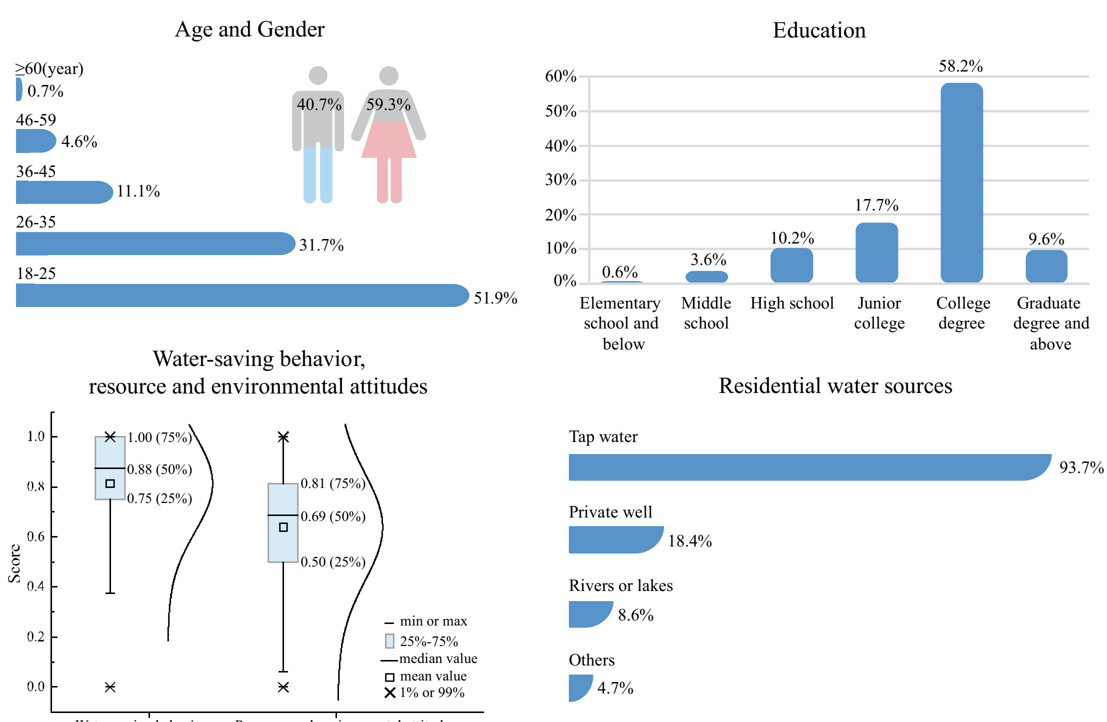

Fig. 2. Demographic statistics of participants and selected properties in the survey of water use perceptions ($n = 3262$, see Supplementary Information for relevant questions in the survey).

previous study (Attari, 2014). Actual water use was estimated based on best evidence from multi-sourced information (see Supporting Information for estimates of actual water use). The perceived water use can be written as a function of the actual water use, based on logarithmic converted values:

$$\log_{10}Perception_{ij} = \beta_{0j} + \beta_{1j}\log_{10}Actual_i + \beta_{2j}(\log_{10}Actual_i)^2 + r_{ij} \quad (1)$$

where *Perception* and *Actual* denote perceived and actual water uses, respectively, i and j represent end use of water and participants, respectively, β_{0j}, β_{1j} and β_{2j} are regression parameters, and r_{ij} is random error. This is the level-1 regression model allowing each participant to have a specific model with β_{0j} and β_{1j}. The quadratic effect is assumed fixed so that parameter β_{2j} is the same for all the participants. Letting the values of $\log_{10}Perception$ and $\log_{10}Actual$ be centered to the mean of $\log_{10}Actual$ in Eq. (1), the intercept β_{0j} indicates overestimation (a positive value) or underestimation (a negative value) for the mean $\log_{10}Actual$. The slope β_{1j} indicates sensitivity of perceptions to difference in actual water uses, and the quadratic coefficient β_{2j} indicates the curvature in that relationship. The accuracy of participants' perceptions of water use can be assessed through the estimates of above parameters. If the perceptions of water use are completely accurate, there is $y = x$, where $\beta_{0j} = 0$, $\beta_{1j} = 1$, and $\beta_{2j} = 0$.

Based on Eq. (1) that allows each participant to have their specific β_{0j} and β_{1j} values, the level-2 regression model is used to investigate the deviation of parameters from their average estimates:

$$\log_{10}Perception_{ij} = \left(\gamma_{00} + \mu_{0j}\right) + \left(\gamma_{10} + \mu_{1j}\right)\log_{10}Actual_i + \gamma_{20}(\log_{10}Actual_i)^2 + r_{ij}$$

$$\beta_{0j} = \gamma_{00} + \mu_{0j}$$

$$\beta_{1j} = \gamma_{10} + \mu_{1j}$$

$$\beta_{2j} = \gamma_{20} \quad (2)$$

where γ_{00}, γ_{10}, and γ_{20} are the average estimates of intercept, slope and quadratic coefficient, respectively, μ_{0j} and μ_{1j} characterize corresponding individually different effects.

In addition, in order to examine individual differences in perceptions of water use in detail, a number of grand-mean centered variables were considered as predictors that may explain variations of μ_{0j} and μ_{1j} in Eq. (2). The extended level-2 regression model is:

$$\log_{10}Perception_{ij} = \left(\gamma_{00} + \sum_{k=1}^{n}\gamma_{0k}z_{kj} + \mu_{0j}\right) + \left(\gamma_{10} + \sum_{k=1}^{n}\gamma_{1k}z_{kj} + \mu_{1j}\right)\log_{10}Actual_i + \gamma_{20}(\log_{10}Actual_i)^2 + r_{ij}$$

$$\beta_{0j} = \gamma_{00} + \sum_{k=1}^{n}\gamma_{0k}z_{kj} + \mu_{0j}$$

$$\beta_{1j} = \gamma_{10} + \sum_{k=1}^{n}\gamma_{1k}z_{kj} + \mu_{1j}$$

$$\beta_{2j} = \gamma_{20} \quad (3)$$

where z_{ks} are predictors of the regression model, n is the number of predictors. γ_{0k} and γ_{1k} are the average regression coefficients of z_{kj} on the intercept and slope, respectively. Where *zks* are predictors of the regression model, including gender, age, household size, education, income, residential water source, water price, resource and environmental attitudes, water-saving behavior and occupation here, n is the number of predictors, which is 10 in this regression for perceptions of water use. The effects of different socio-demographic and other factors on the accuracy of perceptions of water use can be analyzed through the estimates of their corresponding parameters. In the case of a predictor not characterized by numerical values, descriptive properties are assigned numerical values in the regression. For instance, being male and female are assigned values of 0 and 1, respectively (see Supporting Information for details).

Similarly, the relationship between participants' perceived ranks of virtual water embedded in 6 goods and actual virtual water was examined using the multi-level regression model. Actual virtual water was referenced from Hoekstra and Chapagain (2007). The level-1 regression model allowing each participant to have a specific model can be written as:

$$PerceptionRank_{ij} = 3.5 + \beta_{1j}\log_{10}ActualVW_i + r_{ij} \quad (4)$$

where *PerceptionRank* refers to the perceived rank of virtual water embedded in different products, which is an integer assigned between 1 (indicating the product with the least virtual water) and 6 (indicating the product with the most virtual water), and *ActualVW* represents the actual virtual water. Each participant j has a specific slope β_{1j}. The values of *PerceptionRank* and log10*Actual* are centered at their means. As a result, the intercept was fixed as 3.5 (the mean of 1 to 6). The slope of this linear model for perfectly accurate perceptions can be found by applying the correct rank of virtual water embedded in different products using Eq. (4). Comparing the slope derived based on the perceived ranks with the correct slope enables the accuracy of participants' perceived virtual water ranks to be assessed.

Using a level-2 regression model, the deviation of slopes from the average estimate for different participants can be assessed:

$$PerceptionRank_{ij} = 3.5 + \left(\gamma_{10} + \mu_{1j}\right)\log_{10}ActualVW_i + r_{ij}$$

$$\beta_{1j} = \gamma_{10} + \mu_{1j} \quad (5)$$

where γ_{10} and μ_{1j} are average estimate and individually different deviation of the slope, respectively.

In order to understand factors impacting perceptions of virtual water, effects of grand-mean centered socio-demographic and other variables z_{ks} on the slope β_{1j} are examined using the extended level-2 regression model:

$$PerceptionRank_{ij} = 3.5 + \left(\gamma_{10} + \sum_{k=1}^{n}\gamma_{1k}z_{kj} + \mu_{1j}\right)\log_{10}ActualVW_i + r_{ij}$$

$$\beta_{1j} = \gamma_{10} + \sum_{k=1}^{n}\gamma_{1k}z_{kj} + \mu_{1j} \quad (6)$$

where z_{ks} are predictors for perceptions of virtual water, which are the same as those for perceptions of water use, and γ_{1k} are the regression coefficients of z_{ks}.

3. Results

3.1. Perceptions of water use

All the participants estimated the 9 end water uses including a variety of household and other uses. The estimates of each end use of water varied in a wide range that typically covered a few orders of magnitude (Fig. 3, noting that water uses are logarithmically scaled), indicating a large variability of perceived water use by different participants. The first and third quartiles of a perceived water use by different participants embraced the actual value of 3 water uses, and the range of a perceived water use generally embraced the corresponding actual value. The correlation coefficient between perceived and actual end uses of water by each participant was assessed using the logarithmic converted

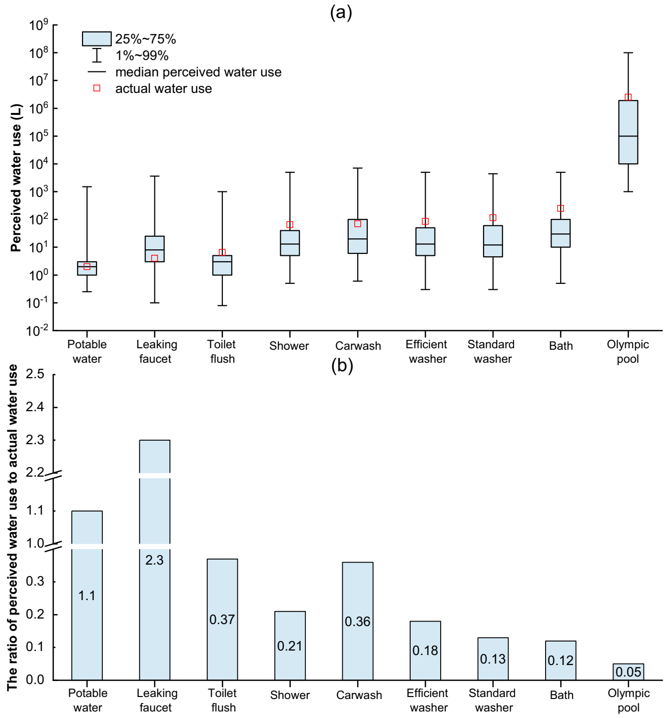

Fig. 3. Perceived end uses of water ($n = 3262$): (a) boxplots depicting the median, first and third quartiles, 1% and 99% percentiles of perceived water use; and (b) ratio of the mean of perceived water use to actual value for different water end use.

values. The mean correlation coefficient between $\log_{10}Perception$ and $\log_{10}Actual$ was estimated $r = 0.93$, implying a generally good understanding of the relative magnitude of different end uses of water. The correlation coefficients distributed in a large range between 0.71 and 0.99 (95% confidence interval), showing considerable difference in individuals' capacity of estimating water uses.

Using Eq. (1), the accuracy of participants' perceptions of water use was examined by fitting a quadratic function to perceived and actual water uses. Fig. 4 displays the results with the mean parameter estimates, together with mean perceptions of the 9 end uses. The curve is below the perfect accuracy line $y = x$, implying that on average the participants tended to underestimate water use. The mean intercept was estimated below zero, $M(\beta_{0j}) = -0.75 \pm 0.013$. This implied that

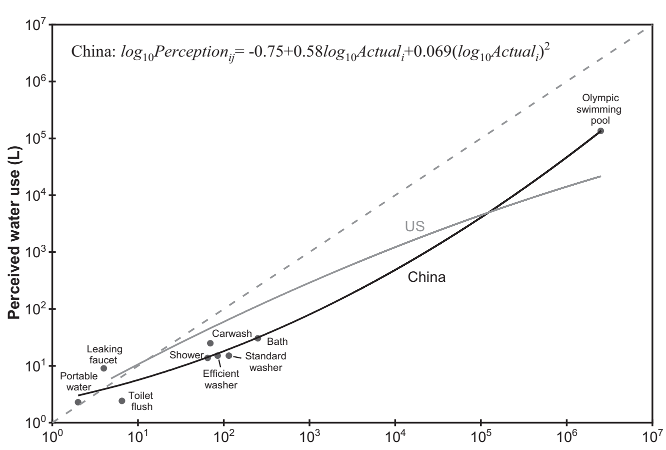

Fig. 4. Mean perceptions of 9 end uses of water. Error bars for 95% confidence intervals are not shown because they are typically smaller than the size of the symbols. The black solid line shows the regression model with average estimates of intercept, slope and quadratic coefficient in Eq. (2). The diagonal dashed line represents perfect perceptions.

perceived water use was on average $10^{-0.75} = 18\%$ the actual water use. The mean slope, estimated at the mean of $\log_{10}Actual$, was positive, but less than slope 1 indicating perfect accuracy, $M(\beta_{1j}) = 0.58 \pm 0.004$. This suggested that participants generally understood relative magnitudes between different end uses, but they tended to underestimate the difference between end uses.

According to the scatter points representing mean perceptions of water use in Fig. 4, participants on average overestimated two end uses of relatively low water use, i.e., daily potable water and leakage from a leaking faucet. These two items were on average overestimated by a factor of 1.1 and 2.3, respectively. In contrast, participants underestimated other items of relatively high water use. Average perceived water uses from toilet flush, shower, carwash, standard and efficient washing machines, bath and Olympic swimming pool were on average 37%, 21%, 36%, 18%, 13%, 12% and 5% of the actual water uses, respectively (Fig. 3). The degree of underestimation increased with actual water use.

We analyzed perceptions of participants in different provincial-level administrative regions in the mainland of China (i.e., hereafter referred as provinces) to examine any difference in perceptions that might be related to geographical locations. According to the mean intercepts and slopes of the multi-regression models at the provincial level, all the mean intercepts were below 0 and slopes were between 0 and 1 (Supplementary Information Fig. S3), indicating that participants from all the provinces on average underestimated water use. However, participants in different provinces showed heterogeneity in the degree of underestimation. This can be explained by different natural water endowment, water policies and water supply strategies in provinces.

3.2. Perceptions of virtual water embedded in 6 products

All the participants ranked the 6 agricultural and livestock products with increasing amount of virtual water embedded in 1 kg product. The perceived rank of each product ranges between 1 and 6, showing high variability of perceptions by individuals. The correlation coefficient between perceived and true ranks of virtual water embedded in the 6 products by each participant was assessed. The mean correlation coefficient was estimated $r = -0.08$. This negative mean correlation coefficient meant that on average the perceived rank of a product tended to be on the opposite side of the respective mean to that of the true rank, suggesting that participants generally did not understand the relative magnitude of virtual water embedded in different products. The correlation coefficient ranged between -0.77 and 0.77 (95% confidence interval). Less than a half of the participants (42.5%) perceived the rankings with a positive correlation coefficient to the true ranks.

The mean perceived ranks showed a small variation among the 6 different products of wheat, milk, rice, chicken, tea and beef (Fig. 5). The average slope was estimated negative and substantially less than the correct slope of 3.35, [$M(\beta_{1j}) = -0.39 \pm 0.024$, P-value < 0.001]. This negative slope indicated that the participants generally confounded virtual water quantities in different products, which was consistent to the mean negative correlation coefficient between the perceived and true ranks.

According to the scatter plots representing the mean perceived rank of virtual water embedded in different products in Fig. 5, rice and chicken were perceived to contain the most and least virtual water with the average ranks of 4.3 ± 0.03 and 3.1 ± 0.03, respectively, in comparison to their true ranks of 3 and 4. The participants on average overestimated the ranks of two products with the least virtual water, i.e., wheat (the perceived rank 3.5 ± 0.03) and milk (the perceived rank 3.6 ± 0.03), and underestimated the ranks of two products with the most virtual water, i.e., tea (the perceived rank 3.1 ± 0.03) and beef (the perceived rank 3.5 ± 0.03). These results revealed that it was difficult for participants to judge which product needs more water in the production process than another. Surprisingly, many participants had not the common sense that more water is required in

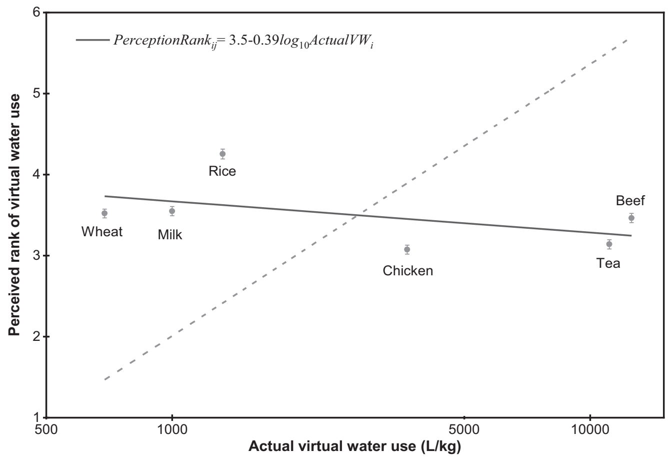

Fig. 5. Mean perceptions of the rank of virtual water embedded in 6 products. Error bars indicate 95% confidence intervals for mean perceptions. The black solid line shows the regression model with average estimates of the slope based on perceived ranks, and the grey broken line shows the regression model derived based on the true ranks for comparison.

the supply chain to produce livestock products than to produce equivalent mass of cereals.

3.3. Factors impacting the accuracy of perceptions

Perceptions of water use and virtual water present high variability among individuals. In order to examine factors impacting the accuracy of perceptions, 10 variables that characterize individual features of the participants were considered as predictors of perceptions. These variables were centered to their means in the extended level-2 regression model using Eqs. (3) and (6). The results are listed in Table 1.

For perceptions of 9 end uses of water, as specified previously, the average intercept of the multi-level regression model was negative (Table 1), indicating underestimation of water use; the average slope was estimated less than the perfectly accurate slope (Table 1), indicating underestimation of water use differences. Therefore, a positive coefficient of a predictor for the intercept means less underestimation of water use corresponding to a higher-value predictor, and a positive coefficient for the slope indicates less underestimation of water use differences corresponding to a higher-value predictor.

The coefficients of gender for predicting intercept and slope were significantly negative (being male and female were assigned 0 and 1 in the regression, respectively), implying that the male participants on average had less underestimated the magnitude and difference of end uses of water than female participants. Age had a significantly positive impact on intercept and slope, meaning that elderly participants tended to provide more accurate water use estimates. In addition, water-saving behavior has contributed to explain perceptions of water use, and positive coefficients for both the intercept and slope proved that participants who were prone to water-saving behaviors generally had more accurate perceptions of water use. Water price exerted a significantly positive impact on the intercept, suggesting that the participants paid a high water price have on average less underestimated the water use. Positive coefficients of and residential water sources, education as well as resource and environmental attitudes for the slope indicated that participants who relied on tap water and have high education and pro-environmental attitudes perceived relative differences in water use more accurately. In contrast, household size, family income and occupation were not significant contributors for explaining individual differences in perceptions of water use.

For perceptions of ranking virtual water embedded in 6 products, the average slope was severely underestimated (Fig. 5). Again, a positive coefficient of a predictor implies more accurate perceptions of ranking the virtual water. Similar to perceptions of water use, the coefficients of gender and education were significantly positive, meaning that male participants and participants receiving a higher education degree had more accurate perceptions. Family income level was likely to have a positive impact on virtual water perceptions, with participants from a higher-income family tending to rank virtual water more accurately. Notably, participants who used water from well/river/lake rather than tap had more accurate perceptions of virtual water. While age, water price, water-saving behavior, and resource and environmental attitudes played a significant role in impacting perceptions of water use, their impacts on perceptions of virtual water were insignificant. Household size and occupation did not have a significant impact on perceptions of water use and virtual water. Estimate of virtual water is difficult. Given common misperceptions of virtual water among the public, targeted community and school education programs are required to aid public to gain knowledge of virtual water.

4. Discussion

Overall, Chinese participants perceived end uses of water highly correlated to actual water use, demonstrating that they did possess knowledge of water use in their daily life. However, they were prone to underestimate water use and compress differences of water use. Participants who had less underestimated water use were also inclined to have better sensitivity of water use differences, as proved by a significantly positive correlation coefficient between the intercept and slope of the regression model for perceptions of water use in Eq. (1) ($r = 0.2$, P-value < 0.001). Nevertheless, there was still a big gap between

Table. 1
Multi-level regression results for predicting perceptions of physical and virtual water uses.

	Predictors	Perceptions of 9 end uses of water: Quadratic term	Perceptions of 9 end uses of water: Slope	Perceptions of 9 end uses of water: Intercept	Perceptions of virtual water embedded in 6 goods: Slope
	Within-participant predictors	0.07 ± 0.001***	0.58 ± 0.004***	−0.75 ± 0.01***	−0.39 ± 0.03***
	Between-participant predictors				
1	Gender (female)	–	−0.05 ± 0.01***	−0.08 ± 0.02***	−0.14 ± 0.06*
2	Age	–	0.003 ± 0.0005***	0.01 ± 0.001***	0.001 ± 0.003
3	Household size	–	−0.003 ± 0.002	0.01 ± 0.01	−0.03 ± 0.02
4	Education	–	0.02 ± 0.004***	−0.01 ± 0.01	0.09 ± 0.03**
5	Income	–	−0.0002 ± 0.0002	−0.0003 ± 0.0006	0.003 ± 0.001*
6	Residential water source (tap water)	–	0.03 ± 0.01*	0.03 ± 0.05	−0.26 ± 0.11*
7	Water price	–	0.001 ± 0.003	0.04 ± 0.01***	0.01 ± 0.02
8	Resource and environmental attitudes	–	0.04 ± 0.02*	0.01 ± 0.06	−0.22 ± 0.14
9	Water-saving behavior	–	0.05 ± 0.02**	0.13 ± 0.05*	0.04 ± 0.13
10	Occupation (primary industry)		0.002 ± 0.002	−0.005 ± 0.005	0.1 ± 0.15

Note: *, ** and *** indicate $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. "±" is the estimated standard error. Please see Supplementary Information for assigning descriptive variables with numerical values.

perceived and actual water uses, which confirmed previous results in other countries (Beal et al., 2013; Attari, 2014; Fan et al., 2014). Efficient policy must be grounded in an understanding of decision making. Even if domestic water users are motivated to reduce their use of water, they will not do so effectively because of inaccurate perceptions (Dietz, 2014).

When fitting a quadratic function to perceived and actual water uses, the estimated coefficients for Chinese participants showed some difference from those for American participants (Attari, 2014). The fitted quadratic functions for Chinese participants had a lower intercept, a milder slope and a larger quadratic coefficient. A comparison of these coefficients showed that on average, American participants were more sensitive to difference of the water use at the lower part of the curve, and Chinese participants better estimated high end uses (as shown in Fig. 4). Nevertheless, both Chinese and American participants generally underestimated water uses and their differences, but understood relative magnitudes between different end uses. When fitting a linear function to perceived virtual water ranks and virtual water, the average slope for Chinese was negative and that for Americans was reported slightly higher than zero (Attari, 2014, noting that the investigated products were different from Chinese survey due to different dietary habits). Participants in both countries did not have a good understanding of relative magnitudes of virtual water embedded in products that were daily consumed.

Generally, elderly participants had more accurate perceptions of water use, which can possibly be explained by their experience of life gained along with the age and their consumer attitude valuing frugality (Attari, 2014; Fan et al., 2014). Male participants were on average more accurate than females. Water-saving behaviors were found to be linked to more accurate perceptions of water use, probably because participants were willing to improve their understanding of water use in order to achieve water saving. In addition, a higher water price generally led to less underestimation on water use. This can be explained by the fact that water price conveys the information of water scarcity to the public and may inspire water conservation (Rogers et al., 2002; Panagopoulos, 2013). Tap water users were more accurate than users of other water sources (i.e., well, river, lake) in perceiving water use, likely because of the water bill received from tap water use (well/river/lake water in many cases does not need to be paid in China). A high education level and resources and environmental attitude helped perceive the differences of water use more accurately, as the participants have stronger cognitive ability and more knowledge of natural water resources. In summary, water price, education and resources and environmental attitude served as predictors for perceptions of water use, and these factors might be manipulated to enhance public's understanding of water use.

For perceptions of virtual water, a majority of participants were not capable of judging which products needs more water in the production process. They even did not have the knowledge that livestock products contain more virtual water than cereals of equivalent mass. There is a substantial knowledge gap in understanding virtual water of daily consumed products. Virtual water seeks to quantify water use throughout the production process of economic goods (Dalin et al., 2012; Sun, 2019), and it is an important concept that may help address local water deficits (Allan, 1998). In principle, consumers may play an important role in water conservation by sending their preference signals to producers through selecting products containing less virtual water (i.e., less water intensive products). However, not knowing the relative magnitude of virtual water embedded in different products hinders the public from conserving water through the daily use of varied products.

As virtual water was an emerging concept that was developed in the recent decades, the elderly and the primary industry practitioners did not necessarily provide better ranking of virtual water embedded in varied products. Being male and owing a high education degree generally led to more accurate perceptions. Besides, participants coming from higher household income families often had more accurate perceptions of virtual water, which may be explained by a positive connection between household income and cognitive ability (Khanam and Nghiem, 2016; Hu et al., 2019). Because high-income people are inclined to have dietary food containing more intensive virtual water (Khan et al., 2009; Yang and Cui, 2014), accurate perceptions of virtual water is of great significance for them to reduce the water footprint. In contrary to water use perception, tap water users had less accurate perceptions of virtual water than well/river/lake water users. Tap water users who have easy access to water may understand less well how much water is needed in the process of agricultural and livestock goods than non-tap water users. Water price, water saving behavior, and resources and environmental attitude were not significant predictors for perceptions of virtual water.

Notably, participants who had more accurate water use perceptions tended to make better virtual water rankings, as indicated by a significantly positive correlation between the slopes for perceptions of water use and virtual water ($r = 0.04$, P-value < 0.05). This positive correlation is likely associated with the cognitive ability of individuals related to the education level, in spite of other different impacting factors.

The results highlight that misperceptions of water use were commonly found in both China and the United States, which represents a great challenge to water conservation and water demand-oriented management. Nevertheless, the impacting factors on perceptions of Chinese participants showed slight difference from those of American participants reported in the United States (Attari, 2014). While education and resource and environmental attitudes were not identified as predictors of Americans' perceptions, they had significantly positive effects on the perceptions of water use in China.

The findings in this study have important implications for water management. Knowledge of how water users perceive the water underpins water conservation and water demand management. Given that underestimation of water use may cause excessive water use, transmission of relevant information to water users needs to be enhanced. Smart water metering may serve to transmit effective information on water use (Beal et al., 2013). Water pricing may provide a financial incentive to water conservation, but its wider impacts (e.g., negative effect on social equality) should be taken into account when using the pricing instrument. Water bills separating different end uses (e.g., uses in kitchen and bathroom) may help users understand residential uses of water and make informed decisions about water conservation. In addition, school-level education, radio and television programs, web sites and demonstration projects are practical approaches of raising awareness. Estimate of virtual water is difficult. Given common misperceptions of virtual water among the public, targeted community and school education programs are required to aid public to gain knowledge of virtual water. Virtual water labelling on products helps inform the consumers of virtual water that is incorporated in the production. Building on adequate understanding of virtual water, virtual water strategy can potentially be used as a policy instrument to save local water use and thereby alleviate regional water scarcity.

Our samples from the online survey represented some selection bias, which is however a shortcoming commonly shared with previous studies based on online survey (Attari, 2014). It should be noted that the scores characterizing participants' resource and environmental attitude and water-saving behaviors were based on self-evaluation and may not fully represent the reality. Uncertainty should be recognized due to sample data constraints, and future efforts to improve sampling combining online and off-line surveys may enhance our ability to understand perceptions of people who do not have access to internet (~72% of the population have access to internet in China as of 2021 according to 48th "Statistical Report on China's Internet Development Status").

5. Conclusions

As securing water supply to meet human society's increasing needs is at the core of sustainable water management and development, demand-oriented water management is gaining increasing attention in order to cap water uses within sustainable limits. Understanding public perceptions of water use should underpin effective water demand management. However, water management used to overlook the potential of water conservation based on public perceptions of water use, particularly in developing countries. This study attempted to shed some light on comprehending Chinese public's knowledge of water use through online surveys. Our findings indicated that overall, Chinese participants underestimated water use and differences of water use. Most participants did not possess the knowledge of virtual water embedded in their daily consumed products. Combined with previous results, we concluded that misperception of water use is likely a common issue that is shared by both the United States and China, representing a major obstacle to local and global domestic water conservation. Individuals showed rather different abilities of assessing water use and ranking virtual water; and we identified gender, age, education, resource and environmental attitude, water saving behaviors, water price and residential water source as predictors that have significant impacts on individual perceptions of water use (or virtual water). The results are useful in informing policies to enhance the public's awareness of water use towards sustainable water management.

This analysis of perceptions of water use was conducted in a national context of China, where water conservation is high on the policy agenda of the local and state governments. Although uncertainty stems from sampling, data sources, models and methods for converting qualitative variables to quantities, the results provide useful information for management and policy decisions. However, understanding the relation between perceptions and actual water use influenced by various demographic and environmental factors remains challenging, and future efforts are needed to improve this understanding and enhance their link to achieve water conservation. This method, which has been successfully applied to the United States and China, can be applied to other countries (e.g., sub Saharan African, South American and other developing and developed countries with different water endowment, economic and cultural contexts) to further understand geographic differences in perceptions of water use.

CRediT authorship contribution statement

Siao Sun and Chuanglin Fang designed the study; Hui Liu designed the online survey and collected the responses; Hui Liu and Siao Sun analyzed the data; Hui Liu, Siao Sun, Pauline van den Berg, Gamze Dane and Jingbao Li, Guangtao Fu analyzed the results; all the authors wrote and proofread 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.

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Appendix A. Supplementary data

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