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ORIGINAL ARTICLE

Gini coefficient to assess equity in domestic water supply in the Yellow River

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Abstract Yellow River, is designated as "the cradle of Chinese civilization" and played a key role not only in the country's economic development but also in the historic and cultural identity of the Chinese people. With the rapid economic development and population growth, water demand for industry and households has increased significantly in the Yellow River basin; this has caused an increasing gap between water supply and demand. Competing water demands triggered conflicts between disparate water users on different scales such as the rich and the poor, or between different sectors and regions, such as domestic and agriculture, agriculture and industry, upstream and downstream, rural and urban areas, etc. Ensuring equity in water supply for conflicting water users is one of the major challenges that facing water managers and in particular water management in the Yellow River basin. In this paper, a method has been developed to calculate the Gini

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coefficient of water use as an indicator to measure the equality in domestic water supply. A dual domestic water use structure model is employed for this purpose. The developed method is subsequently applied to assess the equality in domestic water supply in the Yellow River. Data of population growth, domestic water use and economic development over the time period 1999-2006 are used to calculate the Gini coefficient of water use over the same length of period. The result shows a decreasing trend in Gini coefficient of domestic water use in the Yellow River basin after 2001 which means domestic water use is becoming more and more equitable in the basin. The study justifies that the Gini coefficient of water use can be used and recommended as a useful tool for the water management especially in the context of global change.

Keywords Water demand management · Domestic water use · Gini coefficient · Equity · Yellow River

1 Introduction

Improving water supply has been recognized in the past as an effective way for dealing with water crisis in many parts of the world (Giordano et al. 2004; Zhang 2005; Wang et al. 2009a, b). Rapid population growth and economic development in recent years have made it difficult to meet the increasing in water demand with the finite water resources (Butler and Memon 2006; Wang et al. 2010). A recent research by International Water Management Institute (IWMI) showed that more than a billion people in the developing world are facing lack of safe drinking water. The research also projected that by the year 2025 about 33% of the world population or two billion people (based on UN medium term population growth predictions) would be living in countries or regions with huge water deficits. All countries in the Middle East and North Africa (MENA) would be experiencing absolute water scarcity by 2025 (Nicol et al. 2006). In contrast, people in the developed countries uses at least 150 l of water per day which is much higher than the developing courtiers (Giordano et al. 2004).

Water is a unique and increasingly scarce commodity, that raised many critical issues and questions such as how to ensure people get equitable access to water, or how to guarantee people most benefited by judicious water supply, or how to eradicate poverty and promote growth by assuring continuous water supply. A number of researches have focused on these topics in the past years (Bhattarai et al. 2002; Rogers et al. 2002; Elmahdi et al. 2007; Phansalkar 2007; Cai 2008; Liu and Chen 2008; Lacey 2008; Wang et al. 2009a, b; Rasul and Chowdhury 2010 ;Wang et al. 2011a). The studies showed that management of water resources has critical implications for people's daily life and overall economic development for social prosperity (Butler and Memon 2006; Wang et al. 2010; Rasul and Chowdhury 2010). Social theories of justice, equity and fairness underscore the need for ensuring social justice in water resource management (Syme et al. 1999; Tisdell 2003). The equity concept implies protection of water rights and access to safe drinking water which is a basic human need (Gleick 1996; Syme et al. 1999; Yeshey and Bhujel 2006; Cai 2008). Usually, equity in access to and use of water and the distribution of the impacts of water resource development intervention have four elements (Phansalkar 2007; Rasul and Chowdhury 2010):

(1) Social equity: equity between different groups of people living broadly in the same location.

(2) Spatial equity: equity between people living in different regions.
(3) Gender equity: equity access between men and women efforts to access and use water, and its benefits.
(4) Inter-generational equity: equity in enjoyment of water resources across generations of people.

The Yellow River begins in the Qinghai-Tibetan plateau of Qinghai province from whence it flows across eight other provinces and autonomous regions of China before falling into the Bohai Sea (Liu and Zhang 2002; Xu et al. 2002; Wang et al. 2011b). The basin played a key role not only in the country's economic development but also in the historic and cultural identity of the Chinese people. With approximately 9% of China's population and 17% of its agricultural area, Yellow River is designated as "the cradle of Chinese Civilization" (Liu and Zhang 2002; Giordano et al. 2004). Population and economy of the river basin has grown rapidly in the recent years. Figure 1 shows the increasing trends in population and GDP in Yellow River basin over the period 1980–2005. This has caused a significant increase of water demand for agriculture, industry and households in the basin. Consequently, the gap between water supply and demand has widened in the recent years (Giordano et al. 2004; Barnett et al. 2006; Goncalves et al. 2007).

At present, the whole basin is considered as water scarce region. Shortage of water has triggered conflicts among the water users of the Yellow River. Ensuring equity in water supply for different water users is one of the major challenges that facing water managers and in particular water management in the basin. A meaningful and scientific measure of water equity is necessary to ensure equity in water supply management has met. Without a sound method of equity measurement and assessment, fairness in water use may always be prone to political manipulation. However, no well accepted method to measure equity in water supply that consider all the four elements of equity viz. social equity, spatial equity, gender equity and inter-generation equity is exist at present. The Gini coefficient is an index widely used to measure equality in the distribution of income in a given society. It has been applied in various disciplines as diverse as economics, health science, ecology, chemistry and engineering. As for the water supply management, there still does not have any suitable method for calculating Gini coefficient. In this paper, a model has been proposed and developed for calculating the Gini coefficient for water use to measure the equality level in water supply. The developed model is applied in the Yellow River as a case study to assess the change in equity in domestic water supply under the changing scenarios.

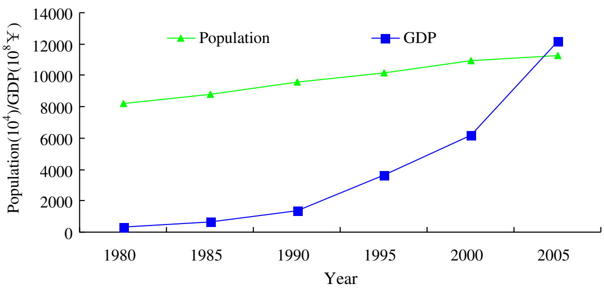


Fig. 1 Changes in population and GDP in the Yellow River basin over the time period 1980–2005

2 Materials and methods

2.1 Data and sources

Population growth, domestic water use and economic development data from 1980 to 2005 were collected from China water resources bulletins (MWR 2004, 2005, 2006, 2007). The recent data of water use efficiency for the upper, middle, and lower reaches of Yellow River basin was collected from the Yellow River water resources bulletins (YRCC 2000, 2001, 2002, 2003). Table 1 summarizes the basic water use information in the three reaches of the Yellow River.

2.2 Gini coefficient of water use

The Gini coefficient, is recognized as a measure of inequality in the distribution of income in a given society was developed by the Italian statistician Corado Gini in 1912 (Xiong 2003; Schechtman and Yitzhaki 2003; Cullis and van Koppen 2007; Behboodian et al. 2007; Rahman et al. 2009). The Gini coefficient is usually defined mathematically based on the Lorenz curve. If the area between the line of perfect equal society and Lorenz curve is A (Fig. 2(a)), this can be plotted as a straight line, and termed the line of equality. In most cases, however, the Lorenz curve is located below the line of equality indicates inequality in the distribution of income. If B is the area under the Lorenz curve, then the Gini coefficient (G) can be calculated as the ratio of the area that lies between the Lorenz curve and the line of equality (area A) and the total triangular area under the line of equality (area A+area B) (Kleiber and Kotz 2002; Xu 2004; Biancotti 2006; Moyes, 2007; Cullis and van Koppen 2007),

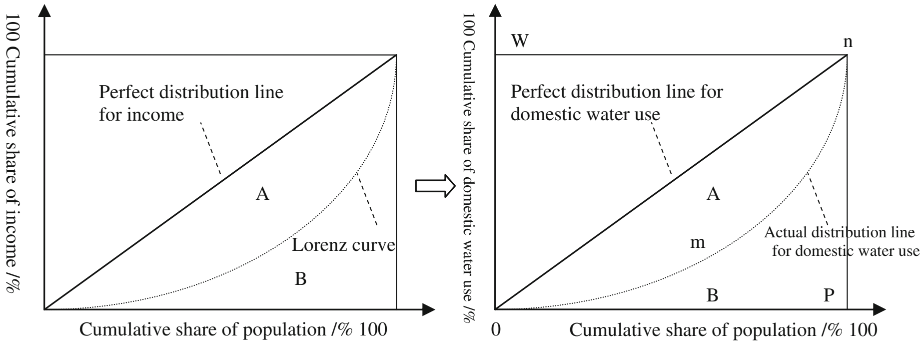
$$G = \frac{A}{A + B} \tag{1}$$

The Gini coefficient ranges from 0 to 1. A low Gini coefficient indicates a more equal distribution, with 0 expressing total equality, while higher Gini coefficients indicate more unequal distribution, with 1 corresponding to complete inequality.

As the Gini coefficient measures inequality by means of a ratio analysis, it is easily interpretable. It can be applied over a time series to show how the inequality changes over a period of time, thus it is possible to show if inequality is increasing or decreasing. However, the Gini coefficient does suffer from number of weaknesses. The Gine coefficient largely lies in its relative nature and therefore, loses information about absolute regional and individual income. In addition, Gini does not address causes behind the inequality.

Table 1 Water use information in the three reaches of the Yellow Rive

Area	Precipitation (mm)	Per captia water consumption (m^3/P)	Irrigation quota (m^3/ha)	Quota of domestic water use(m^3/P.d)	
				urban	rural
Yellow River	407.2	358	6285	153	44
Upper	341.5	829	10560	163	43
Middle	491.8	200	3705	153	43
Lower	576.5	295	4965	115	48
China	610.8	442	6735	211	69



(a) Lorenz Curve of income (b) Lorenz Curve of domestic water use

Fig. 2 Lorenz Curve for income and domestic water use. **a** Lorenz Curve of income **b** Lorenz Curve of domestic water use

However, due to its easy interpretability, Gini coefficient has found wide applications in the study of inequalities in various disciplines. In this paper, the level of equality of domestic water use is studied by using Lorenz curve and Gini coefficients in order to understand the regularity of the domestic water use structure changes in the Yellow River basin.

There are several methods for calculating the Gini coefficient (Kleiber and Kotz 2002; Subramanian 2002; Xu 2004; Biancotti 2006; Moyes 2007; Cullis and van Koppen 2007; Tang and Wang 2009). As for the water resources management, no suitable way for calculating the Gini coefficient is available in literature. Considering the characteristic of domestic water demand, we have proposed a model to study the inequity in domestic water use based on the hypothesis that total domestic water demand is divided into urban water demand and rural water demand, and the difference between them can be obtained through the dual domestic water use structure model.

With the Lorenz curve as shown in Fig. 2(b), we can simplify the Eq. 1 as follow:

$$G = \frac{A}{A+B} = \frac{1/2}{1/2+B} = 1 - 2B \tag{2}$$

In which, A is the area between 0mn and 0n, B is the area between 0mn and 0Pm. Through the Eq. 2, we can find that Gini coefficient for domestic water use has a direct prelateship with B.

According to the characteristic of domestic water use, we can set up dual domestic water use structure model as shown in Fig. 3, where Pr means rural population, and Pu means urban population. Therefore, the total population:

$$P = Pr + Pu = Pr + Pul + Puh \tag{3}$$

In which, Pul is the urban population whose quota for daily domestic use is lower than the average, and Puh is the urban population whose quota for daily water use is higher than the average and Qr, Qul and Quh is the quota of Pr, Pul and Puh, respectively. Under this assumption, we can calculate the $f(p)$ between Qul and Quh (Wang et al. 2011c).

In order to reflect different population for domestic water use, we use α to represent the proportions of each kinds of population account for the total population, as $\alpha r = \frac{Pr}{P}$, $\alpha ul = \frac{Pul}{P}$ and $\alpha uh = \frac{Puh}{P}$ mean proportion of rural population, lower urban population and higher urban population, respectively (Wang et al. 2011c). They have the relationship as follows:

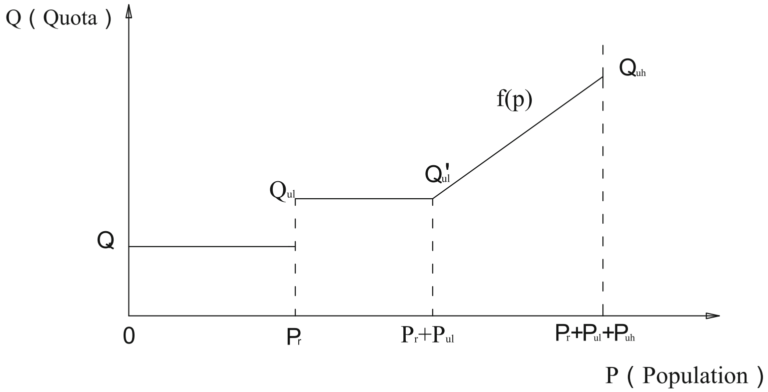


Fig. 3 Dual domestic water use structure model

$$ar + aul + auh = 1 \tag{4}$$

The $f(p)$ can be obtained from (P, Quh) and $(\mathrm{Pr} + \mathrm{P}ul, Qul')$ as the following,

$$f(p) = \frac{Quh - Qul}{Puh}(p - P) + Quh \tag{5}$$

The total domestic water use, S is the area of$0PQuhQul'QulQr$ then

$$\begin{aligned} S &= [QrPr + QulPul + (\tfrac{Qul+Quh}{2})Puh] \times 365/1000 \\ &= P[Qr\alpha r + Qul\alpha ul + (\tfrac{Qul+Quh}{2})\alpha uh] \times 365/1000 \end{aligned} \tag{6}$$

The line $(QrQul, QulQul', Qul'Quh)$means the change of quota. If Qp is the variable of quota, then $365\int_0^P \frac{1}{1000}Qpdp$ is enlarged with the population growth till S. Therefore, $\frac{\frac{365}{1000}\int_0^P Qpdp}{S}$ is also close to 1 when P is changing. This is the same with the 0m0 in Lorenz Curve. Through the integral of 0m0, we can get area B as,

$$\begin{aligned} B &= 365 \times [\tfrac{1}{1000}\int_0^1 (\int_0^P \tfrac{Qpdp}{S})da] \\ &= \tfrac{365}{1000} \times [\int_0^{ar} (\int_0^P \tfrac{Qpdp}{S})da + \int_{ar}^{aul+auh} (\int_0^P \tfrac{Qpdp}{S})da + \int_{aul+auh}^1 (\int_0^P \tfrac{Qpdp}{S})da] \\ &= \tfrac{365}{1000} \times [\int_0^{ar} (\int_0^P \tfrac{Qpdp}{S})da + \int_{ar}^{aul+auh} (\int_0^{Pr} \tfrac{Qpdp}{S} + \int_{Pr}^P \tfrac{Qpdp}{S})da \\ &+ \int_{aul+auh}^1 (\int_0^{Pr} \tfrac{Qpdp}{S} + \int_{Pr}^{Pr+Pul} \tfrac{Qpdp}{S} + \int_{Pr+Pul}^P \tfrac{Qpdp}{S})da] \end{aligned} \tag{7}$$

We can simplify the Eq. 7 as:

$$B = \frac{365}{1000} \bullet \frac{P}{S}[Qr\alpha r(\frac{\alpha r}{2} + \alpha ul + \alpha uh) + Qul\alpha ul(\frac{\alpha ul}{2} + \alpha uh) + \frac{Qul\alpha uh^2}{3} + \frac{Quh\alpha uh^2}{6}] \tag{8}$$

By putting B into the Eq. 2, we get,

$$PG = 1 - 2B = 1 - \frac{2[Qr\alpha r(\frac{\alpha r}{2} + \alpha ul + \alpha uh) + Qul\alpha ul(\frac{\alpha ul}{2} + \alpha uh) + \frac{Qul\alpha uh^2}{3} + \frac{Quh\alpha uh^2}{6}]}{Qr\alpha r + Qul\alpha ul + \frac{(Qul+Quh)\alpha uh}{2}} \quad (9)$$

Assuming the proportion of urban and rural quota δ, and ratio of higher urban water quota and lower urban water quota k, as $\delta = \frac{Qul}{Qr}, k = \frac{Quh}{Qul}$, respectively we get,

$$\frac{Quh}{Qr} = \frac{Quh}{Qul} \cdot \frac{Qul}{Qr} = k\delta \quad (10)$$

Finally, we can get the Gini coefficient as,

$$G = 1 - \frac{2[\alpha r(\frac{\alpha r}{2} + \alpha ul + \alpha uh) + \delta\alpha ul(\frac{\alpha ul}{2} + \alpha uh) + \frac{\delta\alpha uh^2}{3} + \frac{k\delta\alpha uh^2}{6}]}{\alpha r + \delta\alpha ul + \frac{\delta(1+k)\alpha uh}{2}} \quad (11)$$

3 Application: equity in domestic water use in the Yellow River

3.1 Water resources management in the Yellow River

The Yellow River has problems with flood risk and sedimentation for a long time. Water shortage has now emerged as the number one issue for the basin authority and most of the residents. In 1997, there were 226 days of "no flow" when the river failed to reach the Bohai Sea. This caused serious water stress on the river's development (Liu and Zhang 2002; Liu and Xia 2004; Wang et al. 2011a, b, c). With the economic development and population growth, the problem of water shortage progressively become more acute compared to ever before. Some of the main tributaries of Yellow River such as Kuye River, Tuwei River, etc, show a decreasing trend of runoff. Some of the tributaries even dry up in the recent years causing serious negative impact on the natural ecological environment and the water recycle system of the river (Liu and Zhang 2002; Wang et al. 2011a, b, c). It is anticipated that progressive deterioration of water stress situation is caused mainly by two factors: climate changed induced sharp declination of water supply and human activities induced increasing water demand as shown in Fig. 4.

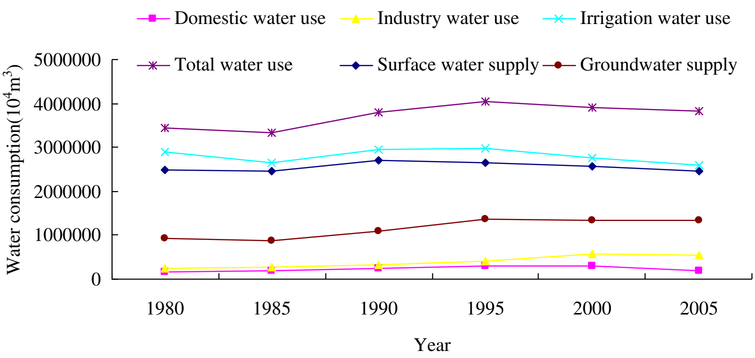


Fig. 4 Changes in water supply and demand in the Yellow River during the time period 1980–2005

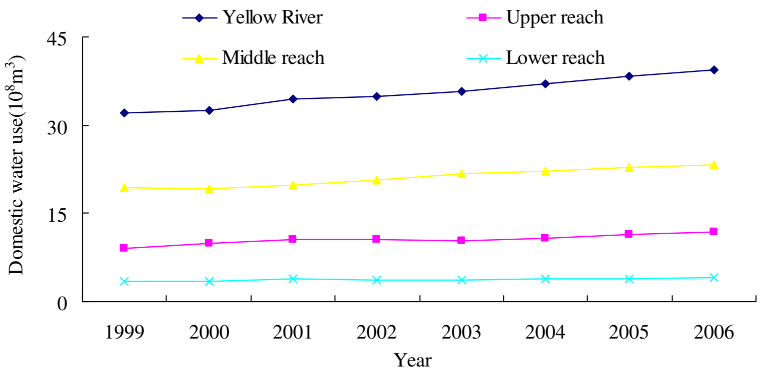


Fig. 5 Changes in domestic water uses in the Yellow River in the recent years

Serious water shortage leads to much focus on water problems in the Yellow River. As water is a finite resource and it's use for one purpose reduces it's availability for other purposes, competing water needs trigger conflicts between disparate water users such as the rich and the poor, or between different sectors and regions, such as domestic and agriculture, agriculture and industry, upstream and downstream, rural and urban areas, etc. Therefore, it is necessary to ensure equity in use of this limited supply.

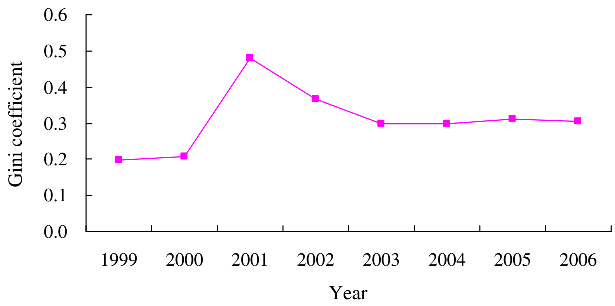
3.2 Equity in domestic water use

With the growth of population, domestic water use in the Yellow River basin has increased significantly in recent years. Fig. 5 shows the increasing trends in domestic water use at different reaches of Yellow River basin in the recent years. To measure the equity in domestic water supply management in the Yellow River basin, Gini coefficient of domestic water use is used in the present paper.

Considering the characteristic of domestic water use and quotas of the upper, middle and lower reaches, the Gini coefficient of the Yellow River basin is calculated by using the Eq. 11. The calculated Gini coefficients of the Yellow River basin for the years 1999–2006 is plotted in Fig. 6.

The result shows that the Gini coefficient of domestic water use in the Yellow River has changed with time. The highest Gini coefficient appeared in 2001, it is even larger than the baseline of 0.4. This can be attributed to low runoff as reported by the observed runoff of Huayuankou station of the Yellow River was 59.5% lower in 2001 compared to the year 2000, even near to the most drought year in the history (1997). Serious water shortage of

Fig. 6 Change in Gini coefficient of domestic water use in the Yellow River



water supply triggered high completion among different sectors which eventually led to high inequality in the Basin in the year 2001. After 2001 Gini coefficient of domestic water use in the Yellow River has decreased significantly over the years.

4 Discussion and conclusion

A mathematical model was developed in this paper to calculate the Gini coefficient of water use to measure the equality in water supply. The proposed model has been applied to assess the trend in equality in domestic water supply in the Yellow River basin. Data of population growth, domestic water use and economic development were used to calculate the Gini coefficient of water use of the basin. The result shows that the Gini coefficient of domestic water use in the Yellow River basin has a decreasing trend after 2001. This means that domestic water use is becoming more and more equitable in the basin in the recent years. However, the trend is very slow and therefore, need more attention to ensure equity in water management. Some questions are important to be considered: (1) equity for water use is a difficult question to deal with. In this paper, we presented a model to estimate and measure equity of water use from time series. However, further consideration is necessary to modify the model to reflect the gender equity and inter-generation equity; (2) Gini coefficient can be calculated by many ways in other disciplines, however still there is no clearly prescribed method for calculating Gini coefficient of domestic water use. In this paper, a method has been introduced for calculating Gini coefficient of water use in a simplified way. Further study is required to introduce the water utilization and changing environment into the model.

Climate change, economic development and population growth have made water supply very critical in many river basins of the world. Equity in access to and use of water is essential to avoid conflicts among the competing water users. It is hoped that the method developed in this paper to measure the equity in water use by using Gini coefficient will assist water management authorities to manage water supply especially in the context of changing scenarios. Further applications for Gini coefficient for domestic water use in other areas or regions are recommended considering different climatic zones and conditions, policy reforms and alternative water use sources.

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