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STUDY ON THE EFFICIENCY OF AGRICULTURAL WATER USE IN THE YELLOW RIVER BASIN

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Abstract

China is expanding its food supply in order to meet the increasing food demand of its growing population. The Yellow River basin, one of the important agricultural production areas in China, has increased agricultural production through improvements in productivity. However, environmental issues, especially water shortages, have become severe, and excessive use of agricultural water may worsen this problem. Therefore, the effective use of water resources is essential if the country is to achieve sustainable food supply and demand. We applied Stochastic Frontier Analysis (SFA) techniques to county and city level datasets to estimate the technical efficiency and water use efficiency of agriculture in the Yellow River basin. We also identified determining factors affecting agricultural water use efficiency using the Tobit model. Results from this study indicate that: 1. average agricultural water use efficiencies have not changed significantly during the estimation period; 2. efficiency tends to be high in the river source region (Qinghai), midstream (except Shanxi), and downstream but tended to be low in upstream (especially in Ningxia and Inner Mongolia); 3. weather conditions, e.g., precipitation and sunlight hours, may affect water efficiency characteristics; and 4. an increase in economic factors, e.g., rural household income, may contribute to the agricultural water efficiency characteristics.

KEYWORDS: *Yellow River basin, agricultural water use efficiency , stochastic frontier analysis*

1. Introduction

Food demand in China is increasing because of rapid population growth, changes in society, and economic development. Food production has therefore become an important state policy issue. Hence, in the Yellow River basin, grain production has expanded dramatically through increases in agricultural

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yield per hectare (Chinese Academy of Engineering, 2001a; Onishi *et al.*, 2005). However, the Yellow River basin is a region that suffers severe water shortages, and there are concerns that excessive water use will deplete the water resources. The Yellow River basin experienced severe water shortages from 1972 to 1999, and there was a total lack of water in the river at certain times and places during this period. One cause of such shortages is increased water use due to the expansion of irrigation-based agriculture (Otsubo *et al.*, 2000).

This river basin is vast, covering about twice the area of Japan (JBIC, 2004), and the conditions for agricultural production vary greatly within it. In the upstream region above Lanzou, about 60% of the water resource in the Yellow River basin exists. However, in upstream regions below Lanzou, there are extensive irrigated areas, including, e.g., the Quintongxia irrigation district in Ningxia and the Hetao irrigation district in Inner Mongolia. These irrigation areas are mostly in arid and semi-arid areas where precipitation is low. Therefore, the extra water needed for grain production is drawn from the Yellow River. The midstream section of the Yellow River is in the Loess Plateau region, which contains arid and semi-arid areas. Grain production is high here, but in the basins of the Fen and Wei Rivers (tributaries of the Yellow River), groundwater levels are dropping because of urbanization and industrialization (Yellow River Conservancy Commission, 1997–2002). The downstream region of the river is in the North China Plain in Shandong Province, where modern agricultural methods, including mechanization and use of chemical fertilizers, have been widely introduced and the region grows wheat and maize with high yields per hectare. Thus, the characteristics of the areas of the river differ, but it is clear that advances in modern agricultural methods have increased grain production, with higher yields per hectare (Onishi *et al.*, 2005), As stated above, however, increases in grain production have come at the cost of excessive use of water, which has exacerbated the drying up of the river. Thus, when considering effective and appropriate use of agricultural water, it is important to consider approaches that limit to the lowest possible level the amount of water used in agriculture to obtain a specific amount of production.

Several studies have evaluated the efficiency of agricultural production or related aspects for the Yellow River basin or for the whole of China. Representative of such work is research by Sonoda *et al.* (2003) and Shirakawa *et al.* (2006). Sonoda *et al.* (2003) used data for the year 2000 from each of China's provinces (and autonomous regions; hereafter the word "provinces" includes autonomous regions) to estimate the efficiency of crop production, using Data Envelopment Analysis (DEA). Using the same approach, Shirakawa *et al.* (2006) evaluated surplus agricultural labor based on 1995 data for each province. These studies used the province as the basic unit; however, it is difficult to evaluate these data within the natural boundaries defined by the river basin. In addition, where evaluations are based on a single year, it is difficult to find representative values of the efficiency obtained. Kaneko *et al.* (2004), Toyota *et al.* (2005), and Shen (1999) used Stochastic Frontier Analysis (SFA) to evaluate the efficiency of production, agricultural water use, and chemical fertilizer use in each province. These studies used multi-year data and examined changes in efficiency but, as with the previous research mentioned above, they did not focus on natural boundaries of the river, because they also used provinces as basic units.

In this study, the units used were administrative river basin boundaries obtained from available county and city level data, which estimate the efficiency of agricultural water use within each province of the Yellow River basin. The analysis focused on the 1990s, when water shortages were severe. In addition, by identifying factors that affect efficiency of agricultural water use, we suggest important directions for future policies and measures that affect water use. This analysis will facilitate discussions about sustainable food production amid constraints on water resources in the Yellow River basin.

2. Background of grain production issues

Grain production in the Yellow River basin has been increasing steadily (Figure 1). Grain production uses irrigation and accounts for about 84% (calculated by the authors from data on the amount of water use from 1988 through 2002)[1] of all water use (Sun *et al.*, 2001; Yellow River Conservancy Commission, 1997–2002). In particular, Shandong Province, Inner Mongolia, and Ningxia have some of the largest irrigation districts in the river basin and use enormous amounts of water for agriculture, accounting for about 60% of use in the entire river basin (Figure 2). Food production per cubic meter of agricultural water used has increased in recent years. The average amount of river basin water used rose from about 15 to 20 tons 10,000 m^{-3} during the 1990s (Figure 3). Drying up of parts of the river first occurred in 1972, but worsened dramatically in the 1990s, with the most extreme event occurring in 1997 (Figure 4). During this period, the amount of water used for agriculture slightly declined, but the Yellow River basin has unstable water resource amounts, so excessive water use soon leads to depletion of water resources. Therefore, it is important that water be used efficiently and rationally. Furthermore, the amount of water used by industry and urban households has increased in recent years, along with industrialization and urbanization (JBIC, 2004; Wang *et al.*, 2006). Thus, it is likely that agricultural water use will be increasingly constrained (Chinese Academy of Engineering, 2001b).To achieve sustainable development in the Yellow River basin under water resource constraints, it is essential to have information about how water can be best allocated, both physically and economically, and the extent to which water use can be reduced in specific regions. Thus, it is important to estimate the efficiency of agricultural water use.

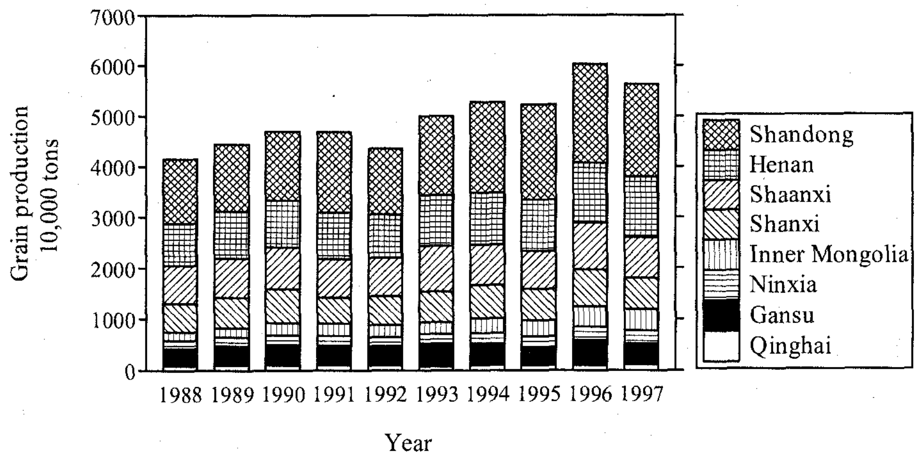

Figure 1. Grain production trends.

Source: Prepared by authors from National Bureau of Statistics of China (1989-1991), National Bureau of Statistics of China[2], and the Institute of Geographic Sciences and Natural Resources Research (Chinese Academy of Sciences)[3].

Notes: (1) Grain Production includes production of rice, wheat, maize, beans, and tubers.

(2) Data for 1992 are an estimate. The estimation method is shown in Table 1.

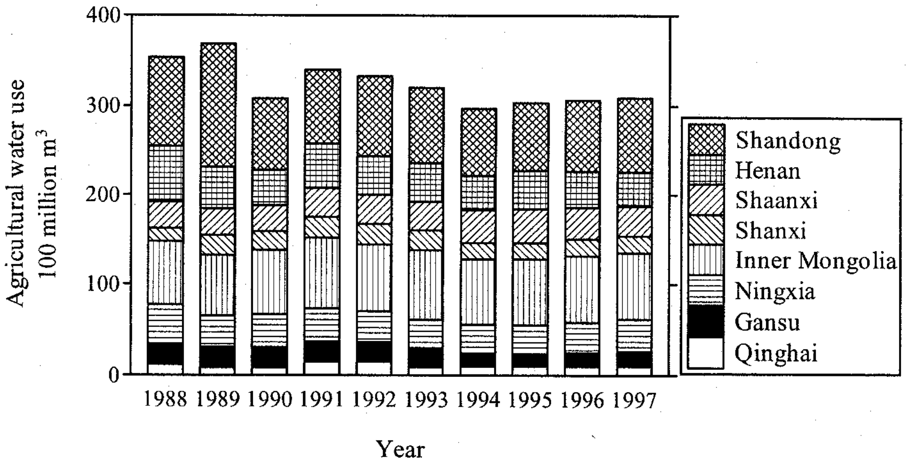

Figure 2. Agricultural water use trends.
Source: Prepared by authors from Sun *et al.* 2001.
Note: Data for 1996 and 1997 are estimates. The estimation method is shown in Table 1.

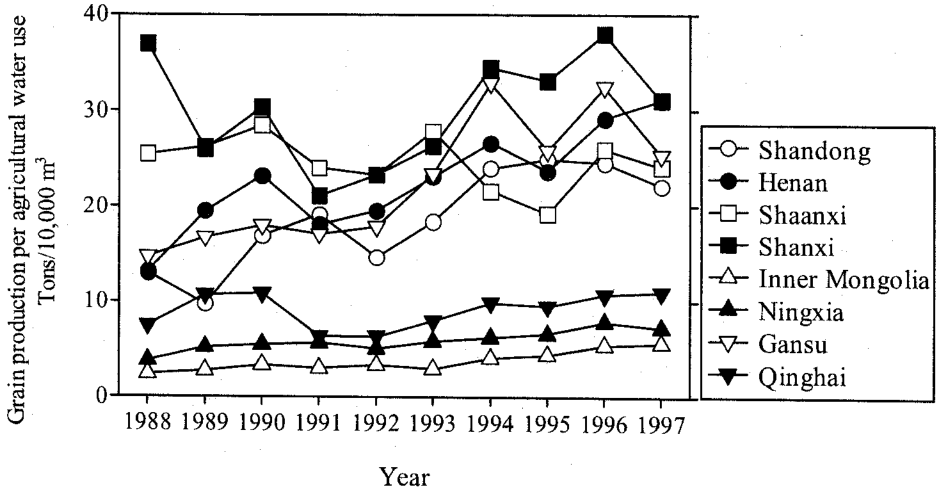

Figure 3. Grain production per agricultural water use.
Source: Prepared by authors by using Figures 1 and 2.

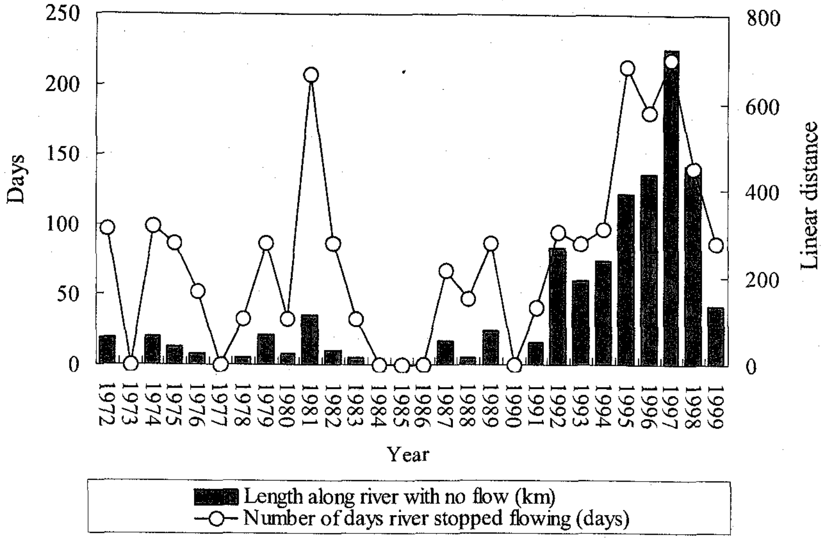

Figure 4. Drying up phenomena: duration and linear distance.
Source: Prepared by authors from Sun *et al.* 2001.

3. Data and administrative river basin boundaries

3.1 Data

In cases where the analysis targeted an area defined by natural boundaries, like the Yellow River basin, statistical data for each province generally include values from outside the basin. To analyze an area within a river basin, it is necessary to have more accurate spatial units than those at the provincial level. It is possible to use data for the smallest administrative units, e.g., counties and cities. However, data for agricultural water use in the Yellow River basin are generally prepared at the provincial level which is only summarized within the basin. Thus, it is necessary to ensure consistency with agricultural water use data—by compiling statistical data from the county and city levels mentioned above to prepare data for each province connected with the river basin. The data prepared using this method represent only the portion of spatial data associated with the parts of the provinces in the river basin. This procedure enables the analysis of relationships between grain production activities within the river basin and amounts of agricultural water use.

The county and city data for grain production and each factor relating to these data are reported in the China County Agricultural Economics Statistics Summary (National Bureau of Statistics of China, 1989–1991). Additional data are available from sources such as the National Bureau of Statistics of China[2] and the Institute of Geographic Sciences and Natural Resources Research (Chinese Academy of Sciences)[3]. In addition, for data on the volume of agricultural water used in the Yellow River basin, figures for each province for the period from 1988 to 1999 are published in Yellow River Water Resource Management (Sun *et al.*, 2001) (although 1996 and 1997 are not included). For meteorological data (precipitation, sunlight hours, and air temperatures), measurements from 190 stations in the river basin were converted from point to plane format using Kriging interpolation (Stein,

Table 1. Data used and details of estimates.

Data item	Data missing	Estimation (if done) and method	Spatial level
Grain production	1992	Rate of change of provincial data	County/city
Sown area of grain crops	1988, 1992	1988: Estimated from 1989 no. of crops, and 1988 cultivation area 1992: Estimated from rate of change of proximate years	County/city
Cultivation area	1992, 1997	Estimated from rate of change of proximate years	County/city
Times of sowing (Sown area of grain crops /cultivation area)	1992	—	County/city
Rural population	1992	Estimated from rate of change of proximate years	County/city
Total power of agricultural machinery	1992, 1993, 1994, 1997 (part)	Estimated from rate of change of proximate years	County/city
Consumption of chemical fertilizer	1992, 1993, 1994, 1997 (part)	Estimated from rate of change of proximate years	County/city
Amount of agricultural water use	1996, 1997	Estimated from rate of change of proximate years	County/city
Maize sown area	Only 1996 obtained	—	County/city
Wheat sown area	Only 1996 obtained	—	County/city
Rice sown area	Only 1996 obtained	—	County/city
Precipitation	—	—	County/city
Average temperature	—	—	County/city
Hours of sunlight	—	—	County/city
(Effective) irrigation area	1992,1993,1994, 1997	Estimated from rate of change of proximate years	County/city
Large-scale irrigation district area	Only recent annual average obtained	—	Irrigation district
Water-conservation irrigation district area	Only recent year average obtained	—	Irrigation district
Total dam capacity	Only values at dam construction stage obtained	—	Dam
Rural household income	—	—	Province (jurisdiction)
Improved area of saline-alkaline land	—	—	Province (jurisdiction)

1999), and then values were calculated for each county and city. Moreover, data on the large-scale irrigation district area (Sun *et al.*, 2001), water-conservation irrigation district area (China Development Center for Irrigation and Drainage, 2002), total dam capacity (Yellow River Conservancy Commission, 1989), rural household income (National Bureau of Statistics of China, 2005), and improved area of saline-alkaline land[4] were obtained. However, county and city data are difficult to obtain; thus, it was not possible to collect complete datasets for all years, and estimates were used where statistical information was not available. Table 1 shows the data used, as well as the estimated data. We prepared a complete dataset from the county and city data from 1988 through 1997, with a focus on the 1990s, when water shortages were most severe.

3.2 Administrative river basin boundaries

In this study, we describe the Yellow River basin using county and city level administrative boundaries. We further reorganize the area in the Yellow River basin, expressed as administrative river basin boundaries, into six provinces and two autonomous regions (Qinghai, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong; note that because only three counties of Sichuan

Province are situated in the river basin, this province was excluded from the study). The following approach was used to prepare the administrative watershed boundaries of the Yellow River. First, the river basin area was defined using a Digital Elevation Model (DEM) with 1:1,000,000 scale data from the National Geomatic Center of China[5]. Second, the area was overlaid with the county and city administrative boundaries to define the area covered by the Yellow River basin. The irrigation districts downstream of water intakes from the Yellow River are located outside of the basin; therefore, areas of these irrigation districts were determined by the references from the China Development Center for Irrigation and Drainage (2002) and the Yellow River Conservancy Commission (2002). Finally, 353 counties and cities were included in the Yellow River basin database. Figure 5 shows the administrative river basin of the counties and cities and provincial jurisdictions in the Yellow River basin.

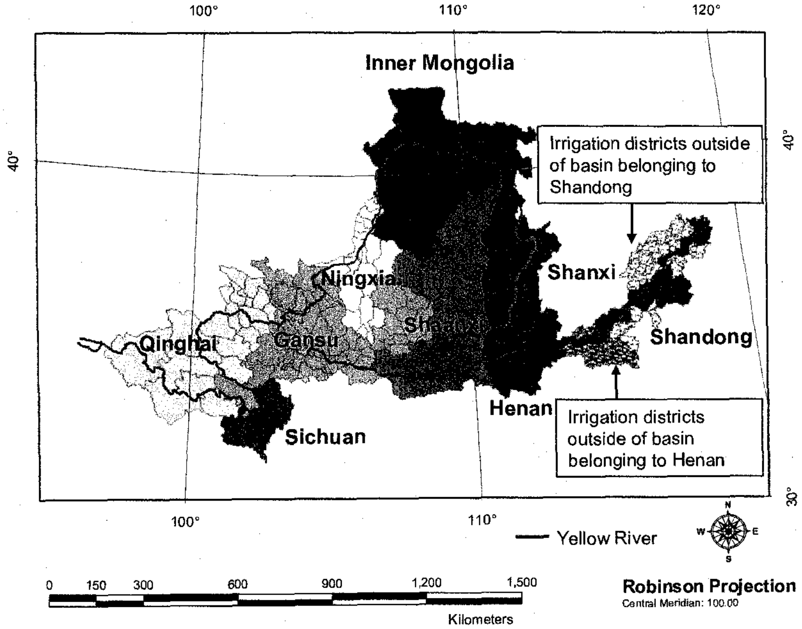

Figure 5. Administrative river basin of the counties, cities, and provincial jurisdictions in the Yellow River basin.

4. Methodology

We estimated the efficiency of agricultural water use in each province of the Yellow River basin and analyzed factors affecting efficiencies of water use. In this study, the efficiency of agricultural water use is defined as the role of agricultural water in the agricultural production function from an economic perspective. The analysis approaches used are described below and variables are summarized in Table 2. First, the efficiency of agricultural water use for each province was estimated by the SFA approach; then the factors that affect agricultural water use efficiency were identified using the Tobit model.

4.1 SFA

SFA (Aiger *et al.*, 1977; Meeusen and Julian, 1977) is an analytical method that assumes a

Table 2. Summary of used variables.

Variable type	SFA	Variable selected	Tobit analysis	Variable selected
dependent variable	Grain production (kg/ha)	Yes	Agricultural water use efficiency	Yes
independent variable	Rural population (persons/ha)	Yes	Times of sown	No
	Agricultural machinery (kW/ha)	Yes	Maize sown ratio (%)	Yes
	Consumption of chemical fertilizer (kg/ha)	Yes	Wheat sown ratio (%)	No
	Agricultural water use (m^3/ha)	Yes	Rice sown ratio (%)	Yes
	Time trends	No	Precipitation (100 mm)	Yes
	Upstream dummy	Yes	Average temperature (°C)	No
	Downstream dummy	Yes	Sunlight hours (1000 hours)	Yes
			Large-scale irrigation districts (%)	Yes
			Water-conservation irrigation districts (%)	Yes
			Total dam capacity (100 million m^3)	No
			Rural household income (10,000 yuan: 1988 level)	Yes
			Improved area of saline–alkaline land (%)	No
			Time trends	No
			Upstream dummy	No
			Downstream dummy	No

Notes:
(1) For dependent and independent variables (except time trends and dummy variables) used in SFA, values were divided by sown area of grain crops.
(2) Times of sowing = sown area of grain crops divided by cultivated area.
(3) Crop ratios for maize, wheat, and rice represent the sown area of the stated crop as a ratio of sown area of grain crops.
(4) Large-scale irrigation districts and water-conservation irrigation districts represent the relative area of each item compared to effective area under irrigation.
(5) Time trend variable indicates a trend change such as technical progress or a policy improvement. We assumed a value of 1 for year 1988 and each value increased by 1 every year.

production function, which is stochastically uncertain, to calculate inefficiencies by separating divergences from the production function into error terms and inefficiencies. Using this approach, it is possible to establish a production frontier curve giving the most efficient possibility set, and this facilitates analysis of the inefficiency of each production entity related to the frontier. The SFA is expressed as:

$$Y_{it} = f(X_{it}, W_{it}, \beta)\exp(V_{it} - U_{it})$$

Where Y_{it} is the frontier production amount in province i in time period t, X_{it} is production input factors other than agricultural water use, W_{it} is agricultural water use, β is the estimated parameter, V_{it} is the random error term ($V_{it} \overset{iid}{\sim} N(0,\sigma_v^2)$), and U_{it} is a non-negative random error term reflecting technical inefficiency and assumed to be half-normally distributed ($U_{it} \overset{iid}{\sim} N^+(0,\sigma_u^2)$).

The Cobb–Douglas and Translog forms are often used for SFA. The Translog form is the most flexible, but, because the estimate includes interaction terms, multicollinearity is likely to occur with the independent variable. We detected severe multicollinearity in our data, preventing the specification of any flexible functional forms. Conversely, with the Cobb–Douglas form, although an elasticity of substitution of one is a precondition, it is possible to obtain more stable calculation results. Thus, in this study estimates assume the Cobb–Douglas form by using the maximum likelihood method:

$$\ln Y_{it} = \beta_0 + \beta_1 \ln L_{it} + \beta_2 \ln K_{it} + \beta_3 \ln N_{it} + \beta_4 \ln W_{it} + \beta_5 Time_{it} + \beta_6 dummyU_{it} + \beta_7 dummyL_{it} + V_{it} - U_{it}$$

Where L_{it} is the rural population, K_{it} is the amount of agricultural machinery, N_{it} is the amount of consumption of chemical fertilizer, W_{it} is the amount of agricultural water use, $Time_{it}$ is the time trend, $dummyU_{it}$ is the upstream dummy, $dummyL_{it}$ is the downstream dummy, i indicates the province, and t is the year. Here, when applied to the SFA to measure the technical and water efficiencies in agricultural production, grain production (representing the economic output of agriculture), the rural population (representing labor), amount of agricultural machinery (representing capital), amount of consumption of chemical fertilizer, and amount of agricultural water use are adjusted to the scale of sown area of grain crops in each province and for each year.

Technical efficiency in this study is expressed by comparing the amount of maximum production by factoring production inputs and the amount of current production. Figure 6 shows the correlation between current production Y_R in relation to the amount of agricultural water input W and amount of production $\hat{Y}$ obtained from the frontier production coefficient. This figure shows that, as for technical efficiency, based on the current amount of agricultural water input W_R, it is possible to increase production from Y_R to $\hat{Y}$. Thus, technical efficiency of the current amount of production Y_R is $Y_R/\hat{Y}$. Similarly, as for the efficiency of agricultural water use, by fixing the amount of imports of other factors of production, defining this as the smallest amount of agricultural water input to reach production amounts Y_R at the current point R, it is possible to reduce the amount of agricultural water input from W_R to $\hat{W}$. Thus, efficiency of the current amount of agricultural water use W_R is $\hat{W}/W_R$. These efficiency values range from zero to one, and the closer the data come to the frontier, the efficiency approaches one.

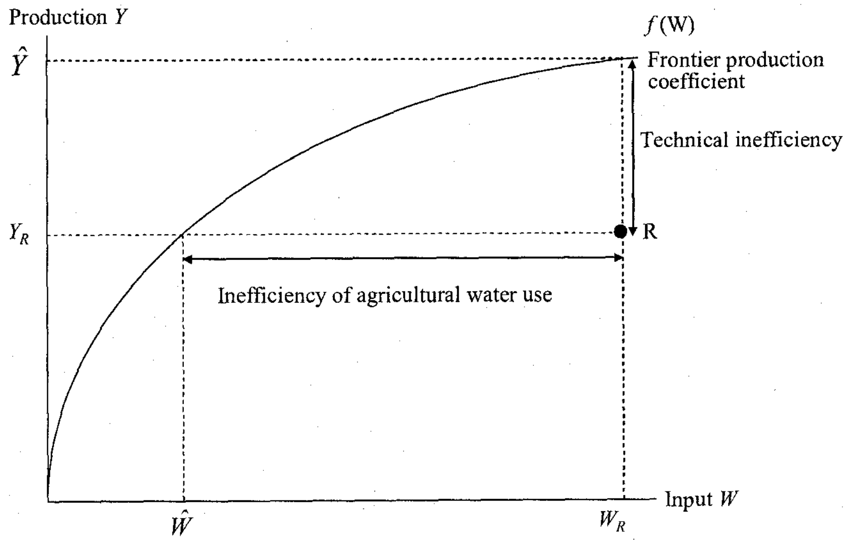

Figure 6. SFA and efficiency.

The level of technically efficient output can be obtained by setting $U_{it} = 0$. Then the technical efficiency (TE) is expressed as:

$$\begin{aligned} TE_{it} &= Y_{it} / \hat{Y}_{it} \\ &= Y_{it} / f(X_{it}, W_{it}, \beta)\exp(V_{it}) \\ &= \exp(-U_{it}) \end{aligned}$$

The logarithm of agricultural water use efficient output $\ln \hat{Y}_{it}^{W}$ is obtained by replacing observed agricultural water use W_{it} with minimum agricultural water use $\hat{W}_{it}$ and setting $U_{it} = 0$ in equation $\ln Y_{it}$. Equating equations for $\ln Y_{it}$ and $\ln \hat{Y}_{it}^{W}$, and using the fact that the logarithm of water use efficiency $\ln WE_{it}$ is $\ln WE_{it} = \ln \hat{W}_{it} - \ln W_{it}$, we obtain the water efficiency estimator, expressed as:

$$WE_{it} = \exp(-U_{it} / \beta)$$

4.2 Tobit analysis

The Tobit model, shown below, was used to estimate the determinant of factors affecting the efficiency of agricultural water use. The dependent variable of water efficiency usually has a discrete jump at zero and at one. The Ordinary Least Square (OLS) method produces biased and inconsistent estimates (Greene, 2003; Kaneko *et al.*, 2004); therefore, the censoring of dependent variables needs to be considered. In this study, we adopted the Tobit model, which is one of the most commonly used applications for censored data:

$$WE_{it} = \begin{cases} 0 & if \quad \lambda S_{it} + \varepsilon_{it} \le 0 \\ \lambda S_{it} + \varepsilon_{it} & if \quad 0 < \lambda S_{it} + \varepsilon_{it} < 1 \\ 1 & if \quad \lambda S_{it} + \varepsilon_{it} \ge 1 \end{cases}$$

where S_{it} is the independent variable affecting water use efficiency, λ is the parameter being estimated, ε_{it} is the random disturbance term and $\varepsilon_{it} \sim N(0, \sigma_{\varepsilon}^{2})$.

5. Results

5.1 Results for technical efficiency and agricultural water use efficiency

We used all the variables shown in Table 2, but where a significant parameter was not obtained, it was excluded from factors of production. Time trends was excluded as a variable, because collinear relationships were identified between consumption of chemical fertilizer and time trends. The results are shown in Table 3. For reference, the results from the Cobb–Douglas form using the OLS method are also shown. The results obtained by both OLS and SFA were favorable, and most coefficients were statistically significant at the 1% level. It is generally known that in China elasticity of consumption of

Table 3. Results of estimations of OLS and SFA.

	OLS	SFA	
	Coefficient	Coefficient	Standard error
Rural population	0.152* (1.936)	0.115* (1.733)	0.066
Agricultural machinery	0.232*** (3.568)	0.209*** (3.195)	0.066
Consumption of chemical fertilizer	0.251*** (4.312)	0.288*** (4.807)	0.060
Agricultural water use	0.061** (2.047)	0.067** (2.244)	0.030
Upstream dummy	-0.060 (-1.235)	-0.048 (-1.105)	0.043
Downstream dummy	0.185*** (4.216)	0.174*** (4.325)	0.040
Constant	5.659*** (15.163)	5.628*** (15.154)	0.371
σ^2		0.026*** (3.203)	0.008
γ		0.872*** (6.729)	0.130
R-squared	0.859		
Adj. R-squared	0.847		
Log-likelihood		67.896	
Number of observation	80	80	

Notes:
(1) Values in parentheses are *t* values.
(2) Asterisks (*, **, ***) represent 10%, 5%, and 1% significance, respectively.
(3) $\sigma^2 = \sigma_v^2 + \sigma_u^2$, $\gamma = \sigma_u^2 / (\sigma_v^2 + \sigma_u^2)$

Table 4. Results for technical efficiency and agricultural water use efficiency.

	Technical efficiency			Agricultural water use		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Qinghai	0.919	0.808	0.961	0.349	0.042	0.551
Gansu	0.891	0.735	0.969	0.255	0.010	0.623
Ningxia	0.888	0.845	0.956	0.200	0.082	0.510
Inner Mongolia	0.843	0.677	0.979	0.230	0.003	0.725
Shanxi	0.870	0.753	0.945	0.186	0.015	0.430
Shaanxi	0.895	0.779	0.966	0.296	0.024	0.594
Henan	0.925	0.859	0.959	0.344	0.104	0.531
Shandong	0.899	0.807	0.956	0.269	0.041	0.511
Mean	0.891	0.783	0.961	0.266	0.040	0.559

chemical fertilizer is high (Peng and Kawaguchi, 2000; Toyota *et al.*, 2005). In this study, the elasticity of chemical fertilizer use also gave the highest value. Estimates of dummy coefficients for the upstream and downstream areas resulted in relatively low production upstream and high production downstream.

Technical efficiency and efficiency of agricultural water use were calculated based on the estimated results obtained above (Table 4). Henan and Qinghai had the highest technical efficiency, and Shanxi and Inner Mongolia the lowest. Qinghai and Henan also had the highest agricultural water use efficiency, and Ningxia and Shanxi the lowest.

Figure 7 indicates that technical efficiency and agricultural water use efficiency tended to be high in the river source region (this region is usually categorized as a part of the upstream: Qinghai), midstream (except Shanxi), and downstream but tended to be low upstream (especially in Ningxia and

Inner Mongolia).

Figure 8 shows the changes in efficiency in the entire river basin from 1988 through 1997. Both technical efficiency and efficiency of agricultural water use fluctuated from year to year but the average trends remained mostly constant.

The differences in efficiency of agricultural water use are usually determined by environmental and external factors. Climate conditions are quite different among provinces in the Yellow River basin because the area is so large. Generally, precipitation tends to decrease from southeast to northwest in the basin, while dryness tends to increase in the same direction. In addition, yearly climate conditions in the basin are quite different. Thus, climate conditions may affect the efficiency of agricultural water use. Also, differences in economic activity, improvements in water utilization, and types of sown grain crops may affect efficiency of agricultural water use. Public works related to water utilization are important in determining differences in economic levels, and high economic activity regions, such as downstream, can expect more tax revenue and can afford to improve water utilization. Therefore, the above factors may affect the efficiency of agricultural water use. In next section, we identify the determining factors affecting agricultural water use efficiency.

The agricultural water use data for 1996 and 1997 used in this study are estimated values; therefore, it will be necessary to reconsider the findings if actual data become available in the future.

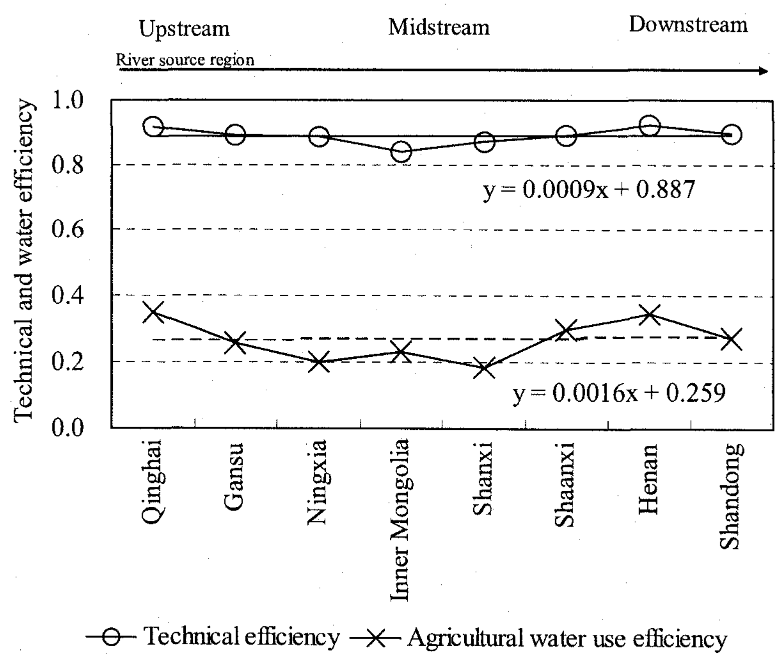

Figure 7. Spatial trends in technical efficiency and agricultural water use efficiency.
Note: The values shown here are the means of the technical efficiencies and agricultural water use efficiencies listed in Table 4.

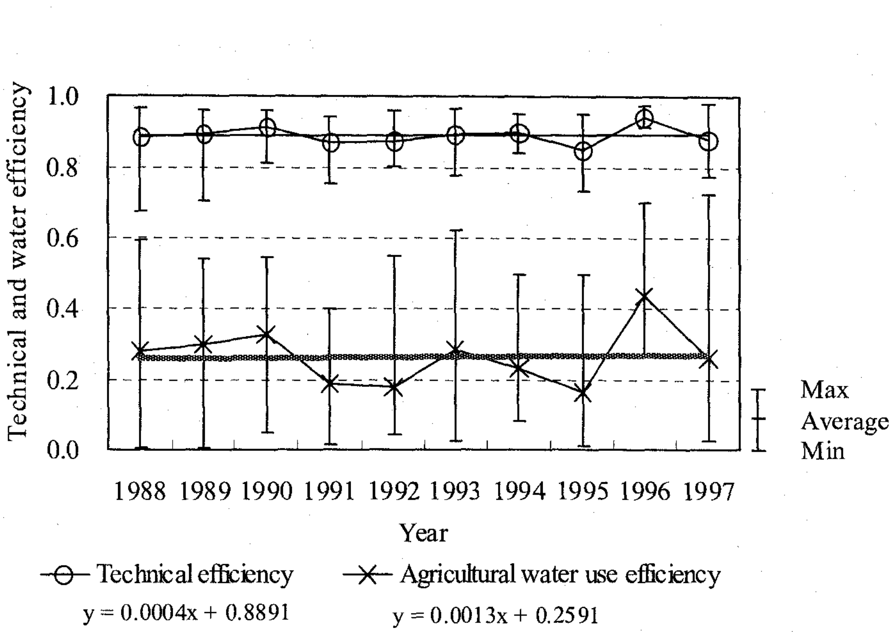

Figure 8. Trends in technical efficiency and agricultural water use efficiency.

5.2 Results of factor analysis for efficiency of agricultural water use

We identified which factors influenced the differences in efficiency of agricultural water use from values obtained in the previous section. Table 2 shows the variables used and results are shown in Table 5. The climate conditions, such as precipitation and sunlight hours, maize sown ratio, water-conservation irrigation districts, and rural household income were significant factors affecting the efficiency of water use, and the elasticity of sunlight hours was most important and scored the highest value.

Various explanations are possible for the effect of precipitation, e.g., efficiency of agricultural water use is high in areas with high amounts of precipitation possibly because there is little need for supplementary agricultural water where water is mainly supplied by rain. On the other hand, efficiency of agricultural water use is low in areas with low amounts of precipitation because of the relatively large need for supplementary agricultural water where rain supplies are insufficient. For example, the difference in average rainfall during the estimation period was approximately 1.7-fold between Inner Mongolia (301 mm), Ningxia (289 mm), and all other provinces (517 mm). Similarly, fluctuations in annual precipitation can improve or worsen efficiency, e.g., in low precipitation years, the efficiency of agricultural water use declines.

In terms of sunlight hours, some regions, such as Inner Mongolia and Ningxia, are in arid and semi-arid regions where more sunlight hours may enhance dryness and have a negative effect on the efficiency of agricultural water use.

The effect of rural household income can be explained in various ways; influential factors include: (1) regions with high income can afford to invest in improvements to water utilization and are therefore more efficient in agricultural production and water use; and (2) higher income in a region may be associated with higher awareness of water utilization, so that economic factors may be connected to improvements in efficiency of agricultural water use.

The coefficients in water-conservation irrigation districts and maize sown ratio were expected to be positive influences, but their signs indicate negative influences. (1) Improvements in physical infrastructure, such as water-conservation irrigation districts, may impact water conservation of agricultural water, but do not directly contribute to increases in production. (2) Since 1996, the Chinese government has started direct investment to improve irrigation facilities and institutional functions (Iijima and Suzuki, 2001). However, the effects of such improvements are not reflected in the current estimation period. The negative effects found may be because the water-conservation area tends to be located in less water use efficiency regions. Thus, the result may reflect this difference in regional characteristics. The area may require more time for the effects of improvements to be measured. For maize, a known water-saving crop (Chinese Academy of Engineering, 2001b; Kaneko *et al.*, 2004), increases in the sown area ratio may not directly contribute to increases in production. The regions that plant more maize are mostly located in arid and semi-arid areas where efficiencies of agricultural water use are not high. Thus, the maize sown ratio variable may reflect differences in regional characteristics. The Chinese government has recently been promoting the planting of crops that consume less water, including maize, especially in arid and semi-arid areas (Chinese Academy of Engineering, 2001a), and this may enhance the efficiencies of agricultural water use in the future.

Further examination of the results will be necessary in the future to evaluate the appropriateness of these conclusions.

Table 5. Results of factor analysis for efficiency of agricultural water use.

Variables	Coefficient	Elasticity
Maize sown ratio	-1.060** (-2.300)	-0.852
Rice sown ratio	-0.054 (-0.060)	-0.005
Precipitation	0.038* (1.760)	0.699
Sunlight hours	-0.290* (-1.700)	-2.864
Large-scale irrigation districts	0.184 (1.280)	0.429
Water-conservation irrigation districts	-0.393** (-2.350)	-0.461
Rural household income	1.667* (1.710)	0.474
Constant	0.897* (1.830)	
Log-likelihood	27.555	
χ^2 (7)	17.34	
Number of observation	80	

Notes:

(1) Values in parentheses are *t* values.

(2) Asterisks (*, **) represent 10% and 5% significance, respectively.

6. Conclusions

This study applied SFA techniques to estimate the efficiency of agricultural water use in individual provinces defined by boundaries of the Yellow River basin using a county and city level dataset focusing on the 1990s when water shortages were most severe. Factors affecting the obtained efficiencies were also analyzed. The major findings are summarized below:

1. Technical efficiency was highest in Henan and Qinghai, and lowest in Shanxi and Inner Mongolia. Agricultural water use efficiency was high in Qinghai and Henan, and lowest in Ningxia and Shanxi.
2. The efficiency of agricultural water use tended to be high in the river source region (Qinghai), midstream (except Shanxi), and downstream, but tended to be low upstream (especially Ningxia and Inner Mongolia). The tendency in efficiency changes for the entire river basin between 1988 and 1997 was mostly constant.
3. The amount of precipitation had a positive effect on the efficiency of agricultural water use in the Yellow River basin. Efficiency increased in regions and years with high precipitation. There may be little need to rely on agricultural water where rain supplies are sufficient. On the other hand, efficiency decreased in regions and years with low precipitation.
4. Sunlight hours had a negative effect on agricultural water use efficiency. In upstream areas, especially in Inner Mongolia and Ningxia, the Yellow River basin is located in arid and semi-arid regions. Therefore, more sunlight hours may increase evaporation and decrease the amount of water available for the grain crops.
5. Rural household income had a positive effect on the efficiency of agricultural water use. Regions with high income may be more able to improve infrastructure, such as through investment in facilities relating to water utilization. In addition, people living in the regions with a high income may be more aware of water conservation. Thus, economic factors may enhance improvements in the efficiency of agricultural water use.

In summary, to achieve sustainable agricultural production in the Yellow River basin under water resource constraints, it is necessary to improve agricultural water use efficiency, especially in upstream where agricultural water use is large. However, the region has a severe climate, including low precipitation and long sunlight hours; therefore, it is likely to require supplementary methods, such as a policy to enhance rural household income, to improve water utilization. To achieve sustainable food production in the Yellow River basin under water resource constraints, further studies of other possible methods for improving agricultural water use efficiency are needed.

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Notes

1. In this study, we used data on agricultural water use as water loss. The amount of water loss is the portion of water that evaporates or is absorbed by soil during transport and use, the portion contained in products, and the portion ingested by the human population and livestock—portions that are not restored to surface water bodies or groundwater layers (Ministry of Water Resources, 2000). In other words, this is the amount of water lost in the course of being used and not returned to the river or groundwater. Agricultural water loss was calculated from the difference between the amount of water used (including losses) and the amount of water recovered in surface water and groundwater (Ministry of Water Resources, 2000). This study defines agricultural water use as the amount of water loss, calculated as the amount of water drawn for irrigation purposes and consumed completely within the region.
2. Statistical values from the National Bureau of Statistics of China were taken from the bureau's website, http://www.stats.gov.cn/index.htm, accessed on 1 October 2006.
3. China Natural Resources Database is from the Institute of Geographic Sciences and Natural Resources Research (Chinese Academy of Sciences), accessed on 1 October 2006: http://www.naturalresources.csdb.cn/index.asp.
4. Foreign Agricultural Service, US Department of Agriculture, PS&D: http://jan.mannlib.cornell.edu/data-sets/international/, accessed 12 October 2006.
5. 1:1,000,000 scale China digital mapping data are based on topographical maps created by the State Bureau of Surveying and Mapping (SBSM).