Study on the efficiency of agricultural water use in the Yellow River basin

Akio Onishi*, Hidefumi Imura**, Tsugihiro Watanabe*, Yoshihiro Fukushima*
*Research Institute for Humanity and Nature,
**Graduate School of Environmental Studies, Nagoya University

1. Introduction

China faces the need to expand its food supply in order to meet the rising food demand of its growing population. The Yellow River basin, one of the important regions in China for agriculture production, has been able to increase its production thanks to by improvements in productivity. Environmental issues, water shortages in particular, have become more serious, however, and excessive agricultural water use may worsen the situation. Therefore, the effective use of water resources is essential if the country is to achieve sustainable food production.

In order to achieve above objective, this study creates administrative/watershed boundaries using available county- and city-level data, and attempts to measure agricultural water use efficiency in each part of the Yellow River Bain, by re-constructing these watershed boundaries using provinces associated with them. The analysis is conducted with a focus on the 1990s, when the river-stoppage phenomenon was at its worst. In addition, by identifying the factors that affect efficiency of agricultural water use calculated here, we suggest important directions for future policies and measures that affect water use. This analysis facilitates discussions about sustainable food production amid constraints on water resources in the river basin.

2. Background of food production issues

Food production in the Yellow River basin has been increasing steadily (**Fig. 1**). Food production is accomplished through the use of irrigation, which accounts for about 84% (calculated by authors from data on the amount of water loss for 1988 through 2002) of all usable water (Sun *et al*. 2001; Yellow River Conservancy Commission 1997-2002). In particular, Shandong Province and Inner Mongolia—home to some of the largest irrigation districts in the river basin—use enormous amounts of water for agriculture, accounting for about 50% of use in the entire river basin (**Fig. 2**). Meanwhile, food production per cubic meter of agricultural water used has been increasing in recent years, suggesting that the efficiency of water use has been improving (**Fig. 3**). The river stoppages were first noticed in 1972, but worsened dramatically in the 1990s, with the most extreme event occurring in 1997 (**Fig. 4**). During this period, the amount of water used for agricultural has been on a declining trend, but in the Yellow River Basin which has unstable water resource amounts, so excessive water use leads quickly to depletion of water resources. For this reason, it is very important that water be utilized efficiently and rationally. Furthermore, the amount of water going to new uses (industrial and urban household use) has been increasing in recent years, along with industrialization and urbanization driven by socio-economic development. Thus, it is likely that the agricultural use of water will be increasingly constrained in the coming years (Chinese Academy of Engineering 2001).

3. Target data and administrative/watershed boundaries

In cases where an analysis targets an area defined by natural boundaries like the Yellow River basin, statistical data for each province will generally include values from outside the watershed. Thus, when the aim is to analyze an area within a river basin, it is preferable to have more accurate spatial units than the provincial units. In such a case, in China it is possible to use data for the smallest administrative units: counties and cities. Meanwhile, for agricultural water data on the Yellow River basin, information is generally prepared using only province-level data. Because of this, some effort is necessary to ensure consistency with agricultural water 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 in this way therefore represents only the portion of spatial data associated with the provinces in the river basin. This procedure makes it possible to analyze the relationships between food

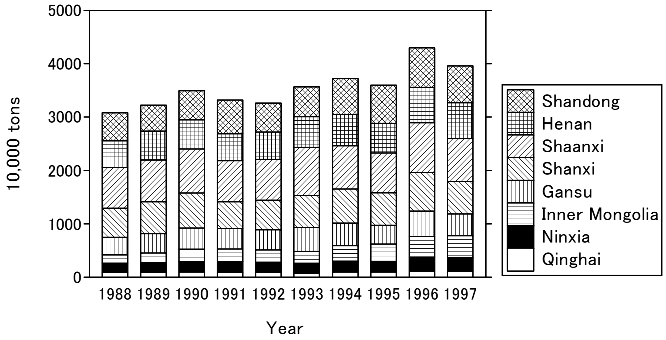

Fig. 1. Food production trends

Source: Prepared by authors from China Statistics Bureau (1989-1991), China Statistics Bureau (1989-1998), and China Natural Resources Database.

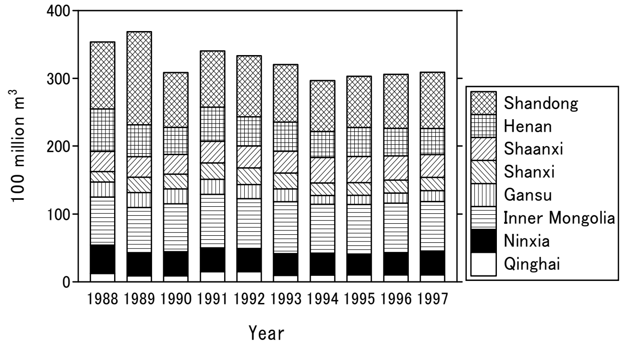

Fig. 2. Trends in agricultural water use

Source: Prepared by authors from Sun et al. 2001.

Note: Figures for 1996 and 1997 are estimates.

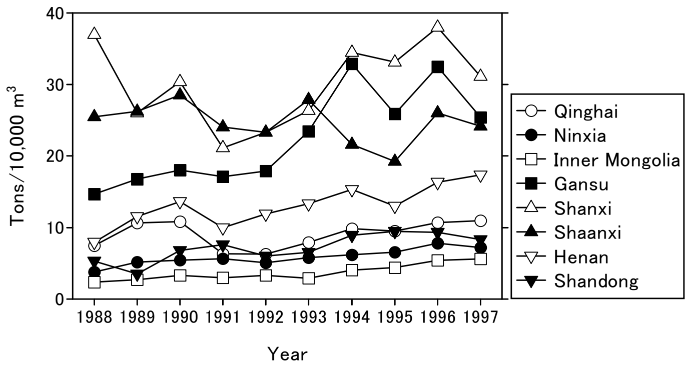

Fig. 3. Food production versus agricultural water use

Source: Prepared by authors.

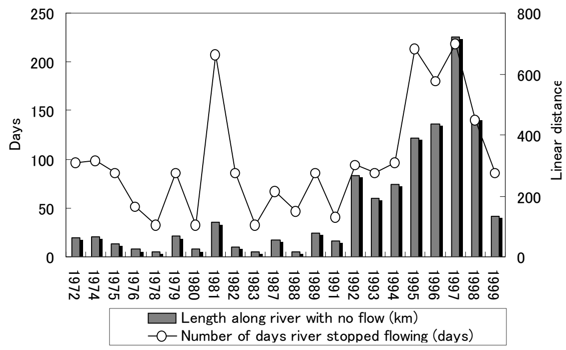

Fig. 4. River flow stoppages: duration and linear distance

Source: Prepared by authors from Sun et al. 2001.

production activities within the river basin and amounts of agricultural water use.

This study calculates the efficiency of agricultural water use in each province from 1988 through 1997. Also, it sub-classifies these provinces into zones (upstream, midstream, downstream) within the Yellow River basin, and conducts a comparative analysis of the efficiency values obtained. For this, it is necessary to determine which province is associated with each zone of the river basin.

Fig. 5 shows the administrative boundaries and river basin zones of the counties, cities and provincial jurisdictions in the Yellow River basin.

4. Analytical methodology

This study calculates the efficiency of agricultural water use in each region of the Yellow River basin, and analyzes the factors affecting the efficiencies thus calculated. To achieve this, analysis is done using the following three approaches. The variables used are summarized in **Table 1**. First, the factors that determine the agricultural water-use constant (amount of irrigation water per hectare of irrigation area) for each province are identified using the ordinary least squares (OLS) method. Next, using stochastic frontier analysis (SFA), we calculate the efficiency of agricultural water use for each region in the Yellow River basin area. Finally, using the Tobit model, factors that affect efficiency are identified.

4.1 Stochastic frontier analysis (SFA)

Stochastic frontier analysis (SFA) (Aiger *et al.* 1977; Meeusen and Julian 1977) is an analytical method that assumes a production function, which is assumed to be stochastically uncertain, to calculate inefficiencies by separating divergences from the production function into error and inefficiency. By this approach, it is possible to establish the production frontier curve as the most efficient possibility set, and this facilitates analysis of the

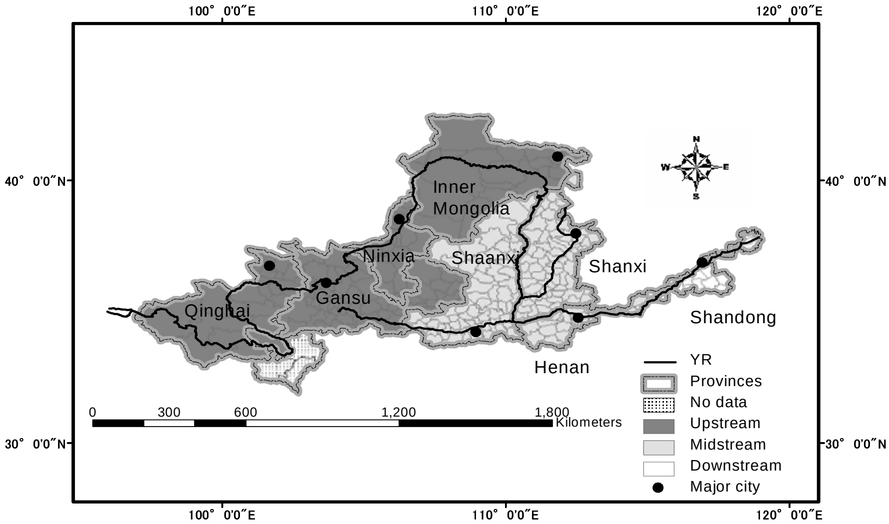

Fig. 5. Map of Yellow River basin showing watershed boundaries and zones

Table 1. Data used and details of estimates

Variable type	Agricultural water constant estimate	Variable selected	Stochastic frontier analysis	Variable selected	Tobit analysis	Variable selected
Non-descriptive	Agricultural water constant (m^3/ha)	Yes	Yield per hectare (kg/ha)	Yes	Value of agricultural water use efficiency	Yes
	Times of plantings	Yes	Rural population (persons/ha)	No	No. of plantings	No
	Maize crop ratio (%)	Yes	Amount of mechanization (kW/ha)	Yes	Maize crop ratio (%)	No
	Wheat crop ratio (%)	No	Use of chemical fertilizers (kg/ha)	Yes	Wheat crop ratio (%)	No
	Rice crop ratio (%)	No	Agricultural water loss (m^3/ha)	Yes	Rice crop ratio (%)	No
	Precipitation (100mm)	Yes	Time-scale trends	No	Precipitation (100mm)	Yes
	Average temperature (℃)	No	Upstream dummy	Yes	Average temperature (℃)	Yes
	Sunlight hours (x 1,000 hours)	No	Downstream dummy	Yes	Sunlight hours (x 1,000 hours)	Yes
	Area ratio of large-scale irrigation districts (%)	Yes			Area ratio of large-scale irrigation districts (%)	Yes
Descriptive	Area ratio of water-conserving irrigation districts (%)	Yes			Area ratio of water-conserving irrigation districts (%)	Yes
	Total dam capacity (100 million m^3)	Yes			Total dam capacity (100 million m^3)	Yes
	Rural household income (10,000 yuan: 1988 level)	No			Rural household income (10,000 yuan: 1988 level)	Yes
	Alkaline soil recovery area (%)	Yes			Alkaline soil recovery area (%)	No
	Time-scale trend	Yes			Time-scale trends	No
	Upstream dummy	Yes			Upstream dummy	No
	Downstream dummy	Yes			Downstream dummy	No

Notes
1. For agricultural water constant, the value used is each province's amount of agricultural water use divided by area under irrigation.
2. For values used in stochastic frontier analysis, values were divided by planted area.
3. No. of plantings ＝ planted area divided by cultivated area.
4. Crop ratios for maize, wheat, rice represent the planted area of the stated crop as a ratio of total planted area for food production.
5. Area ratio of large-scale irrigation districts and area ratio of water-conserving irrigation districts represent the relative area of each item compared to effective area under irrigation.

inefficiency of each production entity in relationship to the frontier.

The stochastic frontier analysis (SFA) model is expressed as shown below.

$$\hat{Y}_{it} = f\left(X_{it}, W_{it}, \beta\right)\exp\left(V_{it} - U_{it}\right) \tag{1}$$

Where $\hat{Y}$ is the frontier production amount, X_{it} is production input factors other than agricultural water, W_{it} is agricultural water input, β is the estimated parameter, V_{it} is the ordinary error term($U_{it} \overset{iid}{\sim} N^{+}\left(0, \sigma_u^2\right)$), and U_{it} is assumed to follow a half normal distribution($V_{it} \overset{iid}{\sim} N\left(0, \sigma_v^2\right)$)

The Cobb-Douglas form (CD-form) and translog form are often used for stochastic frontier analysis (SFA). Of the two, the translog form is the most flexible, but because the estimate includes overlapping items, multicollinearity is likely to occur with the descriptive variable. Conversely, with the Cobb-Douglas form, although an elasticity of substitution of one is a precondition, it is easier to obtain more stable calculation results. Thus, in this study estimates are done using the maximum likelihood method assuming the Cobb Douglas function form shown below.

$$\ln \hat{Y}_{it} = \beta_0 + \beta_1 \ln K_{it} + \beta_2 N_{it} + \beta_3 \ln W_{it} + V_{it} - U_{it} \qquad (2)$$

Where K_{it} is the amount of mechanization, N_{it} is the amount of utilization of chemical fertilizers, W_{it} is the amount of agricultural water loss, i indicates the province in the Yellow River administrative/watershed area, and t is the year.

Technical efficiency in this study is expressed by comparing the amount of maximum production from factor of production inputs and the amount of current production. **Fig. 6** shows the correlation between current production Y_R in relation to the amount of input of agricultural water W, and amount of production $\hat{Y}$ obtained from the frontier production coefficient. This figure shows that, as for technical efficiency, based on current amount of agricultural water input W_R,, it is possible to increase production from Y_R to $\hat{Y}$.Thus the current amount of production Y_R could be said to have an inefficiency of $Y_R/\hat{Y}$. Similarly, as for the efficiency of use of agricultural water, by fixing the amount of imports of other factors of production, by defining it as the smallest amount of agricultural water input that is input to in order to produce a certain amount of production, in order 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 $\hat{W}$. . In other words, the current amount agricultural water input W_R could be said to have an inefficiency of $\hat{W}/W_R$. These efficiency values range from zero to one, and the closer they come to the frontier, the closer they approach one.

Thus, the technical efficiency is expressed as shown below.

$$TE_{it} = \exp(-U_{it}) \qquad (3)$$

Efficiency of agricultural water use (WE_{it}) is expressed as shown below.

$$WE_{it} = \exp(-U_{it} / \beta) \qquad (4)$$

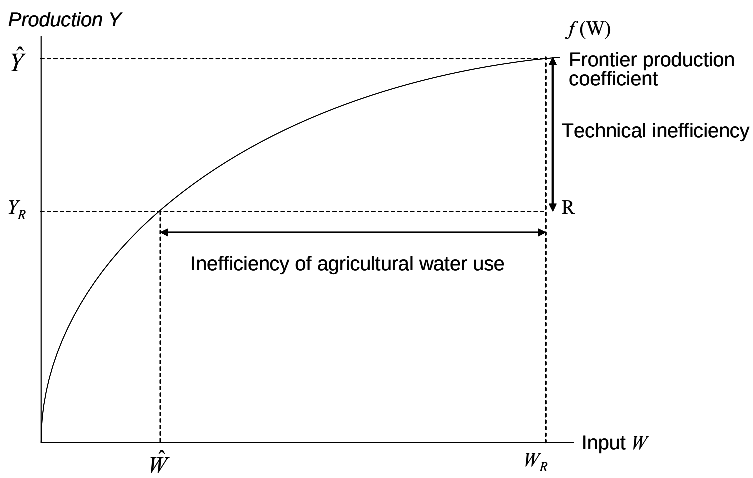

Fig. 6. Stochastic frontier analysis (SFA) and efficiency

4.2 Tobit analysis

In order to estimate what kind of factors determine differences in efficiency of agricultural water use, the Tobit model shown below is used. The Tobit model is used because efficiency takes a value ranging from zero to one.

$$WE_{it} = \begin{cases} 0 & if \quad \sum_j \lambda_j S_{ij} + \varepsilon_i \le 0 \\ \sum_j \lambda_j S_{ij} & if \quad 0 < \sum_j \lambda_j S_{ij} + \varepsilon_i < 1 \\ 1 & if \quad \sum_j \lambda_j S_{ij} + \varepsilon_i \le 1 \end{cases} \qquad (5)$$

Where S_{ij} is the descriptive variable, λ_{ij} is the parameter being estimated (where j is an index of the descriptive variable), ε_i is the error term and $\varepsilon_{ij} \sim N(0, \sigma^2)$.

5. Results

5.1 Analytical results for irrigation constants

As a preliminary step to calculate efficiency of agricultural water use, here we consider what factors determine differences in the amount of agricultural water use. By considering this issue, we can come to understand the physical characteristics of agricultural water use.

Here, we selected variables after considering research by Kaneko *et al*. (2004).When regression is conducted using all variables, however, multicollinearity occurs between the descriptive variables. For this reason, we made a selection of variables. **Table 1** shows the variables that were selected. The results are shown in **Table 2**. Three points can be concluded: (1) the calculation results are favorable, producing high correlation coefficients, and (2) the coefficient obtained is significant, and descriptive variables that have a positive impact on non-descriptive variables include large-scale irrigation districts, upstream dummy, and downstream dummy, whereas (3) descriptive variables with a negative impact include the maize planting ratio, water-conserving irrigation districts, and time-scale trends.

In these results one notices that, in particular, in areas where the ratio of area of large-scale irrigation district is high, the agricultural water constant tends to be high, but in areas where the ratio of area of water-conserving irrigation districts is high, the agricultural water constant tends to be low. Furthermore, one can see that, similar to

Table 2. Results of calculations of factors in agricultural water constants

Name of variable	Partial regression coefficient	Standard partial regression coefficient
No. of plantings	-74.704 (-0.037)	-0.004
Maize crop ratio	-24326.266*** (-3.750)	-0.597
Precipitation	-94.399 (-0.354)	-0.040
Area ratio of large-scale irrigation districts	7416.102* -1.812	0.677
Area ratio of water-conserving irrigation districts	-14028.698*** (-8.099)	-0.537
Total dam capacity	0.872 (0.157)	0.018
Alkaline soil recovery ratio	10451.849 (0.200)	0.094
Time-scale trends	-303.408*** (-4.577)	-0.201
Upstream dummy	3544.276*** (5.239)	0.409
Downstream dummy	7751.202*** (2.670)	0.592
Constant	12755.100*** (6.134)	—
$\underline{R^2}$	0.946	
R^2	0.938	
Number of measurements	80	

Notes: (1) Values in parentheses are t values. (2) Asterisks (*, **, ***) represent 10%, 5%, and 1% significance, respectively.

findings of Kaneko *et al.* (2004), the higher the maize planting ratio, the lower the agricultural water constant tends to be. This may be due to the fact that maize requires relatively less water than other food crops (Chinese Academy of Engineering 2001). Besides these points, although the results obtained are not statistically significant, total dam capacity and area of alkaline soil recovery are factors with a positive sign, for example, while planting frequency and amount of precipitation have a negative sign. The signs here are intriguing, and in the future it will be important to consider these in more detail.

5.2 Calculation results for technical efficiency and agricultural water efficiency

Here, we use each variable shown in **Table 1**, but where no significant parameter is obtained, it is excluded from factors of production. Excluded variables are agricultural population and time-scale trends, as collinear relationships were identified between amount of mechanization and agricultural population, as well as chemical fertilizers and time-scale trends. The results are shown in **Table 3**. For reference, we also display the results of CD-form average production function calculated using the OLS method. The results obtained by both the SFA and OLS methods are favorable, and all the coefficients are significant. It is generally known that in China that elasticity of chemical fertilizers is high (Toyotya *et al.* 2005 ; Peng and Kawaguchi 2000). However, the elasticity of the amount of mechanization exhibits the highest value here. There are at least three reasons for this outcome: (1) the value for amount of mechanization includes the impacts of both mechanization and agricultural population, (2) factors of production in the Yellow River basin are characterized by large influence from the amount of mechanization and agricultural population, and (3) during the period of calculation—1988 through 1997—Chinese agricultural production was at a peak, so high elasticity of chemical fertilizers like during economic reforms and liberalization are not observed. Calculations of dummy coefficients for the upstream and downstream zones resulted in relatively low production upstream and high production downstream.

Technical efficiency (TE) and efficiency of agricultural water use (WE) are calculated based on the calculation results obtained above. The results are shown in **Table 4**. For technical efficiency and efficiency of agricultural water use, Shaanxi Province displayed the highest efficiency, while Inner Mongolia and Shanxi Province displayed the lowest efficiency. It is also evident that efficiency increases as one progresses from the upstream zone to the downstream zone.

Fig. 7 displays the changes in efficiency in the entire river basin from 1988 through 1997. From this figure is evident that both technical efficiency and efficiency of agricultural water use are gradually increasing. In particular one can see remarkable improvements in the minimum values. Based on this outcome, one can tell that technical efficiency is improving, and that the efficiency of agricultural water use is also improving. Meanwhile, efficiency, which had been on an increasing trend, started to decrease in 1997, and it is intriguing to think that this inefficiency in water use may have been a factor behind the river flow stoppages. It should be noted, however,

Table 3. Results of calculations of stochastic frontier analysis (SFA)

Name of variable	OLS	SFA	
	Coefficient	Coefficient	Standard area
Amount of mechanization	0.320*** (5.591)	0.317 (5.806)	0.055
Use of chemical fertilizers	0.157*** (2.779)	0.15 (2.797)	0.054
Agricultural water loss	0.057** (2.284)	0.065 (2.506)	0.026
Upstream dummy	-0.106** (-2.362)	-0.108 (-2.536)	0.043
Downstream dummy	0.187*** (3.623)	0.178 (3.581)	0.05
Constant	6.399*** (24.438)	6.470 (25.651)	0.252
R^2	0.922		
$\overline{R^2}$	0.917		
Log likelihood		63.100	
Number of measurements	80	80	

Notes: (1) Values in parentheses are t values. (2) Asterisks (*, **, ***) represent 10%, 5%, and 1% significance, respectively.

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

	Technical efficiency			Agricultural water use efficiency				Technical efficiency	Agricultural water use efficiency
	Ave.	Min.	Max.	Ave.	Min.	Max.		Ave.	Ave.
Qinghai	0.934	0.896	0.961	0.367	0.183	0.539	Upstream zone	0.916	0.307
Ninxia	0.920	0.898	0.954	0.283	0.190	0.486			
Inner Mongolia	0.892	0.768	0.976	0.276	0.017	0.690			
Gansu	0.918	0.832	0.965	0.301	0.058	0.579			
Shanxi	0.899	0.824	0.936	0.221	0.050	0.361	Midstream zone	0.922	0.312
Shaanxi	0.935	0.893	0.964	0.377	0.173	0.563			
Henan	0.931	0.902	0.951	0.340	0.202	0.458			
Shandong	0.923	0.863	0.951	0.313	0.103	0.462	Downstream zone	0.923	0.313
Ave.	0.919	0.859	0.957	0.310	0.122	0.517	Ave.	0.919	0.310

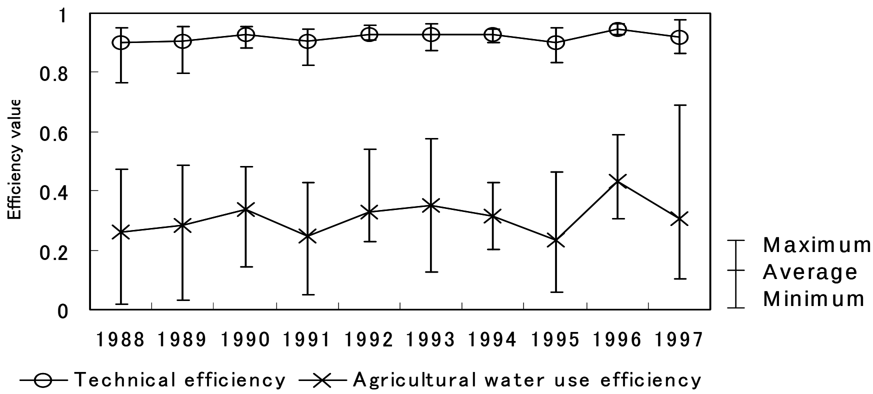

Fig. 7. Trends in technical efficiency and agricultural water use efficiency

Table 5. Estimates using Tobit model

Variable name	Coefficient	Elasticity
Precipitation	0.035** (2.200)	0.931
Temperature	0.001 (0.120)	0.074
Hours of sunlight	-0.088 (-0.840)	-1.403
Total dam capacity	0.000 (-0.610)	-0.029
Agricultural household income	1.444** (2.090)	0.496
Large-scale irrigation districts	-0.033 (-0.440)	-0.124
Water-conserving irrigation districts	-0.228* (-1.650)	-0.374
Constant	0.371* (1.880)	
Log likelihood	52.254	
Number of measurements	80	

Notes: (1) Values in parentheses are t values. (2) Asterisks (*, **, ***) represent 10%, 5%, and 1% significance, respectively.

that agricultural water use data for 1997 are estimated values in this study, so it will be necessary to reconsider these findings if actual figures become available in the future.

5.3 Results of factor analysis for efficiency of agricultural water use

Here we consider which factors influenced the differences in efficiency of agricultural water use obtained in the previous section. **Table 1** shows the variables that were used. The results are shown in **Table 5**. It is evident that the amount of precipitation and the rural household income have an impact on changes in efficiency, and that elasticities are also high.

Regarding the influence of precipitation, various explanations are possible, including (1) the fact that efficiency of agricultural water use is high in areas with high amounts of precipitation, may be due a relatively small need for agricultural water where it is likely that rain-fed agriculture is being conducted; and (2) because fluctuations in annual precipitation can improve or worsen efficiency, in low precipitation years like 1997, the efficiency of agricultural water use worsens.

Regarding the influence of rural household income, factors include the possibility that (1) regions with high income can afford to invest in water conservation-related improvements, and therefore are more efficient in agricultural production, and (2) higher income in a region may be associated with higher awareness about water conservation, so that economic growth is connected to improvements in efficiency of agricultural water use.

It should be noted, however, that the coefficients in water-conserving irrigation districts exert a negative influence, and water conservation contributes to a reduction in the actual agricultural water use, as shown in **Table 2**, suggesting that these are not directly connected to efficiency of agricultural water use. In other words this means that improvements in physical infrastructure, such as water-conserving irrigation districts, are expanding and have an impact on water conservation of agricultural water, but that they are not directly contributing to increases in production. Nevertheless, further discussion will be necessary in the future regarding the appropriateness of this conclusion.

6. Conclusions

Focusing on the 1990s, when river-flow stoppages became more serious, this study used stochastic frontier analysis (SFA) methods to calculate the efficiency of agricultural water use in each part of the Yellow River basin. It also analyzed what factors affect differences in the efficiencies obtained.

References

Aiger, C. A., Knox, L. and Schmidt, T. (1977): Formulation and Estimation of Stochastic Frontier Production Function Models. Journal of Econometrics, 6: 21-37.

China Statistics Bureau (1989-1991): China County Agricultural Economics Statistics Summary, China Statistics Press.

China Statistics Bureau (1989-1998): Urban Statistical Yearbook of China, China Statistics Press.

China Natural Resources Database. http://www.naturalresources.csdb.cn/index.asp.

Chinese Academy of Engineering (2001) : A Series of Reports on Water Resource Strategies for China's Sustainable Development, Vol.1-9, Water Publication Company of China (in Chinese).

Kaneko, S., Tanaka, K. and Toyota, T. (2004): Water efficiency of agricultural production in China: regional comparison from 1999 to 2002. Int. J. Agricultural Resources, Governance and Ecology. 3(3/4): 231-251.

Meeusen, W. and Julian, B. (1977): Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error. International Economic Review, l. 18: 435-444.

Peng, D. and Kawaguchi, T. (2000): Meta-regression regression analysis relating to the elasticity of production of chemical fertilizers in agriculture in China. Anthology of agricultural economics, 51- 2: 23-30 (in Japanese).

Sun, G., Qiao, X. & Sun, S. (2001) : *Yellow River Water Resources Management*, Yellow River Water Conservancy Press.

Toyota, T., Kaneko, S. and Tanaka, K. (2005): Research relating to the use of chemical fertilizers and productivity in agriculture in China—Case studies on the production of rice, wheat, and maize. Compilation of environmental systems research reports 33: 89-96 (in Japanese).

Yellow River Conservancy Commission (1997-2000): *Yellow River Water Resources Gazette*.