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Evaluation Indicators on Water-use Sustainability in Irrigated Paddy Farming

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Abstract

It is important to adopt a common international understanding and perspective in the agreement on the environmental impact of agricultural water-use in the regions of the world. This paper investigates water-use sustainability as a measure of the impact on the environment and natural resources of irrigated paddy farming in 31 countries and regions of the world. A quantification theory was used to analyze the main simplified factors in water-use sustainability. A methodology and overall indicators for the evaluation on a national scale are proposed from an international comparison on water-use sustainability. The study provides a valuable insight into the international agreements on the relationship between agriculture and water resources.

Discipline: Irrigation, drainage and reclamation
Additional key words: impact of agriculture, international environmental agreement, water resources

Introduction

Since 1993, the OECD (Organization for Economic Cooperation and Development) has been conducting a study on the environmental impact of agricultural production and agricultural policy[6]. The study has generated great interest in the multifunctionality analysis of agriculture[12]. Meanwhile, in the international environmental agreements on water resources and water-use in agriculture, a new understanding regarding the importance of proper management of the world's water resources was reached at the Second World Water Forum (Hague) in March 2000[7,11].

Moreover, the 3rd World Water Forum (Kyoto) in March 2003 declared that every effort should be made to reduce unsustainable water management and to improve the efficiency of agricultural water use.

In the Asian monsoon regions, one of the principal humid zones of the world, farming on irrigated paddy fields has been sustained over many years by adapting to hydro-meteorological conditions. Japan has been building man-made irrigation systems and utilizing water resources in agriculture for more than 2,000 years, and paddy field irrigation technology has been passed down through family-based farming operations and local communities.

The water used for irrigation in paddy fields performs a number of important functions for rice cultivation. Although some water is consumed via evapotranspiration, much of it percolates underground where it acts as a solute carrier, delivering nutrients to the rice plants and eliminating harmful substances from the soil. Irrigation also has flow-on benefits in other off-farm areas; by percolating underground and flowing away at ground level, it alters the groundwater and river flows. In humid regions,

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this has a positive impact, supplementing and purifying the groundwater and stabilizing river flows during drought periods. These impacts are now recognized as the multi-functional benefits of agricultural practices in off-farm areas[14].

Today, however, the sustainable productivity of irrigation farming in the world has declined, due to inundation damage and salinity accumulation caused by water shortages and the lack of drainage facilities. Meanwhile, overuse of groundwater and the deteriorating quality of surface water also restrict sustainable water-use. The result is that in some cases, irrigation farming actually exerts a negative rather than positive impact on non-agricultural regions[13].

It is important to adopt a common international understanding and perspective in the agreement on the environmental impact of agricultural water-use, which has regional differences in the various parts of the world. In this context, numerical evaluation of water-use patterns constitutes an important and necessary instrument in the analysis of international policy issues.

This paper looks at water-use sustainability as a headline indicator of the impact on the environment and natural resources of irrigated paddy farming in the main countries and regions of the world, including humid, dry/sub-humid and arid regions (upland farming is not considered). In this study, the term “water-use sustainability” is defined as the degree of water utility in the long-term without imposing negative impacts upon the natural resources in the region.

To this end, the paper identifies the main simplified indicators for evaluating the sustainability of water-use at the global level; uses these indicators to categorize the different regions based on regional data; and applies statistical techniques to develop a quantitative methodology for macro-level international comparison of water-use sustainability.

Materials and methods

Using a combination of regional field studies and surveys of the relevant literature, the authors built up a picture of water resources and water-use in the agricultural sectors of countries where irrigated paddy farming is practiced. Based on data obtained both within and outside Japan, the authors then identified indicators for use in evaluating the sustainability of water-use in each particular region. The focus of this paper is clarification of the relationship between irrigated paddy farming and sustainable water-use. According to the environmental scenario posited by the authors, an inability to maintain sustainable water-use in the agricultural sector would generate additional costs and exert a negative impact on water-use and the regional water resources in off-farm areas. Water-use sustainability was quantitatively evaluated in terms of both the positive and negative effects of water usage on the environment and water resources such as natural river flow and groundwater. Quantification Theory Type I was used to analyze the main factors in water-use sustainability. The sample consisted of 31 regions in 26 countries, primarily OECD member nations where irrigated paddy farming is implemented to some extent, as well as nations which have more than one million hectares of rice fields for harvesting.

Moreover, the overall indicators are proposed from an international comparison on water-use sustainability in irrigated paddy farming.

Results and discussion

1. Overview of irrigated paddy farming throughout the world

Irrigated paddy farming mainly refers to rice production as an internal economy. Outside Japan, paddy field farming is implemented extensively in Asia, and especially Monsoon Asia, as well as Australia, North America and southern Europe. Conditions in each of these regions are summarized below, based on a combination of field studies and surveys of the relevant literature.

(1) Monsoon Asia

Rice farming began in the lower delta region of the Yangtze River in China in around 5,000 B.C. From there it spread into southern Asia, south-east Asia and India, where today’s familiar rice paddy technology gradually evolved in line with the hot, humid climate of Monsoon Asia. Today, rice is the staple diet of the region which, with annual rainfall of over 1,000 mm, contributes in excess of 90% of the world’s rice production in combination with other parts of Asia. The role of irrigated paddy farming in contributing to sustainable resource conservation has already been recognized in prior research[8]. Thus, sustainable water-use has been a feature of this region throughout its long history.

(2) Australia (South-eastern region)

Hayase and Masumoto conducted a study of irrigation farming and resource conservation in the Murray River Basin in New South Wales, currently the only rice-producing region in Australia[4]. While annual rainfall in the region is around 300–600 mm, evapotranspiration is extensive all year around, reaching a total of 1,300–1,700 mm. Irrigation water is drawn from dams and reservoirs on the natural river system in the region, and pumped to the fields via channels and waterways. Since the 1960s, some 500,000 km^2 of forest (approximately half the river basin area) has been converted to grain fields and pasture, and this, coupled with the increase in irrigation, has resulted in rising water tables, as well as major salinity accumulation due to surface water losses[4]. In this way, irrigation has a negative impact on the natural environment in the region, and water-use cannot be considered sustainable.

(3) United States (Arkansas and California) [1,2,9]

In Arkansas, the top rice-producing state in the United States, rice is grown in irrigated fields using nearby underground water by pumps. The groundwater table in the vicinity of Stuttgart, in the center of the Arkansas Grand Prairie region, has dropped from 6 m in 1910 to 38 m in 1996 as a result of excessive water-use. The impact has been particularly severe in the areas farthest from the Mississippi River, which have no alternative water sources. Because of the impermeable cohesive soil, paddy field irrigation is unable to filter through and replenish the underground water supplies.

California is the second-largest rice-producing state in the United States. The main rice-producing region is the Sacramento River Basin in the north, home to 94% of the state's paddy fields, which enjoys relatively plentiful average annual rainfall (for California) of 914 mm. Irrigation water is diverted into dams on the Sacramento River and distributed out to the fields via long-distance irrigation canals.

Rice farming is declining in the San Joaquin River Basin area to the south, where the rainfall is lower, due to concerns over the volume of irrigation water being used and the high cost of transporting the water, as well as water runoff and soil salinity accumulation. Water-use cannot be considered sustainable in the San Joaquin River Basin, which has minimal annual rainfall (240 mm at Fresno).

(4) Southern Europe[10]

In Europe, the largest rice-producing country is Italy, which makes extensive use of irrigated paddy field farming. The middle reaches of the Po River Basin in the north account for 95% of rice production in Italy. Annual rainfall in the region is 840 mm, and the Po River, with its river basin in the Italian Alps, provides plenty of water for irrigation, so productivity is high.

The rice production area is located in an alluvial fan with a slope of 1/1,000. The highly permeable sandy soil in this region allows irrigation water to percolate down into the groundwater, thence to become spring water (artesian wells) in the lower reaches which are in turn used for irrigation. Thus, much of the irrigation water is effectively recycled in what is considered a highly sustainable water-use pattern.

The only rice-producing region in mainland France is the Camargue, on the delta at the mouth of the Rhone River. The Camargue is surrounded by artificial embankments. The upper reaches are used for irrigated rice production, while the lower reaches are taken up with saltwater marshes. Annual rainfall is 600 mm and evapotranspiration is 1,200 mm. Fresh water is pumped up from the Rhone through specially constructed irrigation canals. Irrigation in this way also helps to keep the underground salinity from rising. The water naturally drains away by gravity.

Given that the paddy fields are located close to the river mouth and serviced by fresh water and irrigation and drainage channels continuously, the water-use sustainability is high. Moreover, the paddy field irrigation actively contributes to the conservation of groundwater in the region.

2. Indicators for evaluation

The main benefit of irrigation farming for the environment and natural resources is that it maintains a good supply of water resources for use in human activity and for preserving biodiversity and other aspects of the ecological environment.

On the negative side, irrigation farming can lead to depletion of surface water and groundwater resources, cause inundation damage (due to rising groundwater or waterlogging), and increase salinity levels of both surface soil and groundwater in some semi-arid and arid regions. Based on studies of irrigation farming in various countries, the negative effects of irrigation farming can be broadly divided into two groups as follows.

i) In semi-arid and arid regions, irrigation farming consumes a significant volume of the regional water resources. Furthermore, if proper drainage facilities are not available, irrigation can cause the groundwater level to rise, leading to salinity injury to farms and groundwater by high evaporation. In this way, irrigation markedly prevents sustainable water-use. In particular, because paddy ponding irrigation consumes far more water than upland irrigation such as spraying and drip irrigation, continuous paddy field irrigation has a substantial impact on water resources in these regions.

ii) Even in humid regions, the use of groundwater for irrigation can cause a marked drop in groundwater levels, thereby exerting a negative impact on groundwater replenishment and preventing sustainable water-use.

In consideration of the above and the indispensable natural conditions for rice cultivation, the following items related to water resources and salinity injury are considered to be useful indicators for evaluating the water-use sustainability:

① Climate,
② Soil type (including salts),
③ Irrigation water resource (river, groundwater, water divided from outside of a basin),
④ Use of sustainability strategies such as groundwater management or drainage.

The impacts of irrigated paddy farming on water resources and the general environment with the extracted indicators are arranged in Table 1.

3. Evaluation indicators

Numerical and descriptive indicators for evaluating water-use sustainability in the various countries and regions are described below. These are designed to be easy to apply to generally available statistical information.

(1) Climate classification

This indicator is used to distinguish between humid and arid climates. For the purpose of this study, a humid climate is defined as one with at least 500 mm (approximately) of annual rainfall, the minimum required to carry on agricultural activities without using additional water supplies[5]. A dry/sub-humid climate is defined as one with annual rainfall in the range of 500–1,000 mm[3]. This indicator can be used to evaluate water-use sustainability in terms of the negative impact on water resources (through high consumption levels) and the likelihood of salinity injury. Semi-arid and arid climates are defined as those with annual rainfall of less than 500 mm.

(2) Soil type (Salinity)

Saline soil is a problem common to all arid regions (in humid climates, the plentiful rains tend to wash the salts out of the soil). In arid regions with poor or inadequate drainage, surface salinity typically occurs in low-lying areas, while the saline concentration of groundwater also increases. While annual rainfall is the single largest factor affecting water-use sustainability (by preventing salt buildup, for instance), it is also important to know whether the soil is salty or not. Soil type is selected as a simplified indicator for salinity injury which may obstruct sustainable water use.

(3) Irrigation water resources

Where groundwater is used for irrigation, if the water is taken out of the ground faster than it can be replenished naturally, then irrigation is said to have a negative impact on groundwater resources and, in turn, on water-use sustainability. Supposing the surface water for irrigation is brought in from outside of the basin, then the irrigation farming ultimately impacts on water resources in the source region. Thus, the source of the water used for irrigation is also an important indicator of sustainability. For the purpose of this study, the "both" category is used in situations where both river water and groundwater are used for irrigation, with neither contributing more than 60% of the total.

(4) Groundwater management (anti-salinity control) strategies

Some arid regions that are susceptible to salinity accumulation are still able to conserve water resources and achieve sustainable water-use through the use of proper drainage and/or runoff treatment facilities. Thus, groundwater management by drainage is considered an

Table 1. Impacts of irrigated paddy farming to water resources and the general environment

Indicator	Category	Effect on environment and water resources (positive/negative)
Climate	Humid	Positive
	Dry·Sub-humid	Positive or Negative
	Semi-arid, Arid	Negative
Soil type	Saline	Negative
	Non saline	Positive
Irrigation water resource	River	Positive
	Groundwater	Negative
	Both	Positive or Negative
Groundwater management	Yes (susceptible region)	Negative or minimal
	No (susceptible region)	Negative
	No (not a problem)	Positive or minimal

important factor in relation to sustainability. Table 2 presents international comparisons of evaluation indicators and irrigation patterns.

4. Quantitative analysis of evaluation indicators

(1) Using Quantification Theory Type I
(indicator analysis)

Quantification Theory Type I was applied, using the four indicators identified above as explanatory variables and a sustainability rating delivered by a panel of experts as the response variable, in order to perform a quantitative analysis of the ultimate influence of the indicators on water-use sustainability. Expression (1) given below was applied to the sample of 31 regions in 26 countries and the influence of each indicator on water-use sustainability was calculated as α_{jk}.

The groundwater management indicator was found to have a strong inter-correlation with the climate classification (humid/arid) and the soil classification. It was consequently omitted and the analysis was performed with just three indicators.

$$V_i = \sum_{j=1}^{n_j} \sum_{k=1}^{j_k} \alpha_{jk} \cdot x_i(jk) \qquad (1)$$

where V_i is the estimated value of water-use sustainability for the sample i; α_{jk} is the evaluation coefficient for factor j and category k; $x_i(jk) = 1$ (for factor j and category k) or 0 (for other than factor j and category k); j_k is the number of categories for factor j; and n_j is the number of evaluation elements (= 3 when three indicators are used).

The estimated values for the various countries were converted to data format based on the statistics and other information presented in Table 2 and using the categories shown in Table 4. Table 3 shows the sample data together with the water-use sustainability ratings.

Assessments provided by experts in five fields, hydrology, soil, water usage, rural planning, and hydraulics, were used to calculate a combined evaluation score on a five-point scale. The scores were then used as external standards for calculating the value of α_{jk} in expression (1) above. The evaluation coefficient column in Table 4 shows α_{jk} values calculated using Quantification Theory Type I, while Table 3 shows estimates based on the α_{jk} values corresponding to the sample conditions.

The evaluation categories for each country and region divide the water-use sustainability estimates into three levels: high sustainability (category A), medium sustainability (B) and low sustainability (C). Table 4 shows the correlations between these categories and the various water sustainability indicators. It can be seen that factors such as humid climate (+0.35), absence of soil salinity (+0.72) and use of surface water for irrigation (+0.26) have positive evaluation coefficients, indicating a positive influence on sustainability of water-use.

Among the eight categories, “Soil type: No salinity” has the strongest positive influence on sustainability, while Climate: Arid (–1.43) and Water resources: Groundwater (–1.56) represent the two largest negative influences.

The soil type classification has the largest partial correlation coefficient (0.61) among the three represented indicators, and consequently would be expected to have the strongest influence on the water-use sustainability. However, when the range (1.31) is taken into consideration, the soil type indicator actually has a relatively small influence, and it is therefore considered to be roughly equivalent to the other two indicators in terms of sustainability evaluation.

(2) Water-use sustainability classifications

Table 5 re-arranges Table 3 and shows the quantitative water-use sustainability classifications and grouping of all countries and regions in the sample. Evaluations

Table 4. Influence of evaluation indicators

Indicator	Category	Sample Size	Evaluation Coefficient	Range	Partial Correlation Coefficient
Climate	Humid	18	0.35	1.78	0.57
	Dry·Sub-humid	8	–0.02		
	Semi-Arid, Arid	5	–1.43		
Soil type	Salinity	17	–0.59	1.31	0.61
	No salinity	14	0.72		
Water resources	Groundwater	2	–1.56	1.82	0.53
	Surface water	21	0.26		
	Both	8	–0.29		

Note: Sample size: 31, average evaluation estimate: 3.68, multiple correlation coefficient: 0.85.

Table 2. International comparisons of evaluation indicators and irrigation patterns

No.	Country	Region used for evaluation	Annual rice production (× 1,000 tons/year)	Annual rainfall (mm/year)	Soil basicity	Water usage	Environmental impact/other remarks
1	India	Northwest (Haryana Province)	120,012	796	Yes	Rivers + reservoirs (36.8%), tube wells (48.9%), irrigation ponds (6.9%)	1) Rising water table and salinity in dry areas; 2) Tube well programs and groundwater usage; 3) In Punjab Province, water table falling by 0.3–0.5 m per year
2	India	East (Bihar Province)		1,729		River water (large-scale irrigation) + groundwater	
3	China	Central (Yangtze River Basin)	190,100	1,037	Yes	River water (95%)	Increasing water shortage, especially in north China
4	China	South (Pearl River)		1,684		River water (95%), double cropping	
5	Indonesia	Java	51,165	1,928	No	River water + reservoirs (within river basin), wet and dry cropping, 2.5 crops per year	Water withdrawal as percentage of renewable water resources: 3%
6	Bangladesh	All (delta)	28,008	2,812	No	Wet cropping: dry field to deep wet planting, natural water supplies; dry cropping: underground water (shallow wells = 44%, pumped = 20%, deep wells = 20%), other = 17% Water supply by source; Surface water 27% , Groundwater 73%	Wet cropping: 1) natural rain (using agricultural science- adapted technology), dry cropping: 1) small-scale lift pumping for irrigation (by farmers); 2) falling water table, depletion of groundwater and drinking water supplies
7	Thailand	Chaopraya River Basin (upper and lower delta)	21,800	1,492	Yes (northeast only)	River water + reservoirs, irrigation rate 24%/irrigation channels (upper delta), complete network of irrigation channels (lower delta)	Natural evaporation of salt water from strata containing rock salts during the dry season
8	Thailand	Northeast (Korat tableland)		1,426		Natural rain (55% of total rice fields in Thailand), occasional reservoirs and irrigation ponds	
9	Vietnam	Mekong Delta	26,300	1,872	No	River water (pumped), Water withdrawal: 86% (agricultural)	
10	Myanmar	Central lowlands, Irawaji River Delta	20,865	2,426	No	River water, some underground water, reservoirs in dry season	
11	Brazil		10,035	1,910	Yes	Surface water, Drainage system to prevent water logging	The area salinized by irrigation : 15,000 ha (in the north east)
12	Philippines	Central Luzon plains	11,284	1,769	No	River water (via irrigation facilities), dry season: reservoirs/natural rain (around 50%)	Growing water competition among users
13	Pakistan	Indus River Basin	5,551	100	Yes	River irrigation channels (40.4%), irrigation water + wells (37%), wells (15.4%), irrigation ponds (5.3%), wet and dry cropping	1) Rising water tables, salinification, flood damage; 2) land subsidence in the Indus River Basin, from 40 m in the 19th century to less than 3 m today (42% drop)
14	Japan	All	13,000	1,704	No	River water and reservoirs in river basin area, supplementary irrigation	
15	Cambodia	Mekong Delta	3,390	1,872	Yes	Artificial irrigation (10%), mainly cropping in rainy and flood seasons (low water season)	

Table 2. International comparisons of evaluation indicators and irrigation patterns (Continued)

No.	Country	Region used for evaluation	Annual rice production (× 1,000 tons/year)	Annual rainfall (mm/year)	Soil basicity	Water usage	Environmental impact/other remarks
16	Nigeria	Niger River estuary delta	3,122	2,403	Yes	River water (from the Niger),	The contribution of irrigated agriculture to total crop production is small. (less than 1%)
17	Nepal		3,579	1,361	No	Surface water (large to small rivers and springs), Agriculture (99%)	
18	South Korea	West coast and south coast plains	6,284	1,108	No	Reservoirs (54.6%), surface water (lift pumps) (17%), river water (12.0%), groundwater (2%)	
19	Madagascar		2,600	1,424	Yes	River water, reservoirs	
20	United States	California (Sacramento River Basin)	7,771	914	Yes	River water and reservoirs in river basin area	
21	United States	California (San Joaquin River)		240		Water brought from reservoirs outside river basin area (to the north)	Salinification of farmland (salt concentration = 1,000 ppm)
22	United States	Arkansas		1,267		Groundwater (lift pumps)	Falling water table, increasing pumping costs
23	France	Rhone Estuary (Camargue wetlands)	116	544	Yes	Local river water (unassisted flow), pumped	
24	Italy	Central and lower reaches of the Po River	1,424	915	Yes	Local river water (unassisted flow), natural flow from Alps region	
25	Greece		220	392	Yes	Surface water (65.1%), groundwater (34.9%) (1959 figures for area under cultivation)	
26	Spain	Guadalquivir River and estuary basin	817	759	Yes	Local river water (reservoirs), all used for irrigation	Other crops are grown when water supplies from reservoirs are insufficient for rice
27	Portugal		137	769	Yes	River water	
28	Hungary		15	570	Yes	River water	Alkaline soil
29	Mexico		455	242	Yes	Surface water (84%), groundwater (16%)	Salinity in 7% of irrigated land area
30	Australia	Murray River Basin	951	442	Yes	Surface water, groundwater, all used for irrigation	Salinification
31	Turkey		280	668	No	Groundwater, surface water	Salinity problems in coastal regions

Sources: 1. Rice production: FAO production yearbook vol. 50 (1996).
2. Annual rainfall: Science yearbook 2001 (National Astronomical Observatory).
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6. AQUASTAT: FAO's Information system on water and agriculture.

Table 3. Evaluation indicators and sustainability evaluation ratings

No.	Country	Region used for evaluation	Climate	Soil type	Water resources	Groundwater management	Problems	Rating (V)	
			(1) Humid (2) Dry·Sub-humid (3) Semi-arid, Arid	(1) Salinity (2) No Salinity	(1) Groundwater (2) Surface water (3) Both	(1) Yes (2) No	(1) Yes (2) No	Panel of experts	Estimated value
1	India	Northwest (Haryana Province)	2	1	3	1	1	2	2.78
2	India	East (Bihar Province)	1	2	3	2	2	4	4.45
3	China	Central (Yangtze River Basin)	1	1	2	2	2	5	3.69
4	China	South (Pearl River)	1	2	2	2	2	5	5.00
5	Indonesia	Java	1	2	2	2	2	5	5.00
6	Bangladesh	All (delta)	1	2	2	2	2	4	5.00
7	Thailand	Chaopraya River Basin (upper and lower delta)	1	2	2	2	2	5	5.00
8	Thailand	Northeast (Korat tableland)	1	1	2	1	1	2	3.33
9	Vietnam	Mekong Delta	1	2	2	2	2	5	5.00
10	Myanmar	Central lowlands, Irawaji River Delta	1	2	3	2	2	5	4.45
11	Brazil		1	1	2	2	2	3	3.69
12	Philippines	Central Luzon plains	1	2	2	2	2	5	5.00
13	Pakistan	Indus River Basin	3	1	3	1	1	1	1.36
14	Japan	All	1	2	2	2	2	5	5.00
15	Cambodia	Mekong Delta	1	1	2	2	2	4	3.69
16	Nigeria	Niger River estuary delta	1	1	2	2	2	3	3.69
17	Nepal		1	2	2	2	2	5	5.00
18	South Korea	West coast and south coast plains	1	2	3	2	2	5	4.45
19	Madagascar		1	1	2	2	2	4	3.69
20	United States	California (Sacramento River Basin)	2	1	2	2	2	4	3.33
21	United States	California (San Joaquin River)	3	1	2	1	1	1	1.91
22	United States	Arkansas	1	2	1	2	1	3	3.18
23	France	Rhone estuary (Camargue wetlands)	2	2	2	1	2	5	4.64
24	Italy	Central and lower reaches of the Po River	2	1	2	2	2	5	3.33
25	Greece		3	1	3	1	2	3	1.36
26	Spain	Guadalquivir River and estuary basin	2	1	2	2	1	3	3.33
27	Portugal		2	1	2	2	1	4	3.33
28	Hungary		2	1	2	2	2	3	3.33
29	Mexico		3	1	3	2	1	2	2.78
30	Australia	Murray River Basin	3	1	3	1	1	1	1.36
31	Turkey		2	2	1	2	1	3	2.82

Table 5. Water-use sustainability ratings

A	Japan, East India, South China, Indonesia, South Korea, Bangladesh, Thailand (Chaopraya), France, Vietnam, Myanmar, the Philippines, Nepal
B	Northwest India, Central China, Northeast Thailand, Brazil, Cambodia, Nigeria, Madagascar, Turkey, United States (Sacramento and Arkansas), Italy, Spain, Portugal, Hungary, Mexico
C	Pakistan, United States (San Joaquin), Greece, Australia

Note: The above classifications are based on estimated values *V* as follows.
A: $V \geq 4$ (high water-use sustainability); B: $4 > V \geq 2$ (medium water-use sustainability); C: $V < 2$ (low water-use sustainability)

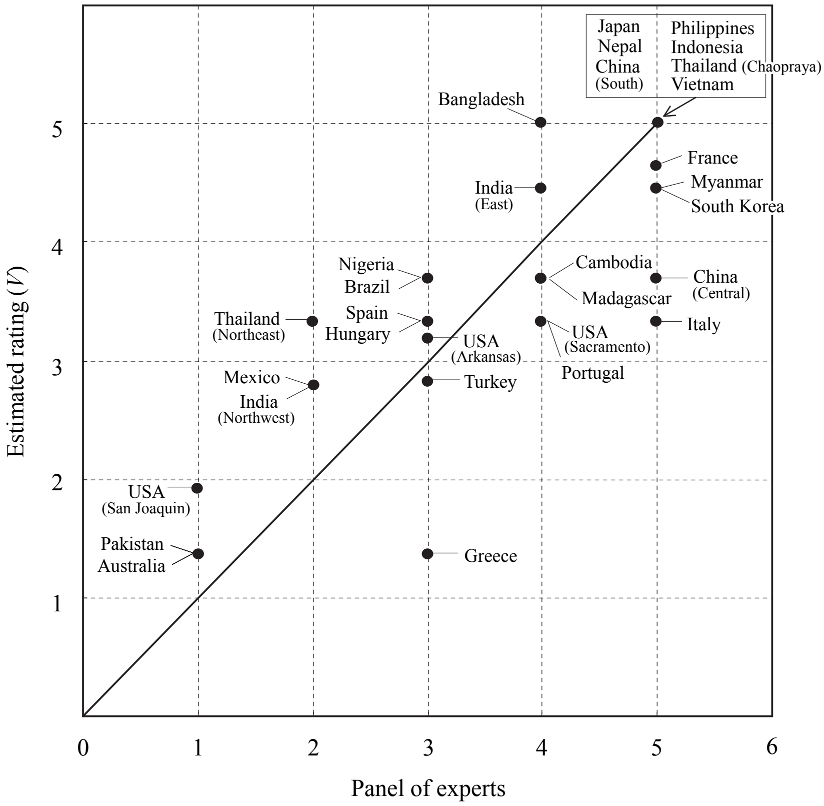

Fig. 1. Comparisons on estimated values with scores from expert panel for the estimated rating (Quantification Theory Type I)

based on the three indicators returned values of 4 or higher for 12 regions (including Japan), for a water-use sustainability classification of A (high). At the other end of the scale, four regions (including Australia) returned values of less than 2 and were graded as C (low). The threshold number ($4 > V \geq 2$) defines the medium borderlines. Figure 1 compares the combined evaluation scores from the panel of experts with the estimated values. The two sets of results correlate well (multiple correlation coefficient = 0.85). Most of the regions with a score of less than two are arid regions with limited rainfall, while the majority of the countries and regions scoring 4 or more are located in the humid zone of Monsoon Asia.

(3) Overall macro-environmental indicators

A study on the relationship between the estimated rating (V) and the overall indicators of water-use sustainability is performed assuming that the humid climate mitigates the salinity of the soil. The annual rainfall and water balance in a region have a great impact to the regional environment. Data related to these are organized in Table 6. The mean annual potential evapotranspiration (P_{ET}) was newly selected as a factor with a great impact on the water balance of a region and one for which data can be obtained throughout a region. This data set is provided on the Web by the United Nations Environment Programme Global Resource Information Database (GRID Center).

Table 6. Relationship between estimated ratings and the selected overall indicators

No.	Country	Region used for evaluation	Estimated rating [V]	Annual rainfall [R] (mm/year)	Mean Annual Potential Evapotranspiration [P_{Et}](mm/year)	R-P_{Et} (mm/year)	R-P_{Et} Medium value (mm/year)
1	India	Northwest (Haryana Province)	2.78	796	1,600 ~ 2,000	–804 ~ –1,204	–1,004
2	India	East (Bihar Province)	4.45	1,729	1,600 ~ 2,000	129 ~ –271	–71
3	China	Central (Yangtze River Basin)	3.69	1,037	800 ~ 1,200	237 ~ –163	37
4	China	South (Pearl River)	5.00	1,684	800 ~ 1,200	884 ~ 484	684
5	Indonesia	Java	5.00	1,928	1,200 ~ 1,600	728 ~ 328	528
6	Bangladesh	All (delta)	5.00	2,812	1,200 ~ 1,600	1,612 ~ 1,212	1,412
7	Thailand	Chaopraya River basin (upper and lower delta)	5.00	1,492	1,600 ~ 2,000	–108 ~ –508	–308
8	Thailand	Northeast (Korat tableland)	3.33	1,426	1,600 ~ 2,000	–174 ~ –574	–374
9	Vietnam	Mekong Delta	5.00	1,872	1,600 ~ 2,000	272 ~ –128	72
10	Myanmar	Central lowlands, Irawaji River Delta	4.45	2,426	1,600 ~ 2,000	826 ~ 426	626
11	Brazil		3.69	1,910	1,600 ~ 2,000	311 ~ –89	111
12	Philippines	Central Luzon plains	5.00	1,769	1,200 ~ 1,600	569 ~ 169	369
13	Pakistan	Indus River Basin	1.36	100	2,000 ~ 2,400	–1,900 ~ –2,300	–2,100
14	Japan	All	5.00	1,704	400 ~ 800	1,304 ~ 904	1,104
15	Cambodia	Mekong Delta	3.69	1,872	1,600 ~ 2,000	272 ~ –128	72
16	Nigeria	Niger River estuary delta	3.69	2,403	1,600 ~ 2,000	803 ~ 403	603
17	Nepal		5.00	1,361	1,600 ~ 2,000	–239 ~ –639	–439
18	South Korea	West coast and south coast plains	4.45	1,108	400 ~ 800	708 ~ 308	508
19	Madagascar		3.69	1,424	800 ~ 1,200	624 ~ 224	424
20	United States	California (Sacramento River Basin)	3.33	914	800 ~ 1,200	–114 ~ –286	–86
21	United States	California (San Joaquin River)	1.91	240	800 ~ 1,200	–560 ~ –960	–760
22	United States	Arkansas	3.18	1,267	800 ~ 1,200	467 ~ –67	267
23	France	Rhone estuary (Camargue wetlands)	4.64	544	800 ~ 1,200	–256 ~ –656	–456
24	Italy	Central and lower reaches of the Po River	3.33	915	800 ~ 1,200	115 ~ –285	–85
25	Greece		1.36	392	800 ~ 1,200	–408 ~ –808	–608
26	Spain	Guadalquivir River and estuary basin	3.33	759	800 ~ 1,200	–41 ~ –441	–241
27	Portugal		3.33	769	800 ~ 1,200	–31 ~ –431	–231
28	Hungary		3.33	570	800 ~ 1,200	–230 ~ –630	–430
29	Mexico		2.78	242	1,600 ~ 2,000	–1,358 ~ –1,758	–1,558
30	Australia	Murray River Basin	1.36	442	800 ~ 1,200	–358 ~ –758	–558
31	Turkey		2.82	668	800 ~ 1,200	–132 ~ –532	–332

Source: http://www-cger.nies.go.jp/grid-j/gridtxt/pet.html.

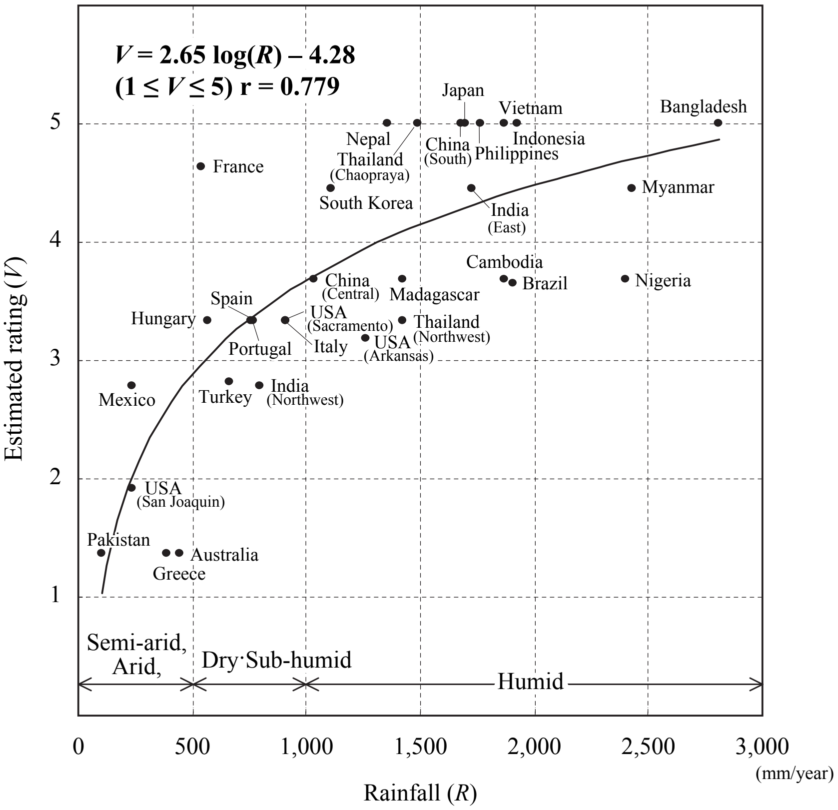

Fig. 2. Relationship between estimated rating (V) and annual rainfall

These data are analog data obtained by dividing P_{ET} into steps in 8 categories (400-mm intervals) for the period from 1951 to 1980. These data were estimated by the Thornthwaite method using average monthly air temperature data and the average day length table.

Figure 2 analyzes the relationship between the estimated rating (V) and the annual rainfall. In the results, the estimated rating in arid and semi-arid regions where the annual rainfall is less than 500 mm/year was 3 or lower in all cases (score of 4 or more: high sustainability, 2 or more but less than 4: medium, less than 2: low).

From Table 4, we can see that non-saline soil has a higher evaluation coefficient (i.e., boosts the estimated rating more) than a wet climate. However, high annual rainfall also has the effect of mitigating salinity buildup in the soil.

The coefficient of correlation (R) of the annual rainfall (mm/year) and estimated rating in each country is r = 0.779, indicating good correlation.

The regression curve for the correlation is approximated by Eq. (2)

$$V = 2.65 \log(R) - 4.28 \quad (1 \le V \le 5) \tag{2}$$

The correlation of rainfall – P_{ET} (median value) as the water balance of a macroscopic region with the assessed value in each country was studied. The statistical analysis was done by making the data for the rainfall – P_{ET} (defined as the Regional Water Balance; R_{WB}) positive by adding 2,500 mm to their values. The coefficient of correlation is shown in Fig. 3. This coefficient of correlation is r = 0.641. In the USA (California, San Joaquin River), Greece, and Australia, which are countries where the assessed value was 2 or less, it deviated from the regression curve. In Pakistan where the assessed value was 1.36 and in countries where it was 3 to 4.5 or less, the correlation was good.

The regression curve is given by:

$$V = 4.00 \log(R_{wb} + 2500) - 9.74 \quad (1 \le V \le 5) \tag{3}$$

As explained above, the annual rainfall and the mean annual potential evapotranspiration in each country or region could be selected as candidate overall macro-environmental indicators related to the water-use sustainability evaluation indicators in paddy irrigated farming. However, the precision of the evaluation of evapotranspi-

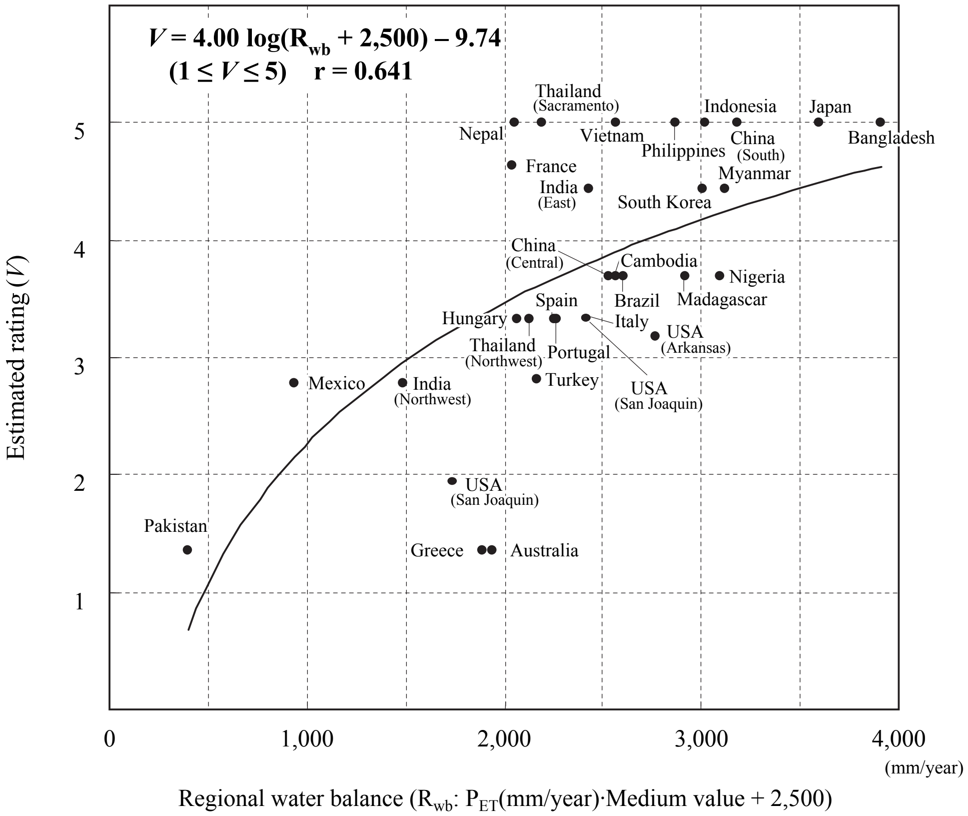

Fig. 3. Relationship between estimated rating (*V*) and regional water balance(R_{wb})

Sources) 1. Rice production: FAO production yearbook, vol. 50 (1996); 2. Annual rainfall: Science yearbook 2001 (National Astronomical Observatory); 3. Soil salinity: US Department of Agriculture, Trade and Commerce, Alfisols and Aridisols (1993); 4. Horii et al., New critique of irrigation systems in Asia (1996); 5. Sano, Small-scale irrigation and life pumping equipment, an environmentally friendly approach to irrigation, Japan Association of Agricultural Engineering Enterprises (JAGREE) (1998); 6. AQUASTAT: FAO's information system on water and agriculture.

ration must be improved by inputting regional meteorological data in the future.

Conclusion

This study proposed an international comparison methodology for estimating water-use sustainability in paddy irrigated farming in 31 countries and regions, including both arid and humid regions. The estimated ratings generated by the technique suggested that annual rainfall and regional water balance are suitable overall indicators of water-use sustainability at the macro level. They provide a valuable insight in the international agreements on the relationship between agriculture and water resources. An in-depth investigation involving more indicators is required in order to achieve more accurate numerical estimations for the countries and regions considered in this study. Nevertheless, the approach used in this study of identifying salient evaluation factors and employing a panel of experts to provide ratings, has been shown to be sound and therefore valid. In order to use this approach to derive more objective data on water-use sustainability capable of withstanding the rigors of international agreements, it would be necessary to obtain more in-depth regional data for each country and to use questionnaires to solicit ratings from experts around the world based on this data.

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