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Sustainable Irrigation Management in Paddy Rice Agriculture: A Comparative Case Study of Karangasem Indonesia and Kunisaki Japan

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Abstract: Irrigated paddy rice agriculture accounts for a major share of Asia Pacific's total water withdrawal. Furthermore, climate change induced water scarcity in the Asia-Pacific region is projected to intensify in the near future. Therefore, methods to reduce water consumption through efficiency measures are needed to ensure the long-term (water) sustainability. The irrigation systems, *subak* of Karangasem, Indonesia, and the *tameike* of Kunisaki, Japan, are two examples of sustainable paddy rice irrigation. This research, through interviews and an extensive survey, comparatively assessed the socio-environmental sustainability of the two irrigation management systems with special reference to the intensity and nature of social capital, equity of water distribution, water demand, water footprint, and water quality, etc. The prevailing social capital paradigm of each system was also compared to its overall managerial outcomes to analyze how cooperative action contributes to sustainable irrigation management. Both systems show a comparable degree of sustainable irrigation management, ensuring an equitable use of water, and maintain relatively fair water quality due to the land-use practices adapted. However, the systems differ in water demand and water efficiency principally because of the differences in the irrigation management strategies: human and structural. These findings could help devise mechanisms for transitioning to sustainable irrigation management in the commercially-oriented paddy rice agricultural systems across the Asia-Pacific region.

Keywords: sustainable irrigated agriculture; irrigation efficiency; social capital; traditional agriculture; GIAHS; sustainable water resource management; water footprint

1. Introduction

Given the frequent and intense precipitation events (e.g., wet seasons, monsoons, annual typhoons, etc.) and the water resource availability, water scarcity in the Asia-Pacific region is a counter-intuitive concept. Nevertheless, this region too is projected to face water scarcity if the populations continue to rise and climate change goes unmitigated [1–3]. The disparity between the water availability (e.g., intense and unevenly distributed rainfall) and the rate of appropriation (e.g., water-intensive agricultural practices, such as paddy rice cultivation) seems to accelerate this impending water crisis. Furthermore, global climate change, particularly the rising global temperature, seems to directly impact the water availability that, as a result, negatively impacts the water-intensive agriculture. A total of 70% of the global freshwater withdrawal is used in irrigation, of which an estimated 60% is wasted because of irrigation systems' inefficiencies and the incompatibility between the crops and the environment they are grown in [4,5]. This points to a *resource management* issue and underscores the urgent need to find sustainable water management and irrigation solutions, especially for water-intensive cropping systems such as paddy rice agriculture.

Besides the aforementioned resource management issue, geo-climatic factors such as porous soils of volcanic origin, narrow rivers, steep topography, high temperature, anomalous precipitation, etc., often make the paddy rice agriculture and irrigation water procurement in these regions rather difficult [6,7]. Despite this, island nations like Indonesia and Japan have successfully devised mechanisms for achieving sustainability in irrigated paddy rice cultivation. This research focused on two examples of sustainable paddy rice irrigation in the islands of Indonesia and Japan. Both of the chosen agricultural communities are assumed successful examples of sustainable irrigation management that overcome the above stated environmental hindrances because of their international recognition as such, either by academic research or by designation as a Globally Important Agricultural Heritage System (GIAHS) program of the Food and Agricultural Organization (FAO). This work, therefore, focused on comparatively analyzing the sustainability aspects of the two irrigation management systems to understand the social and environmental impacts to provide the basis for a sustainable irrigation management model that could be replicated elsewhere.

1.1. The Subak

The first irrigation system investigated is located in the Karangasem regency of Bali, Indonesia that has the driest climate on the island. Extensively investigated since the 1970s, this traditional irrigation management system, subak, is a network of farmers' associations [8]. The subak operates as an autonomous, self-regulating, water management organization that meets regularly to democratically decide the irrigation schedules for all members in the watershed. Farmers meet at beduguls, or water temples, where weirs are typically used to control irrigation flow. Balancing the water demands of upstream farmers while managing the need to flood the downstream paddies to inhibit pest propagation, this management system equipoises both water sharing and pest control [9–11]. The system is the result of centuries of traditional agrarian societies bound together by Hinduism and animism/mountain worship, especially the philosophies of Tri Hita Karana and Tri Mandala, used to regulate land use and humanity's role within those land uses [12].

The origin of the subak system is uncertain and the management structure and the amount of social cohesion vary [13,14]. Among others, a prominent argument concerning the origin of the existing management structure is that it is a result of the kings' mandate to expand production rather than cooperation borne out of the necessity to combat natural pressures [8].

1.2. The Tameike

The second irrigation system investigated is located on the Kunisaki peninsula of Oita Prefecture, Japan. It is a network of man-made ponds, known as tameike, built into the mountain forests of Kunisaki. Tameike accumulates rainwater that is channeled via small canals. The tameike system was built as a practical solution for the low annual rainfall of the region [14] where rainwater is saved and transported efficiently with minimal wastage [15]. Furthermore, tameikes also function like natural ponds and support local biodiversity [16]. For each tameike, there is a water manager known as an *ikemori*. These managers work together to efficiently deliver water to the farmers based on their needs.

Kunisaki's tameike system is part of satoyama; the agrarian communities that live in harmony with their forested mountain environments, reaping social and economic benefits while providing environmental services [17,18]. Like Tri Hita Karana and Tri Mandala, these satoyama landscapes have typical land-use trends where mountains are left undeveloped, homes are built close to the base, and paddies are located below the homes on flatter land closer to the sea. Similar to the subak, religion, or, in this case, Buddhism, has a very strong influence on the society and also on the forming of tameike.

1.3. Aim of the Research

Concerning the traditional agricultural systems, issues such as aging farming populations, the migration of the young workforce to urban centers, the rapid increase of corporate/industrial mass-production methods [19,20], the declining profitability, diminishing availability, and quality of resources, etc., are considered critical and threatening for their existence. Therefore, the FAO's GIAHS program was initiated in 2002 in response to the "global trends that undermine family agriculture and traditional agricultural systems" [21]. Among other things, the GIAHS program strongly focuses on the sustainable management of resources employing the traditional practical knowledge and, in particular, the use of agricultural communities' "cultures, value systems, and social organizations" [21] in key activities, including sustainable irrigation management.

Despite the extensive use of the term sustainability, its definition is still somewhat nebulous and is thus disputable. Accordingly, defining 'sustainable irrigation management' seems rather difficult. However, according to FAO, current GIAHS sites have site-specific sustainable practices, one of which, sustainable irrigation management, is of concern to this work. Therefore, understanding the interplay between social capital and structural elements in irrigation management, as well as the degree of sustainability they elicit in subak and tameike agricultural systems, is aimed at in this work. Given that subak functions in a developing economy and tameike in a developed economy, it is aimed to gain insights into the socio-environmental sustainability of the two irrigation management systems with special reference to the intensity and nature of social capital, the equity of water distribution, water demand, water footprint, and water quality, etc., through a comparative assessment. It is also aimed to understand the prevailing social capital paradigm of each system in relation to its overall managerial outcomes to analyze how cooperative action contributes to sustainable irrigation management.

2. Theory

Lehtonen [22] defines social capital as "networks of social relations characterized by norms of trust and reciprocity that can improve the efficiency of society by facilitating coordinated actions". This can include institutions such as farmers' associations, religious groups, social groups, and NGOs; as well as their respective norms and values. Social capital's strong correlation to sustainable development has been studied and acknowledged by scholars and institutions alike (see for example Isham and Kahkonen [23]).

There are two main approaches to social capital: (a) the Network Approach and (b) the Social Structure Approach. The Network Approach focuses on ties between actors within a community based on three classifications: bonding, bridging, and linking. Bonding social capital is typically shared by family members, close friends, or people who have lived in the same community their entire lives. These ties are usually the strongest with a high degree of network closure but can also have negative effects, such as the exclusion of outsiders or a lack of innovative ideas [24]. Bridging social capital is usually shared between actors of different social groups categorized according to age, gender, occupation, etc. Ties created in this classification are usually weaker than those in bonding social capital but can bring new ideas and innovation to a system. Finally, linking social capital is shared by actors divided by explicit institutional borders, such as farmers and national government offices. These ties are usually weak, as observed in bridging social capital, however, they can provide important benefits to a system, such as subsidies, education, promotions, and other types of support.

In the Social Structure Approach, there are also three classifications of social capital: structural, cognitive, and relational [25]. Structural social capital looks into the culture and identity of a community and the nature of the institution's individuals' connection to one another. Cognitive social capital is measured by prevailing norms, attitudes, and values within a community, or, simply put, it is measured by what people think of their system. Relational social capital refers to the bonds of trust and reciprocity between the individuals. Table 1 summarizes these classifications.

Table 1. Characteristics of network and social structure approaches.

Approach	Classification	Description	Example
Network Approach	Bonding	Connections *within* a social group or community; horizontal ties between people of similar demographics	Family, friends, neighbors, members of a local association
	Bridging	Connections *between* social groups or communities; horizontal or vertical ties between people from dissimilar demographics	People of dissimilar cultural background, economic status, gender, age, etc.
	Linking	Connections *between* social groups or communities where there is a significant hierarchy; vertical ties between people from dissimilar demographics	Patron/Client, Government/Citizen, Teacher/Student
Social Structure Approach	Structural	The social system through which society operates and its typical procedures that facilitate group action	Laws, traditions, modes of government, religion
	Cognitive	Like norms, values, unspoken-rules, taboos, etc., which govern the actors within a social system	Language, culture, ceremonies, narratives
	Relational	Relationships between actors within a social system and the nature of said relationships	Trust, reciprocity, obligations

Both approaches can be used to provide useful insight into a community, hence both are adopted in this work. The Network Approach provides information on the different levels and hierarchies of the water management systems and identifies the different actors involved; from the farmers to the national government agencies. Whereas, the Social Structure Approach allows a look into the qualities and characteristics of each community's social capital.

3. Methodology

3.1. Defining Metrics

Despite the lack of consensus on the definition of sustainable irrigation, a working definition was created by combining some of the main contributing factors found in the current literature. These include: having an appropriate and reliable water source with measures to reduce losses from transportation and percolation [26], protecting the upper watershed from pollution and erosion [27], preventing waterlogging and the buildup of salts in the soil [3,28], and providing water to all members of the system in an equitable manner [29]. Accordingly, this work defined sustainable irrigation management as (1) having a low negative impact on the environment, (2) using water efficiently, (3) maintaining water and soil quality, and (4) fairly and equitably distributing water for all users. The corresponding metrics used to measure the performance of the above factors were: water demand (WD) in meters per square meter, water footprint (WF) in cubic meters per ton of rice, water quality (WQ), and managerial effectiveness (ME).

Social capital was defined by the Network and Social Structure Approaches and assessed using the Likert Scale; a five-point scale from 'strongly disagree' to 'strongly agree' was employed. These answers were then converted to a numerical scale from −2 to 2, and then averaged and compared. The answers were averaged instead of summed because some farmers elected not to answer certain questions. Although the answers were converted to numeric values, they do not represent a social capital 'unit' of any kind. Therefore, the scale is better thought of as a conservative measurement of the social capital 'intensity', rather than a concrete measurement.

3.2. Study Sites

The research compares two examples of sustainable irrigation in Ababi, Bali, Indonesia and Tsunai ward, Kunisaki, Japan. The subjects of this work are as follows: the Tsunai ward of Kunisaki, a sliver of the peninsula with six tameike, which were frequently cited in Kunisaki's GIAHS proposal, and the

Ababi village of Karangasem, a small community centered around the Tirta Gangga water palace cited in Karangasem's GIAHS proposal.

3.3. Data Collection

The total area and number of farmers in Subak Embukan, Ababi are much larger than in Tsunai. In Tsunai ward, there are 5 tameike systems with a total of 11 farmers and 50 hectares of farmland. All 11 farmers participated in the survey. The subak studied in this work, Subak Embukan in Ababi, consists of 336 farmers with 12 branches, and the total cultivated area of their operations is 76 hectares. The data were collected systematically from all 12 of the subak branches and one farmer from each branch was surveyed, meaning that all different systems are represented. In statistical terms, both systems are well represented, however, the sample size for subak may be increased in future studies to improve the data resolution.

Data collection was performed at three levels: macro, meso, and micro. At the macro-level, semi-structured interviews with government officials of each of the irrigation communities were conducted. For Ababi, the deputy head of the Karangasem Office of Forestry and Plantations in Amlapura was interviewed. For Tsunai, it was the chief and two other representatives of the Agricultural Department in Kunisaki City Hall. Questions in these interviews concerned the following 5 criteria: their offices' relationship with the water management system, the agricultural organizations active in their jurisdiction, legalities, and policies concerning the system, development and technology, and environmental impact data.

On the meso-level, semi-structured interviews were conducted with the leaders of the irrigation management bodies themselves. In Ababi, it was the leader of Subak Embukan, and in Tsunai it was two of the five Ikemori, their treasurer/historian, and the Chairman of the Kunisaki-Usa GIAHS promotion council. Questions in these interviews concerned the following 5 criteria: management strategies, duties of managers, trends in management, involved farmers and relationships, and technology used in water transport.

At the micro-level, structured surveys were handed out to the farmers of the irrigation schemes in question. In Ababi, there were twelve respondents; one from each of the twelve branches of Subak Embukan. In Tsunai, all eleven farmers operating in the ward were surveyed. The surveys contained 67 questions divided into four sections: General Information (G), Water Use (W), Social Capital (S), and Economic Assessment (E). Respondents were informed of the purpose of the study as well as their right to choose not to answer any of the questions. The questions in the Water Use section were used to calculate the Water Demand (WD) and Water Footprint (WF) of each farmer's operations, as well as to investigate the difference in farming style between individuals within a community. The Social Capital section was used to measure each community's approximate intensity of social capital based on the six different classifications: bonding, bridging, linking, structural, cognitive, and relational. Many questions were also dually purposed to measure other social phenomena such as the resilience to change, the geographical distribution of social relationships, and Managerial Effectiveness (ME). The Economic Assessment section probed if farmers are able to support themselves financially and what kinds of support they receive; either from the government or from secondary sources of income. It also measured the perceived economic risk of farmers due to natural disasters, rice pests, water scarcity, lack of manpower, lack of access to equipment, and rice imports.

All interviews were conducted in the respondents' native languages assisted by an interpreter. All survey questions were also translated by a proficient native speaker.

3.4. Water Demand and Water Footprint

The Water Demand (WD) and Water Footprint (WF) of rice can be understood as the total amount of water used in growing rice and the efficiency of water-use compared to rice yields, respectively. The WD and WF of each community were calculated based on the method outlined by Chapagain and Hoekstra [30]. The four main stages of rice cultivation that consume water are as follows: saturating the soil (SAT), setting the water level (WL), evapotranspiration during rice growth (ETC), and percolation (PERC). The summation of the above becomes the WD. SAT was assumed to be 20 cm; see [30]. WL was directly obtained from the survey, whereas the ETC was calculated based on the farmers' cropping schedules and climate information from the official meteorological websites of Japan and Indonesia. CROPWAT 8.0, a decision support tool for the assessment of irrigation and crop water requirement [31], was employed for these calculations. Considering the site-specific soil characteristics, PERC was estimated based on the method outlined by Chapagain and Hoekstra [30]. The effective rainfall (P_{eff}) that is required for the fractionation of green water (GW) and blue water (BW) from WD was estimated using the USDA S.C. method [30]. Accordingly, the equations employed for Water Demand (WD) and Water Footprint (WF) computation are as follows:

$$WD = SAT + WL + ET_c + PERC \tag{1}$$

$$WF = \frac{WD - PERC}{\text{Average Harvest}\left(t/m^2\right)} \tag{2}$$

where:

SAT = Sum of area cultivated (m^2) × 0.2 m
WL = Sum of area cultivated (m^2) × reported depths from surveys (m)
ET_C = Sum of area cultivated (m^2) × evapotranspiration (m/day) × FAO crop coefficient (m) × number of days from transplant to harvest
$PERC$ = Sum of area cultivated (m^2) × percolation estimated from surveys (m/day) × number of days from transplant to harvest

3.5. Water Quality

Water Quality, as a proxy for sustainable water management, was measured using the Kyoritsu Chemical Check-Lab Corporation's River Water Test Kit [32]. Tested water quality parameters included: Chemical Oxygen Demand (COD), Phosphates (PO_4), Nitrites (NO_2), Nitrates (NO_3), and Ammonium (NH_4). Additionally, the pH, water temperature, air temperature, etc. were also recorded during testing. Testing of all six tameike in Tsunai and Ababi was conducted and temporal profiles were created. Samples were taken at critical points to assess the water quality continuity throughout the watershed.

4. Results

4.1. Bonding Social Capital

A total of 16 queries in the survey were employed to measure the bonding social capital. The results were indicative of the nature of the relationships between the farmers. In Tsunai, all farmers are Japanese men who live in close proximity to each other and are bound by the rules of the tameike and ikemori. In Ababi, most farmers are Balinese men who live in close proximity to each other (a large group compared to Tsunai) and are bound by the subak's rules of awig-awig. Questions G4–S7 represent proxy and are objective indicators of bonding social capital (Table 2), while questions S9–S16 (Table 3) elicited their opinion or feeling.

Table 2. Questions G4 to S7 from the questionnaires given to farmers and their averaged responses.

No.	Question	Ababi	Tsunai
G4	What is your religious affiliation?	100% Hindu	100% Buddhist
S1	Average time living in the area?	51 years (Whole Life)	70.7 years (Whole Life)
S2	The average amount of generations living in the area:	3.7	4
S3	Do you have any children or grandchildren?	100% yes	91% yes
S4	Do/did any of your children or grandchildren attend schools in your area?	75% yes	90% yes
S5	Do any of your children/grandchildren help with farming?	75% yes	50% yes

Table 2. *Cont.*

No.	Question	Ababi	Tsunai
S6(a)	Do you have a spouse?	92% yes	82% yes
S6(b)	Does your spouse help with farming?	91% yes	72% yes
S7(a)	Have you been in a leadership position before?	50% yes	82% yes
S7(b)	The average amount of time spent in a leadership position?	9.9 years	4.7 years

As Table 2 indicates, both communities were religiously homogenous, and all respondents reported living in their communities their entire lives. Both communities also reported that their families had farmed in the area for at least four generations, suggesting deep historic and cultural ties between all farmers. Children and spouses were more active in agriculture in Ababi than in Tsunai, but more children in Tsunai attended schools within their community while Ababi children commuted to the nearest urban center, Amlapura. Finally, more farmers in Tsunai had been in a leadership position than in Ababi, but Ababi's leaders served longer average terms. The results of these questions indicated a high bonding social capital for both communities but that it was possibly higher in Ababi since farmers are still quite young and seem to receive more agricultural support from family members. It is noteworthy that Tsunai farmers require less manpower due to mechanized rice cultivation methods.

As remarked earlier, S9–S16 estimated farmers' opinions on their relationships and were gauged on the Likert Scale. Questions S10, S11, S13, and S14 were not measured on this scale because they were supplementary to the questions that preceded them: S9 and S12. Instead of measuring intensity, these helped determine more specific qualities about their relationships with other farmers, such as the frequency at which they communicate and what the goal of their communication typically was (Table 3).

Table 3. Questions S9 to S16 from the questionnaires given to farmers as well as their averaged responses.

No.	Question	Ababi	Tsunai
S9	I have neighbors in (system name) with whom I am close.	1.5	0.89
S10	On average, I contact at least one of these neighbors ____. (top 2 answers)	Every day/2–3 times a week	Twice a month/2–3 times a week
S11	I usually talk to them about _____. (Top 2 answers)	Farming/Group or cultural activities	Farming/Everyday things
S12	I have farmers *outside* of (system name) with whom I am close.	1	0.63
S13	On average, I contact at least one of these people ____. (Top 2 answers)	Once a month/Less than once a month	Once a month/Twice a month
S14	I usually talk to them about _____. (Top 2 answers)	Farming/Group or cultural activities	Farming/Everyday things
S15	I mostly agree with other farmers in my system about farming methods and schedules.	1.42	0.5
S16	I mostly agree with other farmers in my system about everyday affairs.	1.36	0.63

Farmers in Ababi consistently reported having close relationships both inside and outside of their communities at a higher rate than farmers in Tsunai. They also reported interacting with these friends and acquaintances more frequently and tended to discuss more cultural/religious topics than Tsunai farmers. Furthermore, farmers from Ababi reported agreeing with their fellow farmers on farming methods and everyday affairs more often than farmers in Tsunai. Ababi appears to have more bonding capital overall compared to Tsunai. These results also indicate that bonding social capital appears to be defined geographically, as both communities reported having fewer close relationships and less frequent encounters outside of their community boundaries.

4.2. Bridging and Linking Social Capital

This Section 4.2 discusses the results of the questions concerning bridging and linking social capital. These questions were designed to explore what connections each of the farmers had that are not directly related to water management or farming in their immediate area. They were also meant to estimate how much information flow there is between these farmers and people from other social classes, genders, nationalities, etc. This would also include each farmer's openness to new ideas, which was measured by question S33/S35 in particular (Table 4).

Table 4. Questions S26/S29 to S33/S35 from the questionnaires given to farmers as well as their averaged responses.

No.	Question	Ababi	Tsunai
S26/S29	I often participate in (system name)'s events, festivals, or ceremonies.	1.5	1
S27/S30	I often participate in events, festivals, or ceremonies outside of (system name).	0.73	0
S29/S32	My spouse is equally active in the community's cultural affairs and events.	1.5	0.33
S33/S35	There is a new organic production method being used and promoted in the town next to (system name). The farmer using it apparently experienced a cut in production costs and a rise in revenue. This farmer gives a workshop on this new method in (system name) and offers to train everyone for free. What do you think best reflects your attitude in this situation? (top 2 answers).	I will try it, but only if a few other farmers in (system name) try it too/I will try it, but only if all the farmers in (system name) try it too.	I will try it, but only if all the farmers in (system name) try it too/I will try it, but only if a few other farmers in (system name) try it too.

For questions S26/S29 and S27/S30, both Ababi and Tsunai tended to participate in more cultural events that are held inside their communities compared to external events. This suggests that social capital related to religious or cultural affairs is locally centered and therefore more relevant to bonding social capital than bridging. Despite, Ababi's participation was higher for both. Spousal participation in cultural affairs was much higher in Ababi as well. Openness for new ideas, as measured by question S33/S35, was low for both systems, once again signifying strong bonding social capital but weaker bridging social capital.

Question S31/S36 asked respondents to give the names of organizations and/or events that they are either personally involved in or have family members who are involved. The purpose of this question was to assess what kinds of influences from bridging or linking capital may exist. Table 5 presents the results of each farmer. Each organization/event is classified as being inside or outside of the system.

Table 5. All organizations and events that respondents revealed they or their immediate family members participate in. Items are counted by either being inside or outside the system boundary. (NOTE: n/a = not answered).

Farmer #	Organizations and Events Participated	Ababi	Outside
1	Subak Leader Water Management Training Program	0	1
2	Fish Farming Coop	1	0
3	Village Choir Group	1	0
4	Gamelan, Government Sponsored Agricultural Classes	1	1
5	n/a	0	0
6	Gamelan	1	0
7	n/a	0	0
8	Gamelan	1	0
9	n/a	0	0
10	Gamelan	1	0
11	Temple Leader	1	0
12	Gamelan	1	0

Table 5. *Cont.*

Farmer #	Organizations and Events Participated	Tsunai	Outside
1	Daishi Matsuri, Ike Matsuri	1	1
2	n/a	0	0
3	Usa-Kunisaki GIAHS Promotion Council, Kunisaki Agricultural Dept., Kunisaki Tourism Department, Kunisaki City Hall Other, Agricultural Coop., Fisheries Coop., Forestry Coop., Land Improvement Bureau, East Oita Promotional Office, Daishi Matsuri, Ike Matsuri	2	9
4	Kunisaki Agricultural Dept., Forestry Coop., Ike Matsuri	0	3
5	n/a	0	0
6	Daishi Matsuri, Suijin Matsuri, Ike Matsuri	3	0
7	n/a	0	0
8	Kunisaki Agricultural Dept., Agricultural Coop., Forestry Coop., Land Improvement Bureau, Suijin Matsuri, Ike Matsuri	2	4
9	Agricultural Coop., Forestry Coop., Ike Matsuri	1	2
10	Daishi Matsuri, Suijin Matsuri, ike Matsuri, Other Matsuri	3	1
11	Agricultural Coop., Daishi Matsuri, Ike Matsuri	2	1

Farmers in Tsunai reported being active in considerably more organizations than farmers in Ababi. This is especially true for organizations outside of their system boundary. Furthermore, most organizations/activities in Ababi were religious, while organizations in Tsunai were more operational or occupation-based. These results show much higher bridging and linking social capital in Tsunai.

4.3. Structural, Cognitive, and Relational Social Capital

This Section 4.3 presents the results of the questions meant to measure structural, cognitive, and relational social capital. A few of the questions from previous sections (i.e. Sections 4.1 and 4.2) are also included here as their functions overlapped for two or more categories of social capital (Table 6). In contrast to bonding, bridging, and linking social capital, which constitute the Network Approach, the Social Structure Approach serves to measure how collective action is facilitated by the structure of the managerial body, the norms and values of its members and how these members interact, rather than focusing on the configuration and scope of the social capital. This would include formal rules and unspoken social norms and how they promote like-action and deter defection.

Table 6. Questions S7b to S30/S33 from the questionnaires given to farmers as well as their averaged responses are outlined below.

Type	No.	Question	Ababi	Tsunai
Structural Social Capital	S7(b)	The average amount of time spent in a leadership position?	9.9 years	4.7 years
	S25/S28	The position and authority of the subak/ikemori are respected.	1.58	0.73
	S26/S29	I often participate in cultural events in (system name).	1.5	1
	S32/S24	Can you estimate how many times you've discovered a leak in the irrigation?	>10	4.13
	S19(Tsunai)	The tameike are necessary for the success of agriculture in Tsunai.	n/a	1.36
	S18/S20	The subak/the ikemori is/are necessary for successful water management in (system name).	1.45	1.2
	S19/S21	The way in which water is disseminated is fair to all farmers in (system name).	1.27	1
	S22(Tsunai)	The price of water from tameike is fair.	n/a	0.9

Table 6. *Cont.*

Type	No.	Question	Ababi	Tsunai
Cognitive Social Capital	S17(Tsunai)	After achieving the GIAHS designation, I have more pride in my community.	n/a	0.89
	S17/S18	Agriculture done in (system name) is special or exceptional among others.	0.6	0.4
	S24/S27	I feel that I have the freedom to farm in the manner in which I please.	−0.3	0.2
	S28/S31	Temples, shrines, and other cultural sites in Karangasem/Kunisaki are important to me.	1.5	0.56
Relational Social Capital	S21/S23	Theft of irrigation water does not occur in (system name).	1.45	0
	S24(Tsunai)	If the population of Tsunai were to increase, the frequency of water theft would also increase.	n/a	0
	S22/S25	I feel that I am included in important decision-making on water management.	1.45	0.9
	S23/S26	I feel that the inclusion of all farmers in decision-making is necessary.	1.6	1
	S30/S33	In regards to farming and my general affairs, ________________.	I usually ask others for advice or help/I usually give and receive advice or help.	I usually give and receive advice or help/I work best alone.

For structural social capital, there was more overall trust and cooperation apparent from the manner in which the subak was governed compared to the ikemori. Although Tsunai's system was more inclusive, with almost every farmer having served as an ikemori at least once, subak leaders in Ababi tend to serve much longer terms, are more respected, and are seen as more necessary for the system's survival. Farmers in Tsunai appeared to find more importance in the built structure of the tameike themselves than those controlling it (compare S19 to S18/S20). This may be why there were fewer leaks discovered in Tsunai than in Ababi, as the concreted canals in Tsunai likely require less management in general.

Cognitive social capital was rather low for both systems excluding how religious sites are viewed in Ababi. Most interestingly, however, the freedom to farm in the manner one chooses was low for both and extremely low in Ababi, showing that all farmers feel a sense of obligation to conform to rules of either the irrigation organization or another authority. This, like the results of the Network Approach, highlights high network closure, and thereupon a possible lack of outside influence.

Relational social capital mirrored bonding social capital in that the relationships between farmers within the same boundaries are stronger in Ababi. Most farmers in Tsunai could not say with certainty that water is not stolen despite the system's small size, and while most of these farmers reported feeling included in decision making, it did not reach the intensity at which Ababi farmers felt included. Question S30/S33 showed the more obvious hierarchy of farmers in Ababi, while Tsunai farmers had relationships that were more or less on even ground. It appears as though there is more general trust in Ababi, despite the trust being held towards superiors rather than equals.

4.4. Water Demand and Water Footprint

Tsunai had a higher water demand (WD) than Ababi, but a much lower water footprint (WF) (see Table 7). This indicates that Tsunai takes more water from the environment relative to its cultivated area, but it also produces more rice per unit of water than Ababi. In other words, Tsunai's agriculture has a higher water intensity with better water productivity, whereas Ababi's agriculture has a lower water intensity with lower water productivity. The ideal scenario of lower water intensity with higher water productivity has not been accomplished.

Table 7. Water Demand and Water Footprint of rice cultivation in Ababi and Tsunai.

	Ababi	Tsunai
Water Demand (m/m^2)	0.84	1.15
Water Footprint (m^3/t)	Blue—3159.89 Green—2088.95 Total—5248.84	Blue—980.84 Green—765.73 Total—1746.57

4.5. Water Quality

Although neither water source was visually suffering from eutrophication and each had significant biodiversity, there were some minor deficiencies in WQ (see Table 8). The COD was high for both systems and was especially high for Tsunai. This is likely due to the stagnant nature of pond water and the fact that tameike, in particular, is only periodically drained for irrigation. This process may increase the content of organic solids, as well as temporarily expose the aphotic zones to sunlight. NO_3 was low for both water sources and PO_4 was a slightly high for Tsunai, however unclear for what specific reason. Additionally, it was also observed that there was a substantial amount of plastic pollution in Ababi's irrigation canals, which may have leached pollutants that are undetectable by the test kit. Whereas, Tsunai's ponds and canals were virtually clear of all litter.

Table 8. Water Quality results for each community vs. ideal conditions.

	Ababi	Tsunai	Ideal Conditions *
pH	6.75	7.04	6.5–8.4
COD	5.125 mg/L	7.97 mg/L	0–5 mg/L
NH_4	0.15 mg/L	0.2 mg/L	≤0.2 mg/L
NO_2	0.0017 mg/L	0.0056 mg/L	≤0.02 mg/L
NO_3	0.4125 mg/L	0.22 mg/L	1–2 mg/L
PO_4	0.01 mg/L	0.058 mg/L	≤0.05 mg/L

* NOTE: As per the Japanese Industrial Standards Committee (see [32]).

4.6. Managerial Effectiveness

According to question S19/S21 (Table 6), most farmers agreed that the way in which water was distributed was fair and equal to all users, and Tsunai farmers either approved or were indifferent to water prices. Still, there was at least one respondent from each system who reported that water theft occurs, which means that in some cases, water may be unavailable to whom it was originally intended. This does not necessarily mean that the water is mismanaged, but it could be an incentive for water theft. Ababi farmers did not list water scarcity among their top three threats.

4.7. Summary of Survey Results

The four indicators of sustainable irrigation management were as follows: (1) having a low negative impact on the environment, (2) using water efficiently, (3) maintaining water and soil quality, and (4) properly distributing water so that it is fair and equitable to all users. These were measured by Water Demand, Water Footprint, Water Quality, and Managerial Effectiveness, respectively. Table 9 summarizes the results as well as the dominant form of social capital in each irrigation system.

Table 9. Summary of survey findings.

	Ababi	Tsunai
Social Capital	Highest social capital overall and especially high bonding, relational, and structural social capital	Somewhat lower overall social capital, but higher amounts of bridging and linking
Water Demand (m/m^2)	0.84	1.15
Water Footprint (m^3/t)	Blue—3159.89, Green—2088.95 Total—5248.84	Blue—980.84, Green—765.73 Total—1746.57
Water Quality	Fair	Fair
Managerial Effectiveness	High satisfaction, but stealing does occur	Medium-high satisfaction, but stealing does occur and water scarcity a concern

The survey confirmed that each system hosted a different configuration of social capital, as well as differing results in irrigation management. What was not clear, however, was how these configurations of social capital translate into their respective results in irrigation management, and whether they are causative, correlative, or neither.

5. Discussion

An analysis of both systems' managerial processes reveals two categories of irrigation management styles: human and structural. Human management methods refer to anything that affects the four criteria of sustainable irrigation management as a result of everyday farmer behavior. Structural management methods refer to anything that affects the four criteria as a result of mechanization, bioengineering, or the structure of the irrigation system itself. Figures 1 and 2 map out the actual managerial processes of both systems. Note that the majority of water-saving measures for Tsunai occurs during the beginning and middle stages of the irrigation life cycle, while water-saving measures in Ababi occur toward the end of the process. This indicates Tsunai's tendency toward structural methods and Ababi's tendency toward human methods of irrigation management.

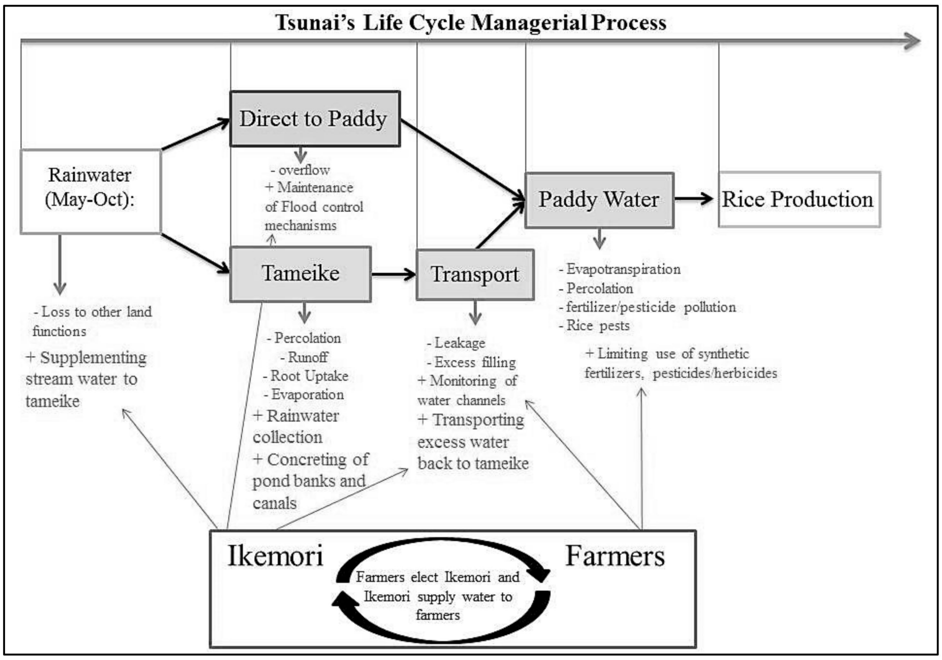

Figure 1. Managerial process of Tsunai irrigation highlighting structural measures for water savings.

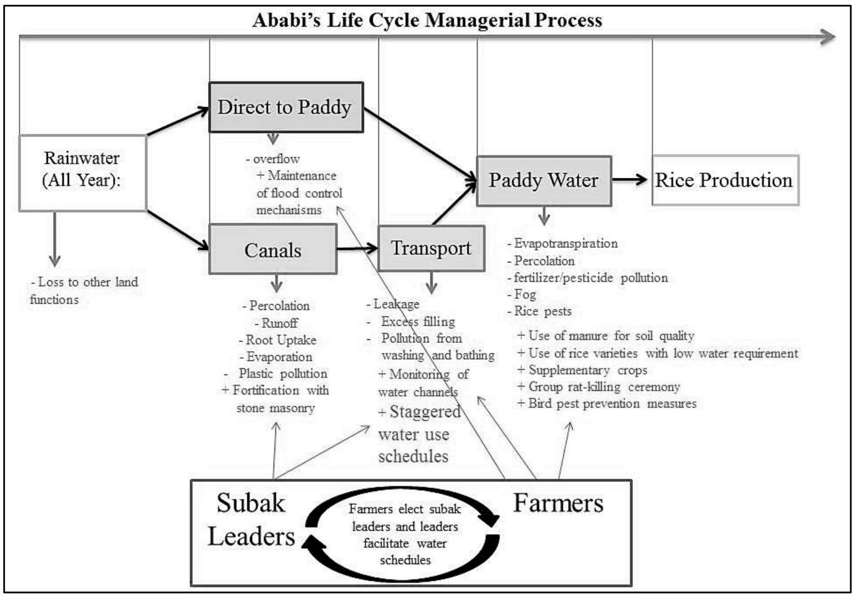

Figure 2. Managerial process of Ababi irrigation highlighting human measures for water savings.

The key to understanding the connection between the sustainability profile of Tsunai and Ababi's irrigation methods and their social capital lies in the concept of structural and human management methods. In Tsunai's case, bridging and linking social capital in the form of farmers' cooperatives, farming subsidies, and local government support have allowed the system to continue to succeed despite a lack of manpower and participation from the younger generation that would have otherwise made up strong bonding social capital. The technology of the tameike today allows for water to be managed easily by just one ikemori. According to one ikemori and the Tsunai historian interviewed, the role of ikemori used to require much more skill as water had to be released by diving to the bottom of the ponds to release the mechanism. In this historical situation, younger, able-bodied farmers would have been necessary, but structural improvements have removed this necessity. Harvesting rice has also become mechanized, enabling one man to harvest his entire field alone and liberating the children of farming households to pursue their own interests. The strain of rice currently grown in Tsunai, hinohikari, was also engineered in the last 40 years to grow well specifically in southern Japan's climate [33,34]. This has allowed the variety to bear more grain relative to the water it consumes, contributing to Tsunai's lower rice WF. Tsunai's entire system is optimized for economic efficiency but has a higher impact on the environment in the form of a higher WD as a result.

Figure 1 indicates that the only role bonding social capital plays, at this point, in the system's lifecycle is influencing the material purchases Tsunai farmers make and keeping general peace between farmers and ikemori. Even so, much of the purchasing is influenced by provisions from Japan Agricultural Cooperatives (JA) and government incentives. The tameike system has been streamlined and optimized to produce a monocrop with no water wasted, but because the focus of structural management methods has mainly been to increase efficiency and yield, the amount of water that is actually taken from the environment is not optimized, and WD remains high.

In Ababi's case, the opposite is true. There have not been major structural changes to the farming operations of Subak Embukan other than the introduction of C4 GMO rice varieties from Java. Many of the farmers interviewed, however, reported problems with this variety being infertile or drying up, and some have returned to growing native Balinese rice, which requires an average WL that is half that of hinohikari (5 cm compared to 10 cm) and has a shorter maturation period (105 days compared to 120 days). This relative lack of augmentation to the natural order of things has left Ababi's WD at what might be called a natural level based on native rice requirements. Without any major structural changes to their system, subak farmers rely on human management methods which are reactionary to the natural order rather than augmenting it. As shown in Figure 2, these methods include staggering planting and irrigation schedules for each branch, using crops other than rice when irrigation water is low and collaborative pest control tactics. This is where bonding social capital creates the tightly knit network needed to achieve success.

One example of necessary bonding social capital that has not been discussed in the literature is Subak Embukan's method of deflecting bird pests. In the weeks leading up to harvest, several bird species like to flock to rice paddies and eat the grain. In response to this, farmers tie strings with noisy objects like aluminum cans across the width of their paddies and shake them to scare the birds away. The only problem with this is if one farmer scares the birds away from their paddy, they will simply flock to the adjacent paddy. The farmer owning this paddy must then do the same and scare off the birds. This becomes a sort of a daily juggling act where all farmers must not only fight off the birds but coordinate and do it at the same time as their neighbors or risk all the birds congregating in their field. Without cultivating bonding social capital and constant communication, one's yield could be severely damaged. The way in which rats are killed is a similar process where all subak members are responsible for doing their share of the work.

As Lansing [35] had posited, water sharing would succumb to chaos without the order brought by the cooperation of subak members, and this is thanks to the subak's ability to react to nature, as opposed to Tsunai's strategy of augmenting nature. Accordingly, this gives Ababi a lower WD that likely resembles what the natural WD would be, but a higher WF due to a lack of technical innovation brought by would-be bridging or linking social capital. Conversely, the bridging and linking social capital that supports Tsunai has allowed it to be more efficient and therefore have a lower WF but a higher WD, as the structural methods employed appear to have been developed with yield as a major focus. This is especially likely according to Tsunai's historian who explained that the tameike themselves were built with the funding and mandate of the Kitsuki domain during the Tokugawa period in an effort to increase food supply. In those times, there was 150% more land cultivated in Tsunai than present day with a wider variety of crops, resembling Subak Embukan's current condition.

6. Conclusions

Sustainable irrigation management in Ababi and Tsunai are similar in that they keep relatively fair water quality thanks to the land-use practices inspired by Tri Hita Karana, Tri Mandala and Satoyama. Both systems also appear to perform somewhat well in ensuring an equitable use of irrigation water; although, slightly more so in Ababi. These systems differ greatly when it comes to the balance of environmental impact; Water Demand (WD) and water efficiency (WF). This research posits that this difference derives from two types of irrigation management strategies: human and structural. Human management methods are borne from bonding, relational, and structural social capital and favor environmental sustainability. Structural management methods are borne from bridging and linking social capital and favor economic sustainability. The former appears to be typical of developing countries, while the latter may be typical of developed countries. The relationship between social capital and irrigation management is summarized in Figure 3.

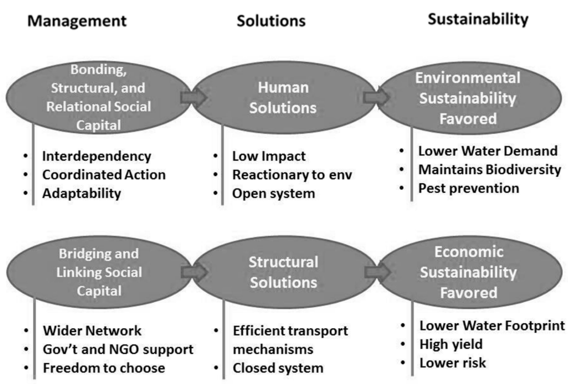

Figure 3. Summary of the relationships between management, solutions, and sustainability.

These findings can offer the GIAHS program and other agricultural organizations active in the Asia-Pacific region a point of reference from which to better support traditional agricultural communities. Communities where structural management methods are dominant likely need policy support to increase human management methods, accomplished by building bonding, relational, and structural social capital. Communities, where human management methods are dominant, would likely be best supported with structural management methods, accomplished by building bridging and linking social capital. How the different paradigms of social capital affect managerial effectiveness are still quite unclear. Further research on community-based irrigation systems is recommended to fully understand the dynamics of the findings of this research.

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