An Automatic Water Management System for Large-Scale Rice Paddy Fields

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Abstract: - An automatic water management system for large-scale paddy fields has been developed. The purposes of that are to supply the paddy fields with water or drain water from that automatically, to decrease water consumption, and to have a good harvest. To accomplish the above purpose, developed system has five functions, (1) prediction of paddy growth stages, (2) water level control corresponding to growth stages, (3) estimation of mean water level, (4) prediction of water consumption, and (5) optimal water allocation for minimizing of damage. In this paper, we especially give a detail description of functions (3) and (5). For (3), we construct estimation model based on Kalman-filter theory, and give an estimation result. For (5), we propose calculation method of the damage rate of paddy from cold weather, and give a simulation result of optimal water distribution to thirty paddy fields.

Key-Words: - Paddy field, Prediction of growth stages, Water level control, Estimating mean water level, Predict field consumption, Optimal water allocation

1 Introduction

Wet-paddy rice agriculture consists of plowing the paddy field, planting, water management, fertilization, weeding, harvesting and threshing. Of these tasks, 20.3% of the farmer's overall labor is spent dealing with issues related to water management in Japan, which involves walking through the paddy twice a day, once in the morning and once in the evening[1]. The decision of how much water to add to the paddy depends on the weather, soil conditions, and the stage of rice plant growth. It is a difficult task that requires experience. Fortunately, there has been progress in the design of facilities around the edges of paddy fields and in pipelines for water supply and drainage. At the same time, research in water management systems, the aim of which is to fully automate water management tasks, has reached the level of practical testing[2].

Wet-paddy rice agriculture is vulnerable to inclement weather and water shortages in Japan, as happened most recently in the widespread damage due to unseasonably cold weather in 1993 and the nationwide crop failure following the severe water shortage of 1994. Taken together, these incidents motivated the authors to undertake R&D into water management systems. In addition, a method was sought to reduce the labor required for patrolling paddy fields and to automate the supply and drainage of water, as well as to reduce the overall usage of water by paddy fields, and to stabilize yields.

Wet-rice culture requires strict management of water levels in the fields at specific stages of plant growth of the plants, from planting through tillering stage, heading time, ripening, etc. to harvest. The system developed in this project predicts the growth stage of the rice plants, sets the desired water level appropriate to that stage and controls the level through valves on supply and drainage lines. This allows the farmer to keep track of the growth progress of the plants while sparing him from the daily walks through the fields and other tasks associated with water supply and drainage. This system is intended to provide improved precision in control of water. It employs measurements of mean field water level using sensors in the field to estimate appropriate controlled variables, while eliminating the contribution of disturbances. It also records water losses based on estimates of water consumption in the field (leaching underground and evaporation). This data will enable the farmer to take measures against losses and reduce water consumption. The system estimates the extent and types of weather damage and the growth stage of the plants, calculates the damage rates in fields, and suggests plans for distribution of water to each paddy in order to avert as much damage as possible. This will help the farmer to ensure a stable yield despite damage due to cold or drought.

The system under development employs five algorithms with the following functions: (1) Monitoring rice growth stage; (2) setting the desired field water level and controlling water supply and drain valves; (3) estimating the mean field water level (controlled variable) while ignoring any disruptions of the measurements; (4) predicting water consumption in the field; and (5) optimizing volumes delivered to multiple fields in order to minimize weather-related damage. Below, Chapter 2 provides an overview of the new system, and the succeeding chapters describe the algorithms numbered above.

2 Overview of the Water Control System

2.1 System components

Figure 1 is a schematic view of the water management system under development. This discussion assumes that the system controls several dozen paddy fields, each of which is 1 ha. Each field is installed with a set of various sensors, plumbing for supplying and draining water, and two field units. The host for the system is located locally. The sensor pack is placed in the paddy and contains semiconductor sensors for measuring the level, temperature, and conductivity of the water. The supply and drain valves are on the roadways joining the pipelines and each field; they consist of butterfly valves, drives and pipe water pressure meters. A drive is operated by a control unit, which draws 0.3 A at 12 V in operation and just 3 mA in standby mode. The data about the valve opening position and the pipe water pressure enable the system to calculate the volumes of water supplied to or drained from the fields. The field unit is placed near the sensor pack and supply/drain valves and is composed of a solar panel and battery, which power the sensor pack and valve drives, a wireless unit, which exchanges data with the water management host, and the control unit that operates the valves in response to signals from the water management host. No permit is required for the specified low-power radio signals (430 MHz, 10 mW) employed for data transmission and ordinary farms may use this system. The range of the signals is short at about 500 m, but repeaters are permitted, enabling this system to be used in large paddy clusters to communicate with a field unit at each paddy.

The water management host consists of a PC, an exterior data storage device, a communications controller and a data management device. It is protected by a surge protector and uninterruptible power supply as it must be on 24 hours a day. It gathers data from the units in each of the fields every 15 minutes, and also receives meteorological information from the climate research Institute, Inc. and other authorities via the phone lines of carrier twice a day. These are reported for a 1-km mesh at 15-minute periods and provide predictions of ambient temperature, humidity, solar radiation, precipitation, wind speed and wind direction for up to four days in advance. Based on these data, it sends commands to the control unit in each field unit to re-set the open/closed condition for the supply and drainage valves every 15 minutes.

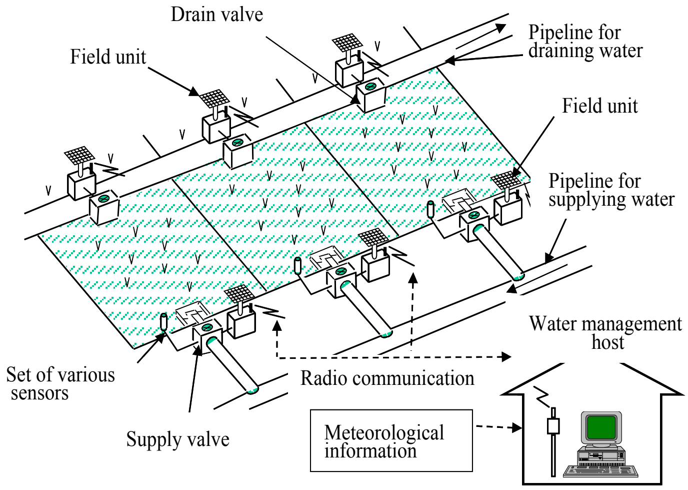


Fig.1 Schematic diagram of water management system for paddy field

2.2 Issues associated with previous systems and features of the system under development

Conventional systems like this typically employ features such as deep-water submergence as a countermeasure against cool weather damage, and also have various labor-saving functions. Several deficiencies prevent them from being used as fully automatic water management systems, however, notably, their lack of functions for minimizing water use and for stabilizing yield:

(1) Water in the field must be maintained at the level appropriate to the stage of the rice plant growth. Therefore, the foremost issue is to keep track of the current stage of the plants. Conventional systems use the height of the plants and an index of leaf area to gauge this, but a human must take measurements and input the parameters at intervals of 1 – 2 weeks, so control is not completely automated.

(2) The paddy water level in rice-growing areas with strong winds can show an elevation difference of several cm between upwind and downwind locations in the same paddy. This can result in large fluctuations in the sensed water level and can cause the system to waste water through unnecessary supply and drainage (hunching), preventing the system capacity for sensitive water management.

(3) Horizontal tunnels dug by moles and crawfish can cause leaks, necessitating otherwise unnecessary refilling.

(4) Paddy water levels can be raised to excessive depths if it rains after a paddy has been re-supplied with water. The excessive drainage that is then required is a waste of this natural water resource.

(5) Automatic commands for extra filling for submergence to prevent cool weather damage assume access to plentiful water resources, and conventional systems have yet to be re-designed to account for scarce water resources. Cool weather damage is of particular concern in rice-growing areas, so it is essential to consider countermeasures against weather damage for multiple paddy fields, not just a single one.

In order to resolve these issues, in this study, five algorithms have been developed and employed on the host computer. The functions of these algorithms are shown in Fig.2.

(1) The growth stage of the plants is estimated daily using ambient temperature data. (2) The desired water level is set by first determining the water level appropriate to the plant growth stage, then controlling the level with the supply and drain valves. When rain is expected in the near future, supply water is minimized, leaving the water level at the permitted lower bound. If particularly cold weather is predicted for the rice plants during the risk period of cold weather damage, water is supplied to fill the paddy to the upper bound in order to submerge the plants. (3) The influence of level fluctuations due to wind pressure on downwind water levels must be subtracted while estimating the mean water levels. These levels are used as controlled variables and provide improved precision of water level control when estimates are accurate. (4) The system predicts the volume of water consumption in the field (the reduction in depth) up to 4 days in the advance based on all weather forecast data available. In regions where rotating irrigation schedules are used, so that any field receives irrigation only at intervals of several days, it becomes possible to support determinations of water volumes that are neither too great nor too few. It also becomes possible to detect leaks by comparing the predicted water consumption in the field with the yearly mean. (5) When there is a limited volume of water in the region to be distributed, water is allocated to each paddy field so as to minimize the weather damage.

Objective	System functions	Algorithm
Automate water management tasks	Predict rice plant growth stage	(1)
	Control water level appropriate to plant growth stage	(2)
Minimize water usage	Correct readings from field water level meters for wind, other disturbances, estimate mean field water level	(3)
	Predict field water consumption (level drop) 4 days	(4)
	Reduce supply when rainfall is expected	(4)
Stabilize yield	Submerge when cold weather is expected	(2)
	Set water level to minimize weather damage	(5)

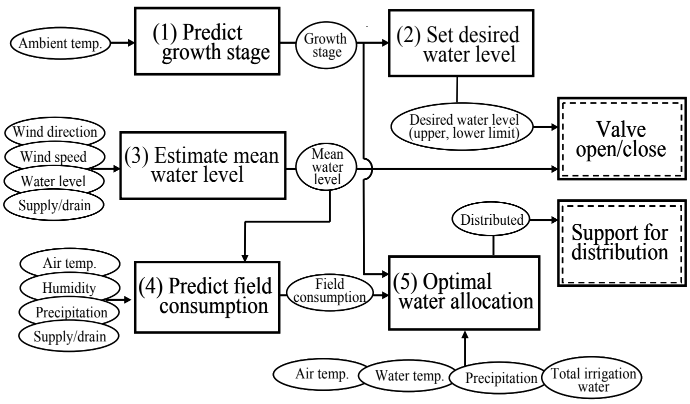


Fig.2 Function and structure of algorithm

The following sections will show procedures for realizing a system that performs the functions of algorithm 5 above.

3 Prediction of Growth Stages

The model used for predicting growth stage[3)] is based on the Development Index Model (DVI), which is used throughout Japan to estimate the growth stage of rice plants solely using the mean daily temperature (MDT).

$$DVI = \sum_{\text{planting date}}^{\text{est. date}} \frac{100}{A}\left(1 - e^{(-B(T_i - C))}\right) \quad (1)$$

where T_i is the MDT (ºC) on the i^{th} day after planting, and A, B, C are parameters determined by the plant species and the region.

The summation on the right side of Eq.(1) represents the speed with which the plant grows, determined by the MDT. This is summed day-by-day to find what is called the "DVI value", which represents the growth stage. The DVI value is 0 at planting, and the undetermined parameters A, B, C are determined in order to set DVI value = 100 on the day of heading.

Least-squares analysis of the heading days for Koshihikari rice(the kind of rice) and the growing season MDT in Ibaraki Prefecture in the seasons 2001-2007 indicates the following values for the parameters: A=72.72; B= 0.25; and C=12.4. The predicted heading days according to Model (1) are then as given in Table 1. These predictions were off by only approximately 1 day. This model is considered to provide predictions that are sufficiently accurate to be of practical use.

Table 1 Results of heading date predictions

Year	Number of days to heading (post-planting)	Expected number of days to heading (post-planting)	Error (days)
2001	88	88	0
2002	84	83	-1
2003	90	89	-1
2004	82	83	+1
2005	88	87	-1
2006	83	83	0
2007	82	82	0

4 Determining Desired Water Level

The desired water level was set using a Desired Water Level Table, which shows the relationship between the plant growth stage (DVI value) and the ideal water level. Figure 3 is an example of such a table. The horizontal axis is the DVI value and the vertical axis is the desired water level. Water level is uniquely determined by any DVI value calculated as given above. A permitted range of water levels is determined and the supply or drain valves are activated under proportional control every 15 minutes as necessary to maintain the level (properly, the mean water level in the paddy field) within the permitted range.

Desired water level tables are made using the rice crop calendar (which indicates the date vs. the desired water level) drawn up for each rice variety by the Agricultural Experiment Station of respective prefectures by converting the calendar date to a DVI value. A table can also be customized by individual farmers.

Supply or drainage is planned in accordance with the following water management rules:

(1) If the expected rainfall during the next 48 hours will exceed 20 mm, then the current desired water level is reduced by 20 mm.

(2) If the rice plants are in the early booting stage (when the plants are most vulnerable to frost damage) and the predicted ambient temperatures are below 20º C, set the current desired water level to 25 cm.

According to rule (1), when rainfall is expected, any fall of the paddy water levels below the lower permitted limit will be made up by the rainfall, so the farmer can economize on supply water.

According to rule (2), when damage from cold weather is expected, damage can be avoided by filling the paddy to a greater depth in order protect the plants, especially at night, when the water temperature will be higher than the air temperature.

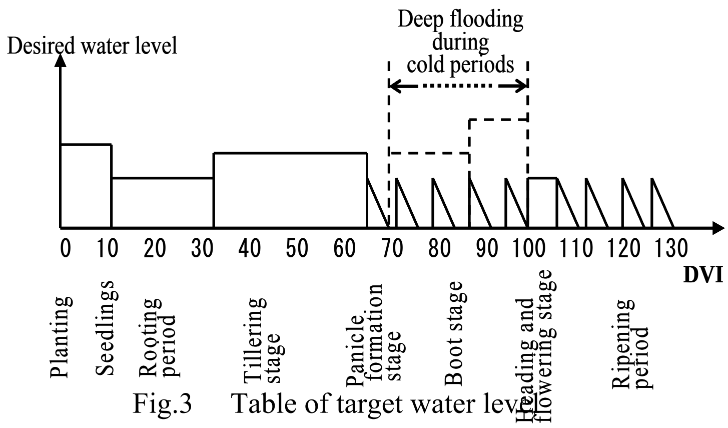


Fig.3 Table of target water level

5 Estimating Mean Water Level

The water level in a paddy can exhibit large fluctuations in response to exterior disturbances such as wind. It is therefore essential to eliminate such disturbances from the measured values to estimate the actual level, a key control variable. The physical quantities that temporarily affect paddy water level are water volume, supply and drain volumes, precipitation, wind direction and wind speed. The effects of these variables were estimated from measured data. A single measuring point was used at one end of the paddy to minimize the system cost and disruptions to farming tasks.

Below, section 5.1 examines the physical phenomenon of wind over the water surface, which has a quite marked effect on the water level. The relationship between wind direction and speed with water level increase is shown. Section 5.2 shows how the present model was designed based on the above relationships and the validation of the model using data from actual paddy fields.

5.1 Water level behavior under the effect of strong winds

Wind-driven fluctuations of paddy water levels take two forms, the movement of water into the downwind section of the paddy and the production of waves[4)]; both must be accounted for in any model for predicting water height. Water level fluctuations due to wind waves have a short period (0.5 s) and the sensor pack outputs the averages of measurements taken every 10 s, so the effect of waves can actually be ignored.

An experimental paddy field was established in the village of Miho in Ibaraki Prefecture and basic data were collected in order to gain a better understanding of the behavior of paddy water under strong winds. Figure 4 shows the scale of the nearly square field and the location of equipment. Water level sensors (1, 2) were placed at opposite corners of the field and a meteorological robot with instruments for measuring wind direction, wind speed, rainfall and other parameters was placed next to the pump station. No meters were installed to track the supply or drain volumes of water. The water levels, wind azimuth and speed and precipitation were measured at 15-minute intervals from May 21 to September 30, 2008.

The component of the wind velocity with respect to the orientation of the water level sensors (from Sensor 2 to Sensor 1 was taken as the positive direction) was designated the corrected wind speed, u, and the signed "wind speed", v, was defined as the second power of the corrected wind speed, i.e., $v = u^2 \cdot \mathrm{sgn}(u)$.

Figure 5 is a scatter plot showing the rise in the wind-driven water level h_w (level 1 – level 2) and the wind speed, v. The regression equation of $h_w = 0.30 \cdot v + 0.06$ was derived from the scatter plot on the 20th day after planting (May 21) and statistical analysis indicated that the regression coefficient represented a significant relationship.

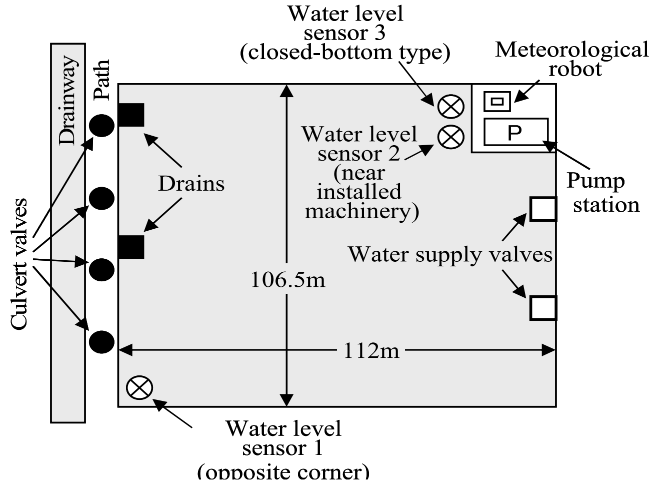


Fig.4 Experimental paddy field equipment

The scatter plot from the heading day (August 4) indicated a regression equation of $h_w = 0.05 \cdot v + 0.55$, but neither the regression coefficient nor the regression constant was significant.

The results of the above experiments indicate that the rise in the wind-driven water level is proportional to the square of the corrected wind speed. It is clear from Fig.5 that this relationship became relatively weak as rice plants matured.

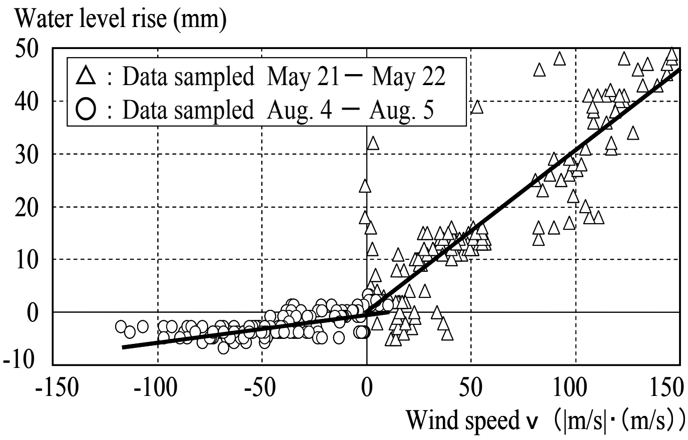


Fig.5 Relationship between wind velocity and water surface slope

5.2 Construction of model, verification

In order to estimate the mean, i.e., the actual water level in the paddy field, we must not only account for the rise in the level due to wind-driven shifts in the water mass, but we also need to model the shape of the water surface under such a situation. The model constructed here assumes that the water surface remains planar.

Under the above assumption, the regression equations introduced in the previous section are used to match the mean water level with the mean levels at the two locations in the paddy. The mean paddy water level is then determined if one knows the wind speed and direction and the water level at any given point. However, the coefficients in the above regression equation change with the growth stage of the rice plant; another serious drawback is that the equation directly represents the highly variable wind speed and measured water level using single estimates. Therefore, a unique model was constructed on the basis of Kalman Filter theory[5)] , which allows model parameters to be estimated on-line and the estimated error variance to be minimized.

If the mean paddy water level and proportional parameters (in the regression equation) are assumed to be state variables, the system and measurement equations can be derived according to Kalman Filter theory as follows. Let us write the measured water level, the mean water level, the corrected wind speed and the proportional parameter at some point in time k as h_k, x_k, u_k and p_k, respectively. Then, from the relationship between the downwind sweeping of water and the wind speed, we find

$$h_k - x_k = p_k \cdot v_k \tag{2}$$

Where $v_k = u_k^{\,2} \cdot \mathrm{sgn}(u_k)$

The nonlinear term $p_k \cdot v_k$ is linearized to establish the measurement equation

$$h_k + p^* \cdot v^* - p^* \cdot v_k = \begin{bmatrix} 1 & v^* \end{bmatrix} \begin{bmatrix} x_k \\ p_k \end{bmatrix} + e_k \tag{3}$$

Here, e_k is the measurement error and the values of p* and v* may be substituted for the known values of p_{k-1} and v_{k-1} at time k−1.

If the precipitation volume and supplied water volume (converted to terms describing paddy water level rise) between time point k−1 and k are r_{k-1} and q_{k-1}, then, the water balance relationship is stated by

$$x_k = x_{k-1} + r_{k-1} + q_{k-1} \tag{4}$$

If we assume that the proportional parameter p_k does not change in a short time, then the system equation becomes

$$\begin{bmatrix} x_k \\ p_k \end{bmatrix} = \begin{bmatrix} x_{k-1} \\ p_{k-1} \end{bmatrix} + \begin{bmatrix} r_{k-1} + q_{k-1} \\ 0 \end{bmatrix} + \begin{bmatrix} w_{k-1} \\ w'_{k-1} \end{bmatrix} \tag{5}$$

where w_k, w'_k represent the system errors.

The Kalman filter algorithm was applied to models (3) and (5) above. Figure 6 shows the results when water level data from 2008 (from meter #2 in Fig.4), precipitation, wind azimuth and wind speed were applied to this model. No data for the supply or drainage volumes were available, so only data from periods of no supply or drainage were used. The estimated results for the month of May showed some fluctuations in water level due to high winds, but even then, the mean water level was approximately constant. It is clear from the figure that the models provided accurate results. In August, however, the proportional parameters decreased to almost zero. This reflects the fact that, due to the growth of rice plants, paddy water levels are no longer influenced by the wind.

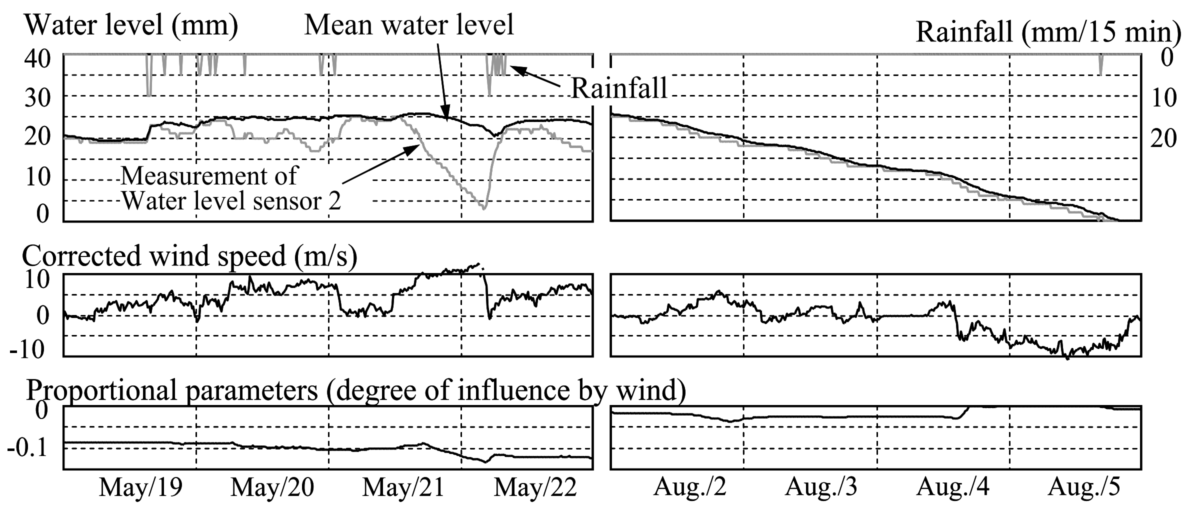


Fig.6 Estimation result of mean water level.

If the actual water level is assumed to be the mean of the readings of #1 and #2, the standard deviation of the error in the estimated water level by the model during the period when the water is most prone to be driven downwind (May 21 – end of May) is 2.0 mm.

Since especially precise management of water is necessary in cold regions, and the precision required is to the nearest centimeter, the precision of 2.0 [mm] is quite sufficient for practical application.

6 Estimating Water Consumption

"Consumption" of water by rice paddies can broadly be divided into evaporation from the water, transpiration and into leaching losses. In order to explain these different processes, it was attempted to make predictions about them using independent models. The well-established Penman equation[6] was employed here to make predictions of evaporation using daily meteorological data (air temperature, humidity, solar radiation, precipitation and wind speed). The predicted data up to four days in the future and the abovementioned daily evaporation estimates were used in an attempt to estimate the evaporation of water four days in the future. Leaching was modeled using the observed values for water balance relationships in the paddy (water level, supply volume, precipitation[7]) along with the evaporation estimates above. Leaching up to the present day was estimated and that trend was extrapolated. The estimated loss through evaporation and transpiration is E and the estimated loss through leaching is C:

$$E = \frac{1}{\ell}\cdot\frac{\Delta}{\Delta+\gamma}\cdot R_n + \frac{\gamma}{\Delta+\gamma}\cdot\frac{e^*(T_a)-e_a}{r_0} \tag{6}$$

$$C = \frac{dh}{dt} + Q + r - E \tag{7}$$

Here, T_a is ambient temperature (ºC), e_a is the vapor pressure of water in the atmosphere (mm Hg, function of air temperature and humidity), e* is the saturated water vapor pressure curve (mm Hg), Δ is the differential of the e* curve at T_a, R_n is the net radiation (function of solar radiation and leaf area coefficient), r_0 is the aerodynamic resistance (function of wind speed), l is the latent heat of evaporation of water (≅ 2.5×10^6 J/kg), γ is the dry-bulb humidity constant (≅ 0.50 mm Hg/ºC), h is the paddy water level (mm), Q is the supplied volume (mm) and r is precipitation (mm).

Figure 7 shows the estimated daily evaporation and losses due to leaching between May 18 - June 17, 2008, predicted by Eqs.(6) and (7). The actual amounts were calculated using the water levels and changes in the water levels detected by a closed-bottom sensor in the experimental paddy. The standard deviation of the estimated error for evaporation was calculated to be 1.12 mm/day. The estimated evaporation losses on both sunny and rainy days were relatively close to the actual losses.

The standard deviation for the estimated error in leaching losses was calculated to be 0.79 mm/day on sunny days and days when there was no supply or drainage. When it rained, the measured increase in paddy water level was greater than the precipitation indicated by the rain gauge, so the actual and estimated values were occasionally negative, which is impossible and was a problem related to meteorological instrumentation. It is therefore necessary to ensure that more accurate measurements of paddy water levels are conducted after rain in order to improve the accuracy of these forecasts.

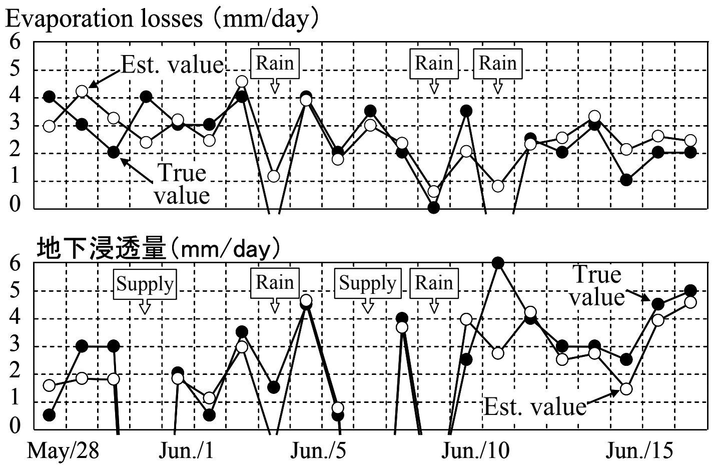


Fig.7 Estimation result of evapotranspiration and infiltration

7 Distribution of Supply Water

Water management in paddies extends beyond merely promoting growth of the rice plants; the manager must possess knowledge that enables them to avoid damage due cool weather, wind, flooding and drought. For example, to protect crops from cool weather, one can take employ submergence to take advantage of the fact that the water temperature is higher than that of the ambient air temperature. Still, weather damage such as cool weather damage, can occur over an entire rice-farming area. If, for example, an area is already experiencing a drought, all of the farmers in the region will not be able to get sufficient water to simultaneously employ submergence as a mitigation measure. Officials in charge of assigning water rights would then be forced into difficult decisions regarding who should be supplied with the available resources[8) 9) 10)] . This system is capable of calculating the minimum water allocations necessary in order to minimize weather damage and will aid authorities in making decisions related to water allocations when only limited water resources are available in an area.

Section 7.1 describes the management initiatives appropriate for minimizing damage to crops due to weather, and 7.2 describes how to estimate damage due to cool weather, which accounts for 61% of weather damage. In 7.3, an optimization problem is constructed for water allotments based on the aforementioned weather damage calculations, and in 7.4, a simulation of optimized water allotment is conducted to minimize cool weather damage associated with a typical cold snap.

7.1 Water management for mitigating weather damage

While wet-paddy agriculture is vulnerable to several kinds of weather damage, including cool weather, flooding, and drought, it is possible to moderate the damage from these with water management. Flooding and drought damage are caused by excesses or deficiencies in water volume, and these are best dealt with by drainage or irrigation. Cool weather damage and wind damage are ameliorated best by submergence.

A water management scheme referred to as "water-saving agriculture" has proven to be an effective method for avoiding damage during periods when water resources are scarce. Water is conserved during periods when the plants are comparatively insensitive to drought damage so that it can be supplied when they are most vulnerable, for example, during transplanting, the boot stage, and the heading and flowering stages. Another aspect of this scheme is that water is preferentially supplied to fields that are undamaged because rice plants tend not to recover once they have been damaged.

In summary, the following principles are followed regarding the allocation of water resources to multiple paddy fields in order to reduce weather damage:

(1) Preferential allocation of water during times of risk to crops

(2) Preferential allocation of water to fields that are still undamaged

7.2 Methods for assessing damage after cool weather

In order to make decisions about how much water to allocate to each of multiple fields, it is essential to be able to undertake quantitative estimates of the damage to paddy fields after employing the above principles. In this section, a method for calculating the degree of damage to a field due to excessively cool weather is used to demonstrate the application of the damage calculations.

The extent of damage from cold depends on the growth stage of the plant, temperatures and number of continuous cold days. The portion of the rice plant that actually bears the damage from cold is the spikelet; exposure to excessively low temperatures prevents its pollen from maturing completely, rendering it sterile. The plant is most vulnerable to cold in the boot stage (the stage when pollen develops inside the spikelet); the lower the temperatures and the longer the period of cold, the greater the damage to the crop.

Figures 8 and 9 show the results obtained from several experiments. Figure 8 is an example of the cumulative histogram of spikelet height above the ground during the boot stage. Figure 9 is an example of the progress of cool weather damage during cool periods under different conditions during the early boot stage.

These quantitative relationships can be used to calculate the extent of damage in any rice paddy from the volume of water supplied to the paddy, as follows:

(1) The spikelet is divided into several height zones (see Fig.8). The rate of appearance of spikelets is calculated using the relationship between the height above ground level and the cumulative histogram for the spikelet for a given plant's growth stage.

(2) The mean daily paddy water level is forecast up to several days previously using the volumes allocated to the paddy, the expected reduction in depth, and the expected rainfall.

(3) The mean daily water level is compared with the above zones of plant height and the temperature to which each zone is exposed (air or water temp.) is forecast several days previously.

(4) The rate of damage to each zone is calculated on the basis of the relationship between cool temperature conditions and cool weather damage rate.

(5) The weighted mean of the damage is calculated on the basis of the above rate of spikelet appearance and the rate of cool weather damage, to give a rate of cool weather damage for each paddy field.

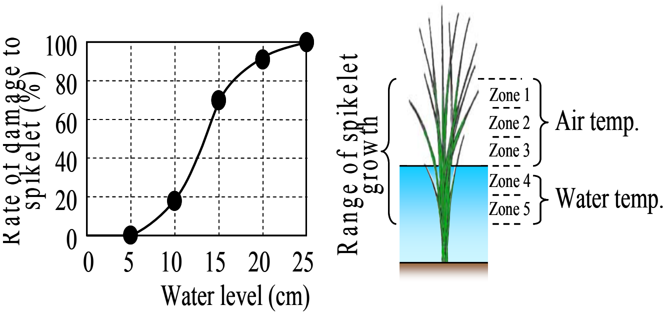
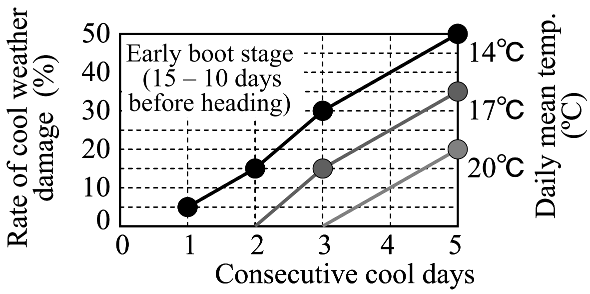


Fig.8 Relationship between water level and rate of spikelet covered with water



* Cool summer paddy damage rate curves redrawn for temperatures other than base temperatures in figure (14ºC, 17ºC, 20ºC) from previously existing curves

** When MDTs are inconsistent, the figure is adjusted to maximize consistency with previous and subsequent days.

Fig.9 Relationship between low temperature condition and paddy damage rate from cold weather

These quantitative relationships can be used to calculate the extent of damage in any rice paddy from the volume of water supplied to the paddy, as follows:

(1) The spikelet is divided into several height zones (see Fig.8). The rate of appearance of spikelets is calculated using the relationship between the height above ground level and the cumulative histogram for the spikelet for a given plant's growth stage.

(2) The mean daily paddy water level is forecast up to several days previously using the volumes allocated to the paddy, the expected reduction in depth, and the expected rainfall.

(3) The mean daily water level is compared with the above zones of plant height and the temperature to which each zone is exposed (air or water temp.) is forecast several days previously.

(4) The rate of damage to each zone is calculated on the basis of the relationship between cool temperature conditions and cool weather damage rate.

(5) The weighted mean of the damage is calculated on the basis of the above rate of spikelet appearance and the rate of cool weather damage, to give a rate of cool weather damage for each paddy field.

7.3 Determination of optimal water distribution problems

When there is a limited amount of supply water available in reservoirs, the allocation of water to each paddy in order to minimize weather damage throughout the supply area is calculated as an optimization problem. The calculation proceeds under the condition that the sum of the allotted volumes is less than the aforementioned available supply volume.

If N is the number of paddies, x_{ij} is the water allotted to paddy i on the j^{th} day, T is the volume of water available to the region, S_i is the undamaged area of paddy i, and the rate of damage in paddy i is $f(x_{ij})$, then

Objective function:

$$\min \quad J = \sum_{i=1}^{N} S_i \cdot f(x_{ij}) \tag{8}$$

Constraint:

$$\sum_{i=1}^{N} x_{ij} \leq T \tag{9}$$

It is assumed that the values necessary for the above calculation, such as initial paddy water level, reduction in water level and precipitation, are already known.

7.4 Simulation of optimization of water distribution

This section describes the simulations obtained for optimizing water allocation to a group of rice paddies in order to minimize the damage due to cool weather for a period ranging from the present to 4 days in the future. The reasons for selecting a 4-day period are because (1) four days is the current limit for reliable predictions of cool weather damage on the geographical mesh, and (2) it is increasingly common to use rotating irrigation schedules in regions that experience water shortages.

Let us assume that a service area consisting of thirty 1-ha paddies is expected to have an MDT of 15ºC, a mean daily water temperature of 18ºC and zero precipitation for the next four days, and that the available supply volume is 21,000 m^3 (approx. 70 mm per paddy). The allocation for each field is calculated as follows:

In order to make the allocations easier to understand, the group is subdivided into three groups of 10 paddies each. Group A contains plants at the early boot stage (vulnerable to cold), and B and C are in the middle boot stage (capable of withstanding cold well), but C has sustained 20% growth damage. Water levels were set for each paddy at random about a mean of 140 mm and the daily reduction in depth was set at 10 mm. Using these conditions, an optimization problem is constructed and is shown in 7.3. The calculation of the extent of damage in the criterion function was determined by the method shown in 7.2. Computations for optimizing the downhill simplex method[11) consists of simply evaluating the criterion function, implying that they are therefore well suited for problems like these, where the criterion function includes non-differentiable points.

Figure 10 presents the extent of damage for the optimized case in all of the paddies.

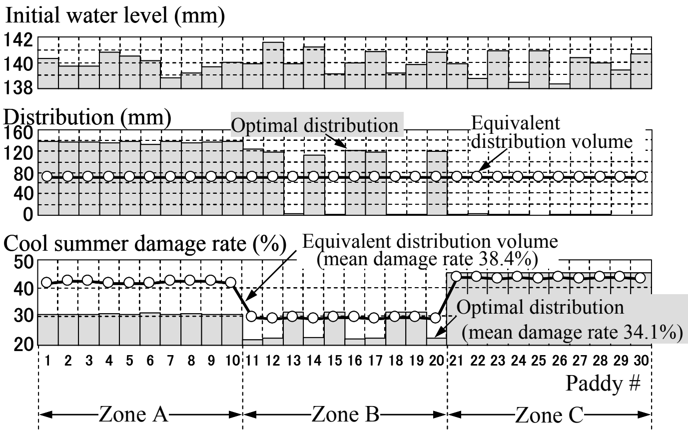


Fig.10 Simulation result for optimal water distribution

The optimal allocation rules provide that Group A is preferentially supplied with water, and Group C received almost no water at all. This indicates that the water management principles for minimizing damage listed in 7.1 were executed. In Group B, the higher the water level each member had at the beginning, the more water it received, reflecting the principle of effective use of water resources. In comparison to the damage rate of 38.4% expected under equal allotments of water, this optimized allotment enabled the managers in this simulation to limit damage to 34.1%, a 4.3% reduction (improvement in balance).

8 Conclusions

Of the five algorithms developed in this study, the methods of Mean Water Level Estimates and Optimized Allocation of Water are new concepts that do not exist in conventional water management methods. In the Mean Water Level Estimates approach, the driving of water to the downwind portion of the paddy was examined as the physical phenomenon most likely to effect water level measurements. Consequently, a model based on Kalman filter theory was constructed for estimating mean water levels. This model was effective, and facilitated an improvement in precision from the centimeter range of the conventional models to the millimeter range. A problem was constructed in which water supply allocations were optimized so as to minimize the overall damage to a variety of different paddies, in anticipation of inclement weather that threatened to damage the crop. A method for calculating the extent of damage to crops during a cold period was described and demonstrated using a simulation employing optimized water allotments.

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