Numerical Investigation into the Effect of Irrigation Water Temperature on Soil Temperature in Paddy Fields under Saturated Irrigation

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Abstract: The effects of irrigation water temperature on soil temperature in rice paddy fields under saturated irrigation are numerically clarified. A numerical model that coupled a heat transport model and a soil water movement model was employed. The governing equations of the heat transport and soil water movement were described as the heat conduction equation and the mixed form of Richards equation, respectively, and discretized by the finite element method for space and the finite difference method for time. A portion of a paddy field that is adjacent to an irrigation canal was used for the computational domain. Given the irrigation water temperatures as the Dirichlet boundary condition, the simulations of time-varying soil temperatures in the domain were implemented. In addition, the effects of the meteorological conditions on soil temperature were investigated. The results show that the irrigation water temperature has an effect on the soil temperature of a paddy field under saturated irrigation. The difference in soil temperature due to the different irrigation water temperature given as the Dirichlet boundary condition significantly appears near the ground surface; the trough or peak values are approximately equal to the difference in the irrigation water temperature, and the difference in the time-averaged soil temperature is about half of the difference in the irrigation water temperature. Consideration of the meteorological conditions makes the surface heat budget during computation period change from a negative value to a positive one, and diminishes the effect of irrigation water temperature on soil temperature. Thus, the effect of irrigation water temperature on soil temperature is small compared to that of the meteorological conditions.

Keywords: Heat damage; Rice paddy field; Saturated irrigation; Heat and moisture coupling model; Finite element method

1 Introduction
The heat damage to rice plants (Oryza sativa) has been of high concern recently, and various countermeasures have been proposed (e.g., Morita, 2008).

The countermeasures relating to irrigation water management include spillover irrigation (Arai and Ito, 2001; Nakamura et al., 2003; Nagahata et al., 2005; Nagata et al., 2005) and cool water irrigation (Wada et al., 2013), which are used with the aim of decreasing water and soil temperatures. However, Tomosho and Yamashita (2009) indicated that these countermeasures were difficult to implement because the additional irrigation water demands increased and, thus, agricultural water supply sectors, such as land improvement districts, could not cope well due to limitations involving water rights and irrigation facilities. On the other hand, Nakamura et al. (2003) and Nagahata et al. (2005) also examined the effectiveness of saturated irrigation, which keeps the soil saturated rather than ponding the field, and found that saturated irrigation was effective in avoiding heat damage to some extent. As such, saturated irrigation is a water-saving countermeasure and is very important in areas where meeting additional irrigation water demands is difficult. Furthermore, Fujihara et al. (2013) compared the soil environment and rice quality achievable by utilizing saturated irrigation and ponding irrigation, and discussed the relationship between the average air temperature after ear emergence and rice quality.

While it is important to determine the amount of heat damage that is reduced due to the use of saturated irrigation, it is also important to determine to what extent the soil temperature decreases. Since the soil temperature in paddy fields depends on the saturation of the soil and the soil water distribution is determined based on the geology, Izumi and Takeuchi (2014) showed the influences of geological conditions on the soil environment via numerical simulations. However, the soil temperature is determined not only by the geological conditions, but also by the irrigation water temperature, rainfall temperature, and other factors. Accordingly, the effect of irrigation water temperature on soil temperature is discussed based on numerical simulations in the present study.

2 Numerical model

The numerical modeling of heat transport and soil water movement based on Izumi et al. (2012), in which the model was validated with observational data, is used in the present study and described in the following subsections.

2.1 Heat transport
A heat conduction equation based on Kondo and Saigusa (1994) was used to simulate the heat transport, under the assumption that the heat flux due to the water movement in the soil was smaller than the heat conduction by solid soil, such as follows:

$$\frac{\partial (C_s T_s)}{\partial t} = -\nabla \cdot (-\lambda\nabla T_s)$$

(1)
with

\[ C_s = (1 - \phi)c_s + \theta c_w \]  
\[ \lambda = b_1 + b_2 \theta + b_3 \theta^{0.5} \]

where \( C_s \) is the volumetric heat capacity of the soil, \( T_s \) is the soil temperature, \( t \) is the time, \( \phi \) is the porosity, \( \theta \) is the volumetric water content, \( c_s \) and \( c_w \) are the volumetric heat capacity of soil particles and of water, respectively, \( \lambda \) is the thermal conductivity of soil expressed by Chung and Horton (1987), and \( b_1, b_2 \) and \( b_3 \) are the model parameters.

### 2.2 Soil water movement

The mixed form of the Richards equation has been used for soil water movement (Huyakorn and Pinder, 1983; Celia et al., 1990). Assuming that the liquid phase is relatively large (i.e., neglecting the vapor fluxes), the equation for saturated-unsaturated flow is as follows:

\[ \frac{\partial S}{\partial t} + W S \frac{\partial \psi}{\partial t} = -\nabla \left( K \left( \nabla h + \frac{\rho(T) - \rho_s}{\rho_s} \nabla z \right) \right) \]

with

\[ W = \begin{cases} 1 & (\psi \geq 0) \\ 0 & (\psi < 0) \end{cases} \]
\[ S_s = \rho_s g (\beta_s + \phi \beta_w) \]
\[ K = K_s (S_s) \]
\[ h = \frac{P}{\rho g} + z = \psi + z \]

where \( S_s \) is the saturation, \( S_s \) is the specific storage, \( \psi \) is the pressure head, \( K \) is the unsaturated hydraulic conductivity, \( h \) is the hydraulic head, \( z \) is the height defined as positive upward, \( \rho \) \((= \rho(T)) \) is the water density at the soil temperature \( T_s \), \( \rho_s \) is the reference water density at the reference soil temperature \( T_r \), \( g \) is gravitational acceleration, \( \beta_s \) and \( \beta_w \) are the compressibility coefficients of soil and water, respectively, \( K_s \) is the saturated hydraulic conductivity, \( K_1 \) is the correction-factor function of soil temperature, \( K_s \) is the saturated hydraulic conductivity, \( S_s \) is the effective saturation, and \( p \) is the water pressure.

### 2.3 Soil hydraulic properties

For the soil water retention curve and the unsaturated hydraulic conductivity, the following models were used.

The VG model (van Genuchten, 1980) was used for the soil water retention curve due to the frequent simulation of water movement in soil:

\[ S_s(\psi) = \left[ \frac{1}{(1 + (\alpha |\psi|)^{n_s})^{m_s}} \right]^{\frac{\theta_s - \theta_t}{\theta_s - \theta_t}} \]

with

\[ m_s = 1 - \frac{1}{n_s} \]

where \( \theta_t \) is the residual water content, \( \theta_s \) is the saturated water content, and \( \alpha, m_s \) and \( n_s \) are the model parameters.

Unsaturated hydraulic conductivity is described as the product of the three variables shown in Eq. (7). The three variables, namely, the relative hydraulic conductivity, the correction-factor function of soil temperature, and the saturated hydraulic conductivity, are represented as follows:

\[ K_s = S_s^{1/2} \left( 1 - (1 - S_s^{1/n_s})^{m_s} \right)^2 \]
\[ K_T = \frac{\mu_r}{\mu(T_r)} \]
\[ K_s = \rho_s g K \]

where \( \mu_r \) \((=\mu(T_r)) \) and \( \mu(T_s) \) are the viscosity coefficients at the reference temperature \( T_r \) and soil temperature \( T_s \), respectively, and \( \kappa \) is the intrinsic permeability.

### 2.4 Discretization and initial/boundary conditions

Equations (1) and (4) were discretized using the combination of the standard Galerkin finite element method for space and the finite difference method for time. As the time integral scheme, the implicit method with the modified Picard method based on Celia et al. (1990) was used for the soil water movement, and the Crank-Nicolson method was used for the heat transport.

After the discretization as mentioned above, the governing equations were subjected to the following initial and boundary conditions and were solved numerically with the iterative partitioned method in terms of coupling the heat transport with water movement:

\[ T_s(x, 0) = T_0(x) \quad \text{in} \quad \Omega \]
\[ \psi(x, 0) = \psi_0(x) \quad \text{in} \quad \Omega \]
\[ T_s(x, t) = \tilde{T_s}(x, t) \quad \text{on} \quad \Gamma^d \]
\[ \psi(x, t) = \tilde{\psi}(x, t) \quad \text{on} \quad \Gamma^w \]
\[ -\frac{\partial T_s(x, t)}{\partial n} = \tilde{q}_s(x, t) \quad \text{on} \quad \Gamma^d \]
\[ -K_s \frac{\partial h(x, t)}{\partial n} = \tilde{q}_w(x, t) \quad \text{on} \quad \Gamma^w \]

where \( T_0(x) \) and \( \psi_0(x) \) are the initial values of the soil temperature and the pressure head, respectively, \( x = (x, z)^T \) is the vertical two dimensional vector, \( \Omega \) is the space domain, \( \tilde{T_s}(x, t) \) and \( \tilde{\psi}(x, t) \) are the values of the soil temperature and pressure head on the Dirichlet boundary, respectively, \( \Gamma^d \) and \( \Gamma^w \) are the Dirichlet boundaries for the heat transport and water movement, respectively, \( \tilde{q}_s(x, t) \) and \( \tilde{q}_w(x, t) \) are the heat and water fluxes on the Neumann boundary, respectively, \( \Gamma^w_n \) and \( \Gamma^d_n \) are the Neumann boundaries for the heat transport and water movement, respectively, and \( n \) is the outward unit normal vector on the boundary.
3 Numerical experiments

The effect of irrigation water temperature on the soil temperature in paddy fields under saturated irrigation were investigated via simulations with the model mentioned above. In the present study, the water management in the saturated irrigation was conducted based on Fujihara et al. (2013), and thus the irrigation water was supplied for one hour from six to seven o'clock to the amount of corresponding the water requirement rate. For simplicity, the water requirement rate was set as 5 mm/d in the present study, though Fujihara et al. (2013) set it as approximately 8 mm/d.

3.1 Computational domain and cases

In the present study, we evaluated the portion of a paddy field that is adjacent to the irrigation canal and, thus, the computational domain was a two-dimensional vertical cross-section of the paddy field, as shown in Figure 1. The soil texture in the entire domain was assumed to be volcanic ash soil (andsol).

The time-varying irrigation water temperatures were prepared based on the work of Shinmura and Taniguchi (2013). They observed irrigation water temperatures to investigate the temperature change of irrigation water flowing down their target irrigation basin. In the present study, the time-varying irrigation water temperatures were treated as a circadian function and thus a set of daily irrigation water temperatures determined from their work was regarded as the standard irrigation water temperature (the black double line in Figure 2). Additionally, irrigation water temperatures that had a deviation of ±2°C and ±4°C from the standard were also used. For comparison, a simulation that did not take the irrigation water temperature into consideration was conducted.

Since soil temperature also depends on the meteorological conditions, simulations that did take the meteorological conditions into consideration were conducted to further clarify the effects of irrigation water temperature.

A total of eight computational cases were conducted, which are listed in Table 1.

3.2 Computation period and initial/boundary conditions

The computation period used in the present study was August 02 to 10, 2012, corresponding to the ripening period of rice grains, since Koshihikari, a major brand in Japan, generally tassels between late July and early August. The computation period was also non-precipitation days in order to exclude the effect of rainwater temperature.

For the initial condition, the soil temperature and pressure head values, which were obtained from the preliminary computation from July 25 to August 01, 2012, were assigned to all of the nodes in the computational grid. The time-varying soil temperatures and pressure heads were computed with a fixed time increment of 1.0 s under the initial and boundary conditions described as follows.

The boundary conditions were set as follows. There were four boundaries in the computational domain as indicated in Figure 1: (i) the ground surface (G-F-E-D), (ii) the irrigation canal (A-H-G), (iii) the lateral segments on the left-hand side (A-B) and right-hand side (C-D), and (iv) the bottom (B-C).

For the heat transport, the Neumann boundary condition was assumed along (i) and the Dirichlet boundary condition was assumed along (ii) for the cases that took the irrigation water temperature into consideration. The flux of the ground heat was assigned for the Neumann boundary condition. The time-varying irrigation water temperatures were assigned for the Dirichlet boundary condition. For the case
that did not take the irrigation water temperature into consideration, the Neumann boundary condition was assumed along both (i) and (ii). In all cases, the Neumann boundary condition was assumed along both (iii) and (iv), and a zero flux was assigned.

For the water movement, the Neumann boundary condition was assumed along (i). The Dirichlet boundary condition was assumed along (ii), and the pressure head corresponding to the water depth (20 cm) in the canal was assigned. Along (iii) and (iv), the Neumann boundary condition was imposed, and a zero flux was assigned.

The heat and water fluxes on the ground surface were divided into the cases that did not and did consider the meteorological conditions, and then calculated as follows:

**Without meteorological conditions**

\[
\bar{q}_w|_{c=\Gamma_s} = \begin{cases} \Gamma_s - H_w & 6:00-7:00 \\ 0 & \text{otherwise} \end{cases}
\]

\[
\bar{q}_w|_{c=\Gamma_s} = \begin{cases} \Gamma_s - H_w & 6:00-7:00 \\ 0 & \text{otherwise} \end{cases}
\]

With meteorological conditions

\[
\bar{q}_w|_{c=\Gamma_s} = \begin{cases} R_n - H_w - I_E & 6:00-7:00 \\ R_n - H_w - I_E & \text{otherwise} \end{cases}
\]

\[
\bar{q}_w|_{c=\Gamma_s} = \begin{cases} P - E + I_t & 6:00-7:00 \\ P - E & \text{otherwise} \end{cases}
\]

where \(\Gamma_s\) is the ground surface boundary, \(R_n\) is the net radiation flux, \(H_w\) and \(H_t\) is the sensible heat flux, \(I_t\) is the latent heat, \(E\) is the evaporation flux, \(P\) is the precipitation flux, and \(I_t\) is the irrigation water flux corresponding the daily water requirement rate.

The sensible heat flux \(H_w\) was calculated as follows:

\[
H_w = c \rho (T_u - I_t (T_s - T_u))
\]

where \(c\) is the specific heat of water, and \(T_u\) is the irrigation water temperature. The net radiation flux \(R_n\) is the radiation budget of short- and long-wave radiation, which was estimated as follows:

\[
R_n = (1 - a) S - \sigma T^4 (1 - 0.51 - 0.066 \sqrt{e_w})
\]

where \(a\) is the albedo of the ground, \(S\) is the solar radiation, \(\sigma\) is the Stefan-Boltzmann constant, and \(e_w\) is the vapor pressure. The sensible and latent heat fluxes \((H_s\) and \(I_E\)) were obtained from the bulk formula as follows (Kondo, 1994):

\[
H_s = c_p \rho S C_i (T_i - T_3)
\]

\[
I_E = \rho c_i \beta C_i (T_i - q_s)
\]

with

\[
\rho_s = \frac{273.15}{1013.25} \left( \frac{p_s}{1-0.378 e_s / p_s} \right)
\]

\[
q_s = \frac{0.622 (e_s / p_s)}{1-0.378 (e_s / p_s)}
\]

\[
e_{sat} = 6.1078 \times 10^{7/6 (T_s - 273.15)}
\]

where \(c_p\) is the specific heat of air, \(\rho_s\) is the air density, \(C_i\) is the bulk transfer coefficient, \(U\) is the wind velocity, \(T_s\) is the air temperature, \(\beta\) is the evaporation efficiency, \(q_{sat}(T_s)\) is the saturated specific humidity at \(T_s\), \(q_s\) is the air specific humidity, \(p_s\) is the air pressure, \(e_{sat}\) is the saturated vapor pressure, and the subscript \(*\) denotes “sat” or “a”. The product of \(C_iU\) is referred to as the exchange speed, and was described as the function of wind velocity by Kondo (2000). Thus, the following function was employed for the exchange speed of the paddy fields:

\[
C_i U = 0.006 U_{10}
\]

with

\[
U_{10} = \frac{\ln (10 / z_0)}{\ln (z_{obs} / z_0)}
\]

where \(U_{10}\) is the wind velocity at 10 m, \(U_i\) is the wind velocity at the observed height \(z_{obs}\), and \(z_0\) is the roughness length for the wind velocity. The evaporation flux \(E\) was estimated as the correction of the potential evaporation flux obtained from the classical Penman’s method (Arai, 2004). The meteorological data obtained from Matsuyama, Ehime Prefecture, in 2012, was used as shown in Figure 3. Figure 3 also includes the time-varying evaporation values, which were estimated as explained above.

The parameter values used in the present study are summarized in Table 2. The saturated water content, residual water content, \(\alpha\), \(n_{vs}\), and saturated hydraulic conductivity were based on Takeshita and Kohno (1993). The compressibility coefficient of soil was inversely calculated from the specific storage based on Anderson and Woessner (1992). The volumetric heat capacity of soil and water, the albedo, and the evaporation efficiency were based on Kondo (1994). The model parameters related to the thermal conductivity were based on Chung and Horton (1987). The roughness length were based on Kondo (2000).

### 3.3 Results and discussion

Firstly, for the simulation results through Cases 1 to 6, the time-varying soil temperatures at the depths of 0, 20, 40, and 60 cm (measured at the segment of 0.6 m from the irrigation canal) are shown through Figures 4 to 9. The differences in temperature between Case 3 with other cases (Cases 1, 2, 4, and 5), which are calculated by subtracting the soil temperatures in Case 3 from those in other cases, are also shown through Figures 10 to 13.

Through Figures 4 to 8, it is found that the soil temperatures gradually decline as time passes and, at the ground surface, fall like a pulse when supplying the irrigation.
Table 2: Parameters used in the present study

| Parameter | Value |
|-----------|-------|
| $\theta_0$ | 0.800 |
| $\theta_l$ | 0.437 |
| $\alpha$ (m/m) | 2.41 |
| $n_{ag}$ | 1.713 |
| $K_v$ (m/s) | $3.0 \times 10^{-4}$ |
| $\beta_v$ (m$^2$/N) | $2.0 \times 10^{-8}$ |
| $\beta_w$ (m$^2$/N) | $4.5 \times 10^{-10}$ |
| $c_v$ (J/(m$^2$K)) | $1.26 \times 10^9$ |
| $c_w$ (J/(m$^2$K)) | $4.20 \times 10^9$ |
| $b_1$ | 0.243 |
| $b_2$ | 0.393 |
| $b_3$ | 1.534 |
| $T_r$ (°C) | 20.0 |
| $a$ | 0.2 |
| $\sigma$ (W/(m$^2$K$^4$)) | $5.670 \times 10^{-8}$ |
| $c_p$ (J/(kgK)) | 1005 |
| $\beta$ | 0.5 |
| $z_0$ (m) | 0.1 |
| $z_{obs}$ (m) | 2.0 |

Figure 3: Meteorological data obtained from Matsuyama (2012)

Figure 4: Time-varying soil temperatures at the segment of 0.6 m from the irrigation canal in Case 1

Figure 5: Time-varying soil temperatures at the segment of 0.6 m from the irrigation canal in Case 2

Figure 6: Time-varying soil temperatures at the segment of 0.6 m from the irrigation canal in Case 3

Figure 7: Time-varying soil temperatures at the segment of 0.6 m from the irrigation canal in Case 4

Figure 8: Time-varying soil temperatures at the segment of 0.6 m from the irrigation canal in Case 5
Secondly, in order to investigate the spatial difference in soil temperature during the computation period, distributions of difference in time-averaged soil temperature between Case 3 with other cases (Cases 1, 2, 4, and 5) in the entire domain are represented in Figures 14, 15, 16, and 17, respectively. The difference in soil temperature is found near the ground surface and the irrigation canal. Those values near the ground surface in Figures 14, 15, 16, and 17 are approximately -2.0 °C, -1.0 °C, 1.0 °C, and 2.0 °C, respectively, which are half of the difference in irrigation water temperature. The difference in temperature in each case also appears to converge with a constant value.

Thirdly, time-varying soil temperatures at the depths of 0, 20, 40, and 60 cm (measured at 0.6 m from the irrigation canal) for Cases 7 and 8 are shown in Figures 18 and 19, respectively, in order to examine the effects of the meteorological conditions on soil temperature. Additionally, the distribution of difference in time-averaged soil temperature between Cases 7 and 8 in the entire domain, which is calculated by subtracting the soil temperature in Case 8 from that in Case 7, is shown in Figure 20. From Figures 18 and 19, it is found that the soil temperatures responded well to the meteorological condition. In Figure 18, it can be also seen that the soil temperatures at the ground surface slightly decrease when supplying the irrigation water. During the computation period, the heat supplies in Cases 7 and 8 are estimated at $1.19 \times 10^8$ and $1.12 \times 10^8$ J/m², respectively. These values are about the same. Compared with the case that did not consider the meteorological conditions, the sign of these values is opposite. This means that the ground surface dissipates heat into
the air in the case that did not take the meteorological conditions into consideration while the ground surface absorbs heat from the air in the case that did take the meteorological conditions into consideration. From the Figure 20, it is found that the effect of the irrigation water temperature on soil temperature appears only near the irrigation canal under considering the meteorological conditions. Thus, the effect of irrigation water temperature on the soil temperature is smaller than that of the meteorological conditions.
4 Conclusions
The effect of irrigation water temperature on the soil temperature in paddy fields under saturated irrigation was numerically investigated. A numerical model that coupled a heat transport model with a soil water movement model was used. Numerical simulations using five types of irrigation water temperature datasets based on previous observations were performed. For comparison purposes, one case that did not take the irrigation water temperature into consideration was also simulated. Additionally, the effect of the meteorological conditions on soil temperature was examined.

The results indicate that the irrigation water temperature has an effect on the soil temperature. The difference in soil temperature due to the difference in irrigation water temperature significantly appears near the ground surface; the trough or peak values are approximately equal to the difference in irrigation water temperature, and the difference in time-averaged soil temperature is about half of the difference in irrigation water temperature. From the simulations in the case that did take the meteorological conditions into consideration, the surface heat flux during computation period changes from a negative value to a positive one, and the effect of irrigation water temperature on soil temperature cannot be perceptible. Thus, it is also indicated that the irrigation water temperature has a small effect on soil temperature compared to the meteorological conditions.

References
[1] Anderson, M.P., and Woessner, W.W. (1992): Applied Groundwater Modeling, Simulation of flow and advective transport, Academic Press, Inc., p.41.
[2] Arai, T. (2004): Hydrology for Regional Analysis, Kokon Shoin, Publishers, 309p. (in Japanese).
[3] Arai, Y., and Ito, H. (2001): Effects of flow irrigation on high temperature ripening in paddy field rice, Tohoku Journal of Crop Science, (44), pp.89-90. (in Japanese).
[4] Celia, M.A., Bouloutas, E.T., and Zarba, R.L. (1990): A general mass-conservative numerical solution for the unsaturated flow equation, Water Resour. Res., 26(7), pp.1483-1496.
[5] Chung, S-O., and Horton, R. (1987): Soil heat and water flow with partial surface mulch, Water Resour. Res., 23(12), pp.2175-2186.
[6] Fujihara, Y., Toriyama, K., and Fujii, S. (2013): Effects of saturated irrigation on soil environment and rice quality, Water, Land and Environmental Engineering, 81(4), pp.273-276. (in Japanese).
[7] Huyakorn, P.S., and Pinder, G.F. (1983): Computational Methods in Subsurface Flow, Academic Press, 473p.
[8] Izumi, T., Fujihara, M., Takeuchi, J., and Kawachi, T. (2012): Inverse modeling for variably saturated water flow coupled with heat transport in field soil. Irrigation, Drainage and Rural Engineering Journal, 282, pp. 7-14.
[9] Izumi, T., and Takeuchi, J. (2014): Influences of geological conditions on the soil environment in paddy fields under saturated irrigation, Journal of Rainwater Catchment Systems, 19(2), pp.11-17.
[10] Kondo, J. (1994): Meteorology of the Water Environment –Water and Heat Balance of the Earth’s Surface—, Asakura Shoten Press, 348p. (in Japanese).
[11] Kondo, J. (2000): Atmospheric Science near the Ground Surface, University of Tokyo Press, p.143. (in Japanese).
[12] Kondo, J., and Saigusa, N. (1994): Modelling the evaporation from bare soil with a formula for vaporization in the soil pores, J. Meteor. Soc. Japan, 72, pp.413-421.
[13] Morita, S. (2008): Prospect for developing measures to prevent high-temperature damage to rice grain ripening, Jpn. J. Crop Sci., 77(1), pp.1-12. (in Japanese with English abstract).
[14] Nagahata, H., Nakamura, K., Ino, M., Kuroda, A., and Hashimoto, Y. (2005): The cultivation management to make the occurrence of the milky white kernel and the cracked rice reduce under the high temperature during the ripening period, Bull. Ishikawa Agr. Res. Cent., (26), pp.1-10. (in Japanese with English abstract).
[15] Nagata, K., Kodani, T., Yoshinaga, S., and Fukuda, A. (2005): Effects of water managements during the early grain-filling stage on grain fissuring in rice, Tohoku Journal of Crop Science, (48), pp.33-35. (in Japanese).
[16] Nakamura, K., Hashimoto, Y., and Nagahata, H. (2003): Effect of water management during ripening period on the occurrence of cracked grain and milky-white grain, The Hokuriku Crop Science, (38), pp.18-20. (in Japanese).
[17] Shinmura, M., and Taniguchi, T. (2013): Water temperature change in an irrigation basin including paddy fields, Water, Land and Environmental Engineering, 81(4), pp.293-296. (in Japanese).
[18] Takeshita, Y., and Kohno, I. (1993): A method to predict hydraulic properties for unsaturated soils and its application to observed data, Ground Engineering, Journal of Chugoku Branch, JGS, 11(1), 95-113. (in Japanese).
[19] Tomosho, T., and Yamashita, T. (2009): Problems and future directions of agricultural water management as measures against grain damage under high temperatures during ripening of rice, Tech. Rep. Natl. Inst. Rural. Eng. Japan, (209), pp.131-138. (in Japanese with English abstract).
[20] van Genuchten, M.Th. (1980): A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, pp.892-898.
[21] Wada, Y., Ooekek, F., Kobayashi, T., and Kumeekawa, H. (2013): Effects of cool water irrigation on reduction of grain quality of rice by high air temperatures during the ripening period, Jpn. J. Crop Sci., 82(4), pp.360-368. (in Japanese with English abstract).

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