Evaluation of the Spatial Distribution of Digested Slurry Supplied with Irrigation Water to an Irregularly Shaped Rice Paddy Field

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Abstract

The objectives of this study were to evaluate the spatial distribution of methane fermentation digested slurry (i.e., digested slurry) supplied with irrigation water in an irregularly shaped rice paddy field by considering the effects of the wind, evapotranspiration, and infiltration on the surface water and solute movements, and to suggest a method of supplying spatially-uniform digested slurry. A two-dimensional simulation model is introduced to describe the surface water and solute movements in the rice paddy field. To verify the accuracy of the model, a field observation was conducted. The electrical conductivity (EC) and total nitrogen (TN) values for the surface water were measured while the digested slurry with the irrigation water was supplied to the observational field. The EC and TN values showed that the digested slurry accumulated at the vicinity of the inlet and did not reach the outlet region. The trend in the simulated TN values at the inlet and outlet regions was in good agreement with the measurement data, and the accuracy of this model was confirmed. Using this model, an effective method for uniformly supplying digested slurry to irregularly shaped rice paddy fields was considered. The simulation results indicated that this could be achieved by using an additional inlet and by controlling the inflow flux and the TN in each inlet.

Keywords: Biomass, Biogas Slurry, Liquid manure, Biomass, Recycling society

1 Introduction

Producing renewable energy is currently one of the most important global issues. Anaerobic methane fermentation is a method for producing methane gas from biomass. However, there is a problem with the production of digested slurry, which is a waste material produced during fermentation processes. Since digested slurry contains nitrogen, it is used as a fertilizer for plants such as tomatoes (Miyata and Ikeda, 2006) and grass (Matsunaka et al., 2006). In Japan, it is also beginning to be used in rice paddy fields. Mihama et al. (2011) studied the effect of digested slurry on the growth and yield of rice. Since rice is the major crop in Japan, a large amount of slurry consumption would be expected. In a rice paddy field, the digested slurry is generally supplied with irrigation water from an inlet. However, during this process, the slurry tends to accumulate around the inlet and it is difficult to ensure a uniform supply to all parts of the field. This causes the spatial distribution of the rice growth and yield of the rice paddy field. There have been many studies that attempted to solve this problem. Inomura et al. (2010) clarified the spatial distribution of digested slurry supplied with irrigation water to an area of 5 m² by a rice paddy lysimeter. Yuge et al. (2013) developed a numerical model to evaluate the spatial distribution of digested slurry in a rice paddy field supplied with irrigation water from an inlet. However, the methods used in these studies were for regularly shaped rice paddy fields. Although rice
paddy fields have been widely constructed in flat areas and consolidated as rectangular lots with a standard size of 100 m × 30 m, fields located in mountainous areas of Japan and have irregular shapes. In addition, most of the rice paddy fields in developing countries have not been readjusted and have irregular shapes. As the surface water movement in irregularly shaped rice paddy fields becomes more complicated, it is more difficult to apply the digested slurry uniformly, and much more time is required than in the case of a standard-shaped rice paddy field. Therefore, a method to supply digested slurry with irrigation water should be established by considering various factors that have an effect on the surface water and solute movement. Wind is one such factor that has an effect on water flow (Abo et al., 1992; Yoshioka et al., 2010). In addition, the effects of evapotranspiration and infiltration on the surface water and solute movement should be considered in such fields.

The objectives of this study are to evaluate the spatial distribution of digested slurry that is supplied with irrigation water to irregularly shaped rice paddy fields by considering the effects of the wind, evapotranspiration, and infiltration on the surface water and solute movement, and to determine a method for achieving a uniform supply. A two-dimensional simulation model is introduced to describe surface water and solute movement in the irregularly shaped rice paddy fields. The accuracy of the model was evaluated by comparison with field observations.

2 Methodology

2.1 Governing equations

To simulate the spatial distribution of digested slurry supplied with irrigation water in a rice paddy field, a numerical model based on unsteady two-dimensional flow and solution transport, MIKE21 (DHI, 2012) was introduced and considers the effects of the wind, evapotranspiration, and infiltration on the surface water and solute movement.

Surface water movement in a rice paddy field can be described as follows:

\[
\frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = s
\]  
(1)

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial y} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) + gh \frac{\partial z}{\partial x} + \frac{gpq}{c^2 h^2} - \frac{1}{\rho_s} \left[ \frac{\partial}{\partial x} (h \tau_{sx}) + \frac{\partial}{\partial y} (h \tau_{sy}) \right] 
- f(u)VV_x + \frac{h}{\rho_w} \frac{\partial}{\partial x} (P_x) = 0
\]  
(2)

\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) + gh \frac{\partial z}{\partial y} + \frac{gqp}{c^2 h^2} - \frac{1}{\rho_s} \left[ \frac{\partial}{\partial x} (h \tau_{sx}) + \frac{\partial}{\partial y} (h \tau_{sy}) \right] 
- f(u)VV_y + \frac{h}{\rho_w} \frac{\partial}{\partial y} (P_y) = 0
\]  
(3)
where \( h \) is the water depth (m), \( \zeta \) is the surface elevation (m), \( d \) is the time varying water depth (m), \( p \) and \( q \) are the flux densities in the \( x \) and \( y \) directions (m\(^2\) s\(^{-1}\)), \( s \) is the sink (m s\(^{-1}\)), \( g \) is the gravitational acceleration (m s\(^2\)), \( C \) is the Chezy resistance (m\(^{1/2}\) s\(^{-1}\)), \( \tau_{xx} \) and \( \tau_{yy} \) are the normal stresses in the \( x \) and \( y \) directions (N m\(^{-2}\)), \( \tau_{xy} \) and \( \tau_{yx} \) are the tangential stresses in the \( x \) and \( y \) directions (N m\(^{-2}\)), \( \rho_w \) is the density of water (kg m\(^{-3}\)), \( f(\nu) \) is the wind friction factor, \( V, V_x \) and \( V_y \) are the wind speed and components in the \( x \) and \( y \) directions (m s\(^{-1}\)), and \( P_a \) is atmospheric pressure (kg m\(^{-1}\) s\(^{-2}\)).

The Chezy coefficient can be calculated by using the Manning coefficient \( M \) and water depth as follows:

\[
C = M h^{1/6} \\
h = \begin{cases} 
  p^n_{j+1/2,k} \geq 0 & \Rightarrow h_{j+1/2,k}^n \\
  p^n_{j+1/2,k} \leq 0 & \Rightarrow h_{j+1/2,k}^n 
\end{cases}
\]  

(4)

The wind friction factor can be calculated by using wind speed \( V \) as follows:

\[
f(V) = \begin{cases} 
  f_0 & \text{for } V \leq V_0 \\
  f_0 + \frac{V-V_0}{V_1-V_0}(f_1-f_0) & \text{for } V_0 \leq V \leq V_1 \\
  f_1 & \text{for } V \geq V_1 
\end{cases}
\]  

(5)

where \( f_0 = 0.00063, f_1 = 0.0026, V_0 = 0 \) (m s\(^{-1}\)), and \( V_1 = 30 \) (m s\(^{-1}\)).

The advection and dispersion of the solution of the irrigation water can be described by the following equation:

\[
\frac{\partial}{\partial t} (hc) + \frac{\partial}{\partial x} (uhc) + \frac{\partial}{\partial y} (vhc) = \frac{\partial}{\partial x} \left( hD_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( hD_y \frac{\partial c}{\partial y} \right) - Fhc 
\]  

(6)

where \( c \) is the concentration (mg L\(^{-1}\)), \( u \) and \( v \) are the velocities in the \( x \) and \( y \) directions (m s\(^{-1}\)), \( D_x \) and \( D_y \) are the dispersion coefficients in the \( x \) and \( y \) directions (m\(^2\) s\(^{-1}\)), and \( F \) is the linear decay coefficient (s\(^{-1}\)).

In this study, the transport of nitrogen, which is one of the most important fertilizer components of digested slurry, was simulated using Eq. (6).

2.2 Boundary conditions and model structure

To solve Eqs. (1), (2), (3), and (6), the finite differential method was adopted in MIKE 21. Figure 1 shows schematic views of the numerical model introduced in this study. The surface of the rice paddy field is divided into cells. The block cells represent the rice paddies. These cells prevent the movement of the surface water and digested slurry. The computational domain is represented by white cells, which are surrounded by a levee that is shown by gray cells. For the levee, the water movement and solution transfer are neglected. The flux and TN of the digested slurry supplied with the irrigation water are given at the inlet shown in Fig. 1. Evapotranspiration and infiltration are considered as the sink (\( s \)) in Eq. (1).
Evaluation of the spatial distribution

3 Field observations

To verify the accuracy of the model and to obtain the input data for the simulation, a field observation was conducted in a rice paddy field (area of 5,000 m²) located in Oita Prefecture (33.12°N, 130.56°E), southwestern Japan. Figure 2 shows a schematic view of the observational field. In this field, direct seeding was adopted instead of the process of transplanting of the rice paddies, and the rice paddies became spatially random. The intervals between the rice paddies were measured in various sections and the average $H$ and $B$ shown in Fig. 1 were 100 mm and 300 mm, respectively. There were trenches created by agricultural machines on the soil surface of the field. The average trench depth was 3 mm. Below the plow layer, a gravel layer existed. The digested slurry was supplied with the irrigation water from inlet A shown in Fig. 2 for 200 minutes, and inlet B and the outlet were closed. The inflow rate of the irrigation water and digested slurry was measured. Water level gauges (UIZ-WLR060, Uizin) were placed at point No. 1 to measure the depth of the surface water automatically. The evapotranspiration and infiltration were calculated from the data of the surface water levels. Multi-parameter water quality meters (WQC-24, DKK-TOA) were placed at points No. 1 and No. 2 to automatically measure the EC. Water sampling was conducted at the points No. 1 and No. 2 to measure the TN for 240 minutes after the digested slurry with the irrigation water began to be supplied. The TN for each sample was measured in the laboratory. The wind speed and direction were obtained from the Hita meteorological station (33.19°N, 130.56°E). The wind components in the x and y directions in Eqs. (2) and (3) were determined based on the wind direction measured at this station.
4 Results and discussion

Figure 3 shows the temporal changes of the TN and EC of the surface water in the observational field measured at No. 1 and No. 2 (Fig. 1). The supply of digested slurry was stopped after 200 min. As shown in Fig. 3(b), the TN and EC at point No. 2 were measured after 100 min, since this was when the digested slurry in the irrigation water reached this point. The TN and EC values measured at point No. 1 increased abruptly after 200 min, which is considered to be caused by an increase in the flux of the irrigation water and digested slurry at approximately 180 min. At point No. 2, the TN and EC values remained low and almost constant. These results indicate that the fertilizer component of the digested slurry was distributed in the vicinity of the inlet and did not reach the outlet regions for the entire measurement period. The amount of evapotranspiration and infiltration calculated based on the water depth data, which was measured by using water level gauges, was 55.7 mm day$^{-1}$. In the observational field, there was gravel under the plow layer and the infiltration was relatively high compared to that for rice paddy fields with hard plow sole.

To evaluate the spatial distribution of the nitrogen component of the digested slurry, the TN of the surface water was simulated using the numerical model shown in Fig. 2. As the boundary condition, the inlet flux representing the flow rates of irrigation water and digested slurry was assigned the value shown in Table 1. As the inlet flux changed with time, the boundary condition was set by considering the time variation of the inlet flux. The evapotranspiration, infiltration, and TN were set based on the measurement data shown in Table 1. The TN in the irrigation water was calculated using the total amount of supplied digested slurry to the entire field. The initial surface water depth was set to 0 cm for the entire field. In the vicinity of the inlets, the surface water depth was set to 5 cm, because there is the puddle around inlets at the beginning of the observation. Wind speeds
and directions from the Hita meteorological station were used to evaluate the surface water flow. The parameters for Eqs. (1)–(4) and (6), which include the eddy viscosity coefficient, Manning number, dispersion coefficients, and linear decay coefficient, are shown in Table 1 (Inomura et al., 2010; Yuge et al., 2013). Figure 4 shows a comparison of the simulated and measured TN values. The trend of the TN values simulated in the inlet and outlet regions agree well with the measurement data.

**Table 1** Parameters for the simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Time step</td>
<td>s</td>
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</tr>
<tr>
<td>Initial water depth</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>Inlet flux</td>
<td>m³ s⁻¹</td>
<td>2.2 × 10⁻³ ~ 8.6 × 10⁻³</td>
</tr>
<tr>
<td>Evapotranspiration and infiltration</td>
<td>mm day⁻¹</td>
<td>55.7</td>
</tr>
<tr>
<td>Eddy viscosity coefficient</td>
<td>m² s⁻¹</td>
<td>1.0 × 10⁻²</td>
</tr>
<tr>
<td>Manning number</td>
<td>m¹/³ s⁻¹</td>
<td>10 ~ 15</td>
</tr>
<tr>
<td>Initial TN of surface water</td>
<td>mg L⁻¹</td>
<td>0</td>
</tr>
<tr>
<td>TN in irrigation water</td>
<td>mg L⁻¹</td>
<td>50 ~ 300</td>
</tr>
<tr>
<td>Linear decay coefficient</td>
<td>s⁻¹</td>
<td>3.5 × 10⁻⁵ ~ 8.0 × 10⁻⁵</td>
</tr>
<tr>
<td>Dispersion coefficients in the x direction</td>
<td>m² s⁻¹</td>
<td>1.0 × 10⁻²</td>
</tr>
<tr>
<td>Dispersion coefficients in the y direction</td>
<td>m² s⁻¹</td>
<td>1.0 × 10⁻²</td>
</tr>
</tbody>
</table>

**Fig. 3** Temporal changes of TN and EC of the surface water
Yuge et al. (2013) clarified that drainage of the surface water and trenches at the soil surface was effective for spatially uniform application of digested slurry with the irrigation water in rice paddy fields. The surface water was drained before supplying the digested slurry in the observational field. However, it is difficult to organize the trenches in an irregularly shaped field. In this study, the effect of controlling the inlet inflow rate and the TN value at the inlet on the spatial uniformity was evaluated. To achieve a uniform supply of digested slurry, a scenario in which it was supplied from both inlets A and B in Fig. 2 was simulated. The flux at inlet A changed with time during the observation as shown in Table 1. In this scenario, constant fluxes were set at each inlet. The fluxes of inlets A and B were $6.0 \times 10^{-3}$ and $4.0 \times 10^{-3}$ m$^3$ s$^{-1}$, respectively. The average inlet flux estimated from the observational data was applied to inlet A. The flux at inlet B was smaller than that at inlet A, since inlet B was located downstream. The TN value for the digested slurry from inlets A and B was 87 mg L$^{-1}$ and 129 mg L$^{-1}$, respectively. Since the amount of nitrogen supplied to the observational field was estimated to be 20 kg, the TN values for each inlet were determined in order to supply similar amounts of nitrogen as those observed. As shown in Fig. 4, a problem exists in which the fertilizer component does not reach the outlet regions of the rice paddy field. To solve this problem, the concentration of the digested slurry downstream from inlet B was set higher than the concentration upstream of inlet A. The TN values for each inlet were determined so as to supply similar amounts of nitrogen from both inlets. The other parameters were set as shown in Table 1. Figure 5 shows the spatial TN distributions simulated using this scenario. The isoconcentration line between 60 and 90 mg L$^{-1}$ reached the outlet from the
inlets approximately 120 minutes after the application was conducted. After 180 minutes, the TN value became over 60 mg L\(^{-1}\) for the entire field. This result indicates that the digested slurry was applied uniformly by adding another inlet and controlling the flux and concentration of digested slurry in both inlets.

**Fig. 5** Spatial TN distribution when an additional inlet was used and the inflow flux and TN in each inlet were controlled

### 6 Conclusions

To evaluate the spatial distribution of digested slurry supplied with irrigation water in irregularly shaped rice paddy fields while considering the effects of the wind, evapotranspiration, and infiltration on the surface water and solute movements, a numerical model describing the unsteady two-dimensional flow and
solution transport of the irrigation water was introduced. Since the movement of surface water and solute in irregularly shaped rice paddy fields is complicated, the wind, evapotranspiration, and infiltration effects on the surface water and solute movement are taken into consideration in this model. A field observation was conducted in a rice paddy field to obtain input data for the numerical model and to verify the accuracy of the model. The EC and TN values for the surface water were measured while the digested slurry with the irrigation water was supplied to the observational field. The EC and TN values showed that the digested slurry accumulated in the vicinity of the inlet and did not reach the outlet region. This could cause the spatial distribution of the rice yield and growth in a rice paddy field.

The simulated trends in the TN values in the vicinity of the inlet and outlet were in good agreement with the measurement data. This result verifies the accuracy of the numerical model. Using this model, an effective method for uniformly supplying digested slurry to irregularly shaped rice paddy fields was considered. The simulation results indicated that using an additional inlet and controlling the inflow flux and TN in both inlets were effective for achieving spatially uniform application of digested slurry.

Using the simulation model established in this study, the spatial distribution of the digested slurry supplied with the irrigation water in the rice paddy field can be clarified with high accuracy, because the effects of various factors including the evapotranspiration, infiltration, and wind on the surface water and solute movement were considered. This approach is effective for determining a method of supplying a uniform distribution of digested slurry to an irregularly shaped paddy field, thus promoting a biomass-oriented society.

References


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