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Evaluation of a grass field for reduction of sediment runoff from agricultural areas

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ABSTRACT

This study evaluates a centipede grass field for reduction of reddish fine sediment runoff from agricultural areas in Okinawa, Japan. Grass fields are expected to provide an additional countermeasure for the reduction of sediment runoff. However, the practical effectiveness of grass fields has not been examined under sediment runoff conditions in Okinawa. A numerical model simulating sediment transport in grass was used to analyze the effect of a centipede grass field on sediment runoff. The model was verified using data obtained from flume experiments. The analysis showed that the efficiency of sediment removal decreased with an increase in the inflow rate into the field. However, a grass field with a higher inflow rate removed more sediment and had a greater water treatment capacity under unsubmerged flow conditions. Therefore, the analysis showed that centipede grass fields with inflow control at a higher inflow rate under unsubmerged flow conditions are more effective as an additional countermeasure against reddish fine sediment runoff from agricultural areas.

Keywords: Grass field; Numerical model; Sediment removal efficiency

1. Introduction

Reddish fine sediment runoff from agricultural areas results in coastal environmental problems in Okinawa, Japan. The sediment delivered to the coastal areas causes water pollution, sedimentation, and degrades the coastal ecosystems and fishery resources. Agricultural fields are one important source of sediment runoff in Okinawa [1, 2]. Nakasone et al. [3] reported that sediment from agricultural fields accounted for 70% of the total sediment runoff. Sediment ponds are constructed at the downstream sites of agricultural areas to reduce sediment runoff after rainfall from these areas. The sediment ponds catch drainage stream water, settle out the sediment suspended in the water and discharge clean water downstream. However, these ponds are insufficient for trapping fine suspended sediment because of a slow settling velocity of the sediment. Nakandakari et al. [4] reported that 21–47% of the reddish fine sediment flowing into a sediment tank in Okinawa passed through the tank. Therefore, additional countermeasures to reduce fine sediment runoff are required.

Grass strips, a zone of vegetation through which sediment and pollutant-laden flow are directed before being discharged to a concentrated flow channel, are one sediment control measure [5, 6]. Several studies have reported the effectiveness of a grass buffer for sediment runoff reduction [7, 8]. A few studies have shown effectiveness of 0.5–3.0 m length grass strips located at the down-slope end in the direction of flow of an agricultural

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field for reducing runoff of reddish fine sediment from agricultural fields into streams in Okinawa [9, 10]. Therefore, grass fields that have a long slope are expected to provide an additional countermeasure for reduction of the fine sediment runoff from sediment ponds (Fig. 1). The grass fields receive overflow water from the ponds through drainage channels, trap fine sediment from the water and discharge the filtered water into the channels. The grass fields can be established in abandoned agricultural fields downstream of the sediment ponds. However, the practical effectiveness of the field has not been examined under sediment runoff conditions in Okinawa. Therefore, the objective of this study was to evaluate a grass field as an additional countermeasure against reddish fine sediment runoff from agricultural areas by a numerical model analysis.

2. Methods

A numerical model simulating sediment transport in grass was employed to analyze sediment reduction of a grass field. The model was verified by data obtained from flume experiments.

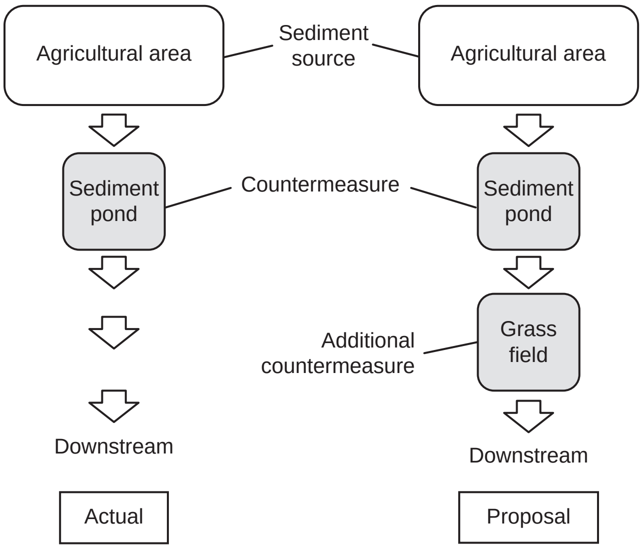

Fig. 1. Schematic of sediment control measures in Okinawa.

2.1. Flume experiments

The flume experiments were conducted to simulate fine sediment transport in a grass field. Centipede grass (*Eremochloa ophiuroides* (Munro) Hack.), a perennial turf grass, was used in the experiments. Shiono *et al*. [10] showed a strip of centipede grass was effective for reduction of reddish sediment loads under typical farmland conditions in Okinawa, Japan. Dead grass was substituted for living grass in this experiment because the shape and the stiffness of the dead grass was almost the same as the living grass and multiple flume experiments could be conducted under the same grass conditions. Grass was collected from a field in the National Agricultural Research Center for Kyushu Okinawa Region in Kumamoto, Japan. The grass was fully developed to a height of 10 cm and cover ratio of 100%. The aerial part of the grass was glued on plastic plates. The plates were installed throughout a flume that was 12.0 m long, 0.145 m wide and had a 2.0% slope.

A clean water experiment was carried out with a constant flow of clean water supplied from a constant head tank to the upstream end of the flume. Water levels of the flow along the length of the flume were measured at 0.2 or 0.5 m intervals with a point gauge (KENEK Inc., PH-340) after the state of the flow was stabilized. The flow rate was measured with an HS flume [11] at the flume exit. We performed 5 runs, A-1 to A-5, with different unit flow rates (Table 1).

A sediment-laden water experiment was carried out with constant flows of clean water and reddish sediment-water mixture supplied to the upstream end of the flume. The clean water was supplied from a constant head tank. The mixture was added uniformly in the cross-sectional direction of the flume. The mixture was stored in 120 l buckets, mixed with mixers during the experimental run and introduced from the buckets into the flume with a metering pump (Masterflex Inc., 7523–60). The duration of the experiment was 60 min.

Table 1
Summary of experimental conditions and results of clean water experiments.

Run	Unit flow rate ($m^2 \cdot s^{-1}$)	Uniform flow depth (m)	Cross-sectional mean velocity ($m \cdot s^{-1}$)	Vegetation permeability coefficient K_s ($m \cdot s^{-1}$)
A-1	1.27×10^{-3}	3.31×10^{-2}	3.83×10^{-2}	3.21×10^{-1}
A-2	2.91×10^{-3}	6.75×10^{-2}	4.31×10^{-2}	3.61×10^{-1}
A-3	4.30×10^{-3}	8.13×10^{-2}	5.28×10^{-2}	4.43×10^{-1}
A-4	5.79×10^{-3}	9.17×10^{-2}	6.23×10^{-2}	5.29×10^{-1}
A-5	7.72×10^{-3}	9.79×10^{-2}	7.89×10^{-2}	6.60×10^{-1}

Inflow and outflow of the sediment-laden water were collected at 10 min intervals with 200 ml bottles to obtain sediment concentrations and an equivalent sediment particle size distribution. We performed 6 runs, B-1 to B-6. The flow rates and sediment concentrations of the inlet flows for these runs are shown in Table 2.

Sediment used in the experiment was prepared by passing a red soil through a 0.5 mm sieve. The soil was collected from the Arashiyama field site in Nago on the northern part of the Okinawa main island (26°38′N, 127°59.5′E). The specific gravity of the soil was 2.74. The mean soil particle diameter, d_{50}, was 1.58×10^{-2} mm. Mean fractions of four equivalent particle size classes of the sediment supplied to the flume were 8% for 0–0.002 mm, 38% for 0.002–0.02 mm, 52% for 0.02–0.2 mm, 3% for 0.2–0.5 mm. The sediment contained a high percentage of silt and fine sand.

2.2. Model verification and analysis

A numerical model simulating surface flow and sediment transport in a centipede grass was employed in this study. The model was based on the energy equation for steady non-uniform flow given in Equation (1) and the continuity equation for sediment given in Equation (2). The model showed good validity for calculation of sediment concentration in the surface flow through the centipede grass strips of 0.5–3.0 m length in the direction of flow [12]. A similar model was proposed and tested with flume experimental data for a vetiver grass strip [13].

$$\frac{dz}{dx} + \frac{dh}{dx} + \frac{d}{dx}\left(\frac{u^2}{2g}\right) + \frac{n^2 u^2}{h^{4/3}} + \frac{1}{K_s^{\,2}} u^2 = 0 \qquad (1)$$

$$\frac{\partial z}{\partial t} + \frac{1}{1-\lambda}\left\{\frac{\partial \sum (q_{bi})}{\partial x} + \sum \left(q_{sui} - w_{0i} C_i\right)\right\} = 0 \qquad (2)$$

where z is bed level, x is distance from the lower end of the grass field, h is flow depth, u is flow velocity, g is gravity acceleration, n is Manning's roughness coefficient, K_s is the vegetation permeability coefficient, λ is porosity of deposited sediment, q_{bi} is bed load transport rate per unit width of sediment in an ith size class, q_{sui} is pick-up rate of suspended load per unit area of sediment in an ith size class, w_{oi} is settling velocity of sediment in an ith size class, C_i is sediment load concentration in an ith size class. q_{bi} is calculated by the Meyer-Peter Müller formula. q_{sui} is assumed to be zero based on our preliminary experiment for unsubmerged water flow in a centipede grass.

Numerical calculations with the model determined water level, sediment concentration of flow and sedimentation depth for each position and time. Equation (1) was solved using Newton's method. Downstream boundary conditions were the known flow discharge and the critical depth. Equation (2) was solved using the finite difference method. Upstream boundary conditions were the known sediment concentrations and the fractions of the four classes with equivalent sediment particle size. The four size classes were 0–0.002, 0.002–0.02, 0.02–0.2 and 0.2–2 mm. The sediments classified as the finer two classes were treated as suspended load and the others as bed load in the calculation.

The model was verified by data obtained from the flume experiments. We compared model outputs with measurements for the sediment concentrations of the outflow in each equivalent sediment particle size class.

Model simulations were conducted to evaluate the centipede grass field as an additional countermeasure against reddish fine sediment runoff from agricultural areas in Okinawa. Table 3 shows the values of factors used for the simulation. The values are representative values under typical conditions in agricultural areas of Okinawa. Sixty minutes of inflow of sediment-laden water into the field was set in the simulation. We calculated the sediment concentration of outflow from the

Table 2
Summary of experimental conditions and results of sediment-laden water experiments.

Run	Unit flow rate ($m^2 \cdot s^{-1}$)	Sediment concentration* ($m^3 \cdot m^{-3}$)		Sediment removal efficiency (%)
		Inlet flow	Outlet flow	
B-1	1.33×10^{-3}	5.54×10^{-4}	7.20×10^{-5}	87.0
B-2	1.33×10^{-3}	1.29×10^{-3}	1.69×10^{-4}	86.8
B-3	2.86×10^{-3}	8.67×10^{-4}	1.15×10^{-4}	86.8
B-4	2.86×10^{-3}	2.08×10^{-3}	4.28×10^{-4}	79.4
B-5	5.27×10^{-3}	9.15×10^{-4}	2.07×10^{-4}	77.4
B-6	5.27×10^{-3}	2.19×10^{-3}	8.23×10^{-4}	62.5

*time-averaged value

Table 3
Values of factors for numerical stimulations.

Factor	Value
Length of the grass in the direction of flow (m)	10–50
Unit inflow rate ($m^2 \cdot s^{-1}$)	$1.0 \times 10^{-4} - 1.0 \times 10^{-2}$
Slope gradient (%)	1, 3, 5
Sediment concentration ($m^3 \cdot m^{-3}$)	3.7×10^{-4}, 1.8×10^{-3}, 3.7×10^{-3} (= 1,000, 5,000, 10,000 ppm)
Equivalent sediment particle size ratio (%)*	
0–0.002 mm	12
0.002–0.02 mm	88
0.02–0.2 mm	0
0.2–2 mm	0

*Observed values for suspended sediment classes (Shiono *et al.*, 2007)

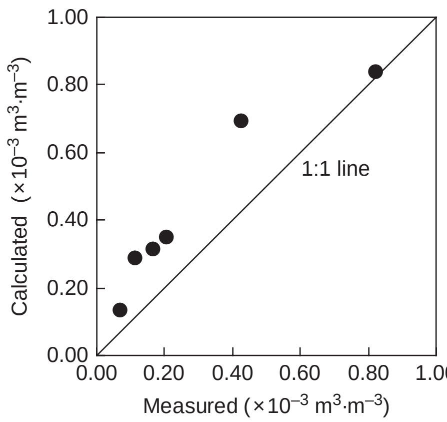

Fig. 2. Relationship between the measured and calculated values for the time-averaged total sediment concentrations of outflow.

field in each equivalent sediment particle size class at each time. Then, sediment removal efficiencies were obtained based on the simulation results.

A sensitivity analysis was performed to gain insight into the dependence of the model outputs on the model parameters. In this analysis, we focused on four factors; sediment concentration of inflow, slope gradient, unit inflow rate and slope length of the field. Parameters of the base case for the analysis were 1.8×10^{-3} $m^3 \cdot m^{-3}$ (= 5000 ppm) of sediment inflow, 3% slope gradient, 1.0×10^{-3} $m^2 \cdot s^{-1}$ unit inflow rate and 40 m slope length. The values shown in Table 3 were given by this analysis. Moreover, the relationship between the efficiency and the major factors were determined.

3. Results and discussion

3.1. Experimental results

Table 1 shows parameters for water flow in the grass obtained from the clean water experiment. The uniform flow depth was 9.79×10^{-2} m at a 7.72×10^{-3} $m^2 \cdot s^{-1}$ unit flow rate. Moreover, our simulation results showed that the uniform flow depth in the grass was from 9.37×10^{-2} to 1.12×10^{-1} m at a 1.0×10^{-2} $m^2 \cdot s^{-1}$ unit flow rate under a 1–5% slope gradient. These depths were approximately equal to the height of the centipede grass used in the experiments. This suggests the maximum unit flow rate is roughly 1.0×10^{-2} $m^2 \cdot s^{-1}$ to maintain unsubmerged flow conditions in the centipede grass field.

Sediment removal efficiency varied with unit flow rate and equivalent sediment size class in the sediment-laden water experiment. The efficiencies were 87.0 and 86.8% at a 1.33×10^{-3} $m^2 \cdot s^{-1}$ unit flow rate and 77.4 and 62.5% at a 5.27×10^{-3} $m^2 \cdot s^{-1}$ unit flow rate (Table 2). The efficiencies decreased with an increase in the unit flow rate. Additionally, the efficiencies for the size classes of 0–0.002 mm, 0.002–0.02 mm, 0.02–0.2 mm and 0.2–0.5 mm were 19–69%, 31–72%, 90–100% and 100%, respectively. The grass trapped a part of the sediment smaller than 0.02 mm in diameter and most of the sediment larger than 0.02 mm in diameter.

3.2. Validity of model

Figure 2 shows the relationship between the measured and calculated values for the time-averaged total sediment concentrations of outflow in the sediment-laden water experiment. The calculated results were generally in good agreement with the measured, though some over calculations were observed. Magnitude of relative error, *MRE*, ranged from 2 to 151% and mean magnitude of relative error, *MMRE*, was 75%. The *MRE* and *MMRE* are given in Equations (3) and (4).

$$MRE = \left| \frac{V_m - V_c}{V_m} \right| \tag{3}$$

$$MMRE = \frac{1}{k} \sum_{i=1}^{k} MRE_i \tag{4}$$

where V_m is measured value, V_c is calculated value, k is number of measurements, and MRE_i is *MRE* for the *i*th measurement.

Moreover, the calculated results were generally in good agreement with the measured for sediment size classes smaller than 0.02 mm, though some over calculations were observed. The *MMRE* value was 142% for the 0–0.002 mm size and 66% for the 0.002–0.02 mm size sediment. All calculated results for the time-averaged sediment concentrations of outflow for both classes larger than 0.02 mm were zero, which closely agreed with the measurements. Therefore, the model described here is valid for determining sediment concentrations from outflow in the flume experiments. The validation results indicate the model is useful to evaluate grass fields for reduction of sediment runoff.

3.3. Important parameters

The sensitivity analysis determined the relative importance of parameters for evaluation of grass fields. Figure 3 shows the results of the sensitivity analysis on sediment removal efficiency of the strip. The removal efficiency was 86.4% for the base case. The efficiency varied from 28.0 to 91.2% for unit inflow rate and from 54.1 to 87.7% for slope length of the grass field. In contrast, the efficiencies stayed constant with sediment concentrations and slope gradients. The unit inflow rate and the slope length had a large effect on sediment removal whereas the slope gradient and the sediment concentration of inflow into the grass field had little effect on sediment removal. Therefore, the analysis showed that the slope length of grass fields and the unit inflow into the field greatly affect the efficiency of sediment removal.

3.4. Evaluation of grass field

Figure 4 shows the relationship between the sediment removal efficiency of the grass field and the slope length of the field under each unit inflow rate. The values in the figure were obtained by the simulations with a sediment concentration of inflow of 1.8×10^{-3} m^3·m^{-3} (= 5000 ppm) and slope gradient of 3%. The efficiencies for 1.0×10^{-3} and 1.0×10^{-2} m^2·s^{-1} unit inflow rates when the slope length of the field was 50 m were 88 and 33%, respectively. Similar results were shown by Deletic and Fletcher [14]. Their experiments showed that a grass swale 65 m long with a slope of 1.6% removed 57–88% of suspended solids with a $d_{50} = 9.4 \times 10^{-3}$ mm including water flows under 1.4×10^{-3} to 6.3×10^{-3} m^2·s^{-1} unit inflow rates. Their results support the adequacy of our simulated results.

The sediment removal efficiencies increased with an increase in the slope length of the grass field and increments of the efficiencies varied according to the unit inflow rate. The efficiency for 1.0×10^{-4} m^2·s^{-1} unit inflow rate increased sharply and converged to approximately 90% at a 6 m slope length. Meanwhile, the efficiency for a 1.0×10^{-2} m^2·s^{-1} unit inflow rate increased gradually and continued to increase.

The sediment removal efficiencies decreased with an increase in the unit flow rate. The efficiencies for 1.0×10^{-4}, 1.0×10^{-3} and 1.0×10^{-2} m^2·s^{-1} unit inflow rates were 91%, 86% and 28%, respectively (Fig. 4), when the slope length of the field was 40 m, a typical slope length of agricultural fields in Okinawa. These results indicate a lower unit inflow rate into the grass field achieves higher removal efficiency.

However, inflow control for the higher efficiency results in less total sediment removal by the grass field. Figure 5 shows the relationship between sediment removal per unit time and unit inflow rate into the grass field with a 40 m slope length. The sediment removal per unit time increases with an increase in unit inflow rate. Similar results were found under 10–50 m slope lengths. Therefore, the grass field with a larger unit inflow rate removes more sediment than a smaller unit inflow rate.

Moreover, inflow control for the higher efficiency results in less water treatment capacity of the grass field, suggesting a smaller catchment area. Figure 6

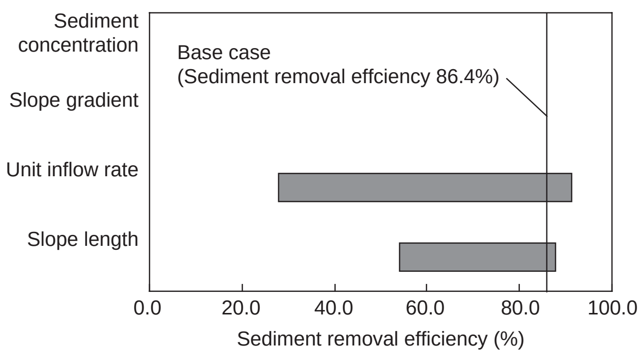

Fig. 3. Result of sensitivity analysis on sediment removal efficiency of grass field.

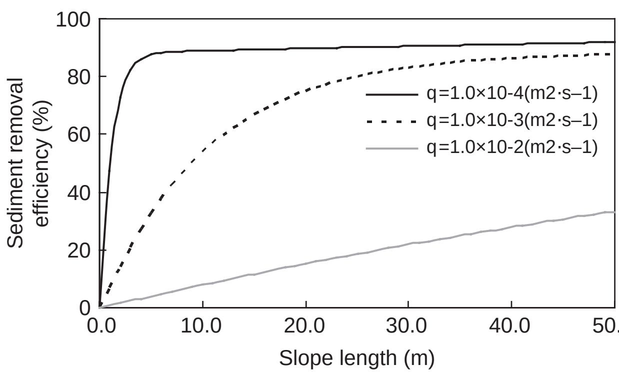

Fig. 4. Relationship between sediment removal efficiency and slope length of grass field. q is unit inflow rate.

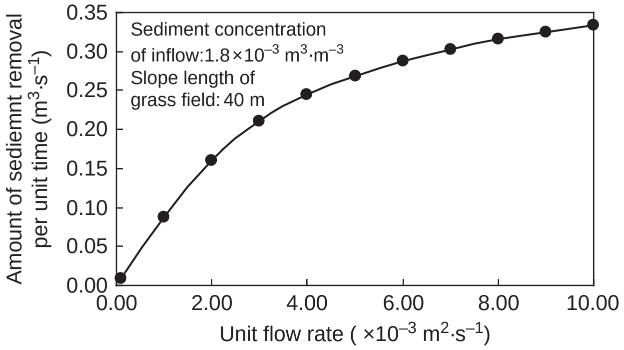

Fig. 5. Relationship between amount of sediment removal per unit time and unit inflow rate.

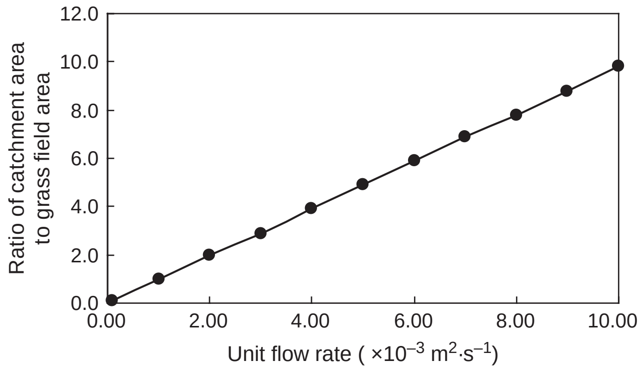

Fig. 6. Relationship between ratio of catchment area to grass field area and unit inflow rate. The ratios were obtained based on a design flood discharge of 0.255 m3·s^{-1}·ha^{-1}.

shows the relationship between ratio of the catchment area to the grass field area and unit inflow rate. The ratios were obtained based on the design flood discharge, 0.255 $m^3·s^{-1}·ha^{-1}$, shown in a guideline for reddish sediment control set by the Okinawa Prefectural Government. The ratio increases linearly with an increase in unit inflow rate. The ratio of the catchment area to the grass field area for a 1.0×10^{-3} $m^2·s^{-1}$ unit inflow rate was 1.0. This shows that a grass field is the same size in area as a field assigned to the sediment source if the design flood discharge is actually used. Therefore, inflow control for a 1.0×10^{-3} $m^2·s^{-1}$ unit inflow rate would be unrealistic in terms of water treatment capacity. In contrast, the ratio of the catchment area to the grass field area for a 1.0×10^{-2} $m^2·s^{-1}$ unit inflow rate was 9.8. This value appears to be feasible even if the design flood discharge actually occurs. When the area of the grass field is 0.2 ha with a 40 m slope length and 50 m width, the catchment area is 1.96 ha. This design appears suitable for this unit inflow rate because the actual catchment areas of sediment ponds in Onna, Okinawa range from 0.87 to 32.2 ha.

In conclusion, the results showed that centipede grass fields with an inflow control for a higher unit inflow rate under unsubmerged flow conditions remove more sediment and have a larger water treatment capacity. Therefore, inflow designs that take into account the total amount of sediment removal and catchment area are more effective as an additional countermeasure against reddish fine sediment runoff from agricultural areas.

4. Conclusions

A numerical model simulating sediment transport in vegetation is valid to evaluate centipede grass fields for reduction of reddish fine sediment runoff. The sensitivity analysis of the model indicated that the unit inflow rate into the grass field and slope length have a great effect on the sediment removal efficiency. The model analysis showed that lower inflow into the grass field promotes higher sediment removal efficiency. However, the grass fields with a higher unit inflow rate removed more sediment and had a greater water treatment capacity under unsubmerged flow conditions. In conclusion, the analysis shows that centipede grass fields with inflow controlled for a higher unit inflow rate under unsubmerged flow conditions is more effective as an additional countermeasure against reddish fine sediment runoff from agricultural areas. Further research is required to assess the applicability of grass fields to actual sites under natural conditions.

Nomenclature

z	bed level
x	distance from the lower end of the grass field
h	flow depth
u	flow velocity
g	gravity acceleration
n	Manning's roughness coefficient
K_s	vegetation permeability coefficient
λ	porosity of deposited sediment
q_{bi}	bed load transport rate per unit width of sediment in an *i*th size class
q_{sui}	pick-up rate of suspended load per unit area of sediment in an *i*th size class
w_{oi}	settling velocity of sediment in an *i*th size class
C_i	sediment load concentration in an *i*th size class
MRE	magnitude of relative error
$MMRE$	mean magnitude of relative error
V_m	measured value
V_c	calculated value
k	number of measurements

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