MIXING STRUCTURE AND FLOW EVOLUTION RESULTING FROM VARIATION IN THE DENSITY OF RIPARIAN VEGETATION ALONG THE BANKS OF A MAIN CHANNEL IN A COMPOUND CHANNEL

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Abstract: This research elucidated the process of change in mixing mechanisms associated with change in vegetation density, as well as the process of change directly upstream and downstream from the vegetation, and considered flow field transition distance. It was found that immediately downstream from the vegetation, the abrupt inflow of the floodchannel flow into the main channel resulted in extensive horizontal mixing that exceeded the mixing between flows inside and outside of the vegetation. Another important characteristic was that the vigorous mixing immediately downstream from the vegetation is diffused by large-scale horizontal eddies. As with cases of density that is greater downstream, the process of mixing development is one in which the development of large-scale eddies changes the main channel layer's velocity distribution, resulting in vertical mixing.

Keywords: Riparian vegetation, compound channel, Reynolds stress, large horizontal eddy, transition distance

1. INTRODUCTION

The vegetation that often grows along the banks of the main channel of a compound watercourse presents the issue of flood-flow resistance that lowers the river's transport capacity during flooding. Flood control and environmental management therefore necessitate a full understanding of the flow properties of compound waterways where riparian vegetation grows.[1]

For compound watercourses having riparian vegetation, Fukuoka and Fujita, et al., [2] have developed a quasi-two-dimensional analysis method that utilizes a boundary mixing coefficient and that has been used in actual flood control planning in Japan. Nadaoka and Yagi, [3] as well as Fukuoka and Watanabe et al., [4] have published researches on horizontal two-dimensional analysis; Fukuoka et al. have reproduced the large-scale horizontal eddies and horizontal flow field resulting from vegetation in actual flooding in the Tone River.

Although vegetation normally varies longitudinally in density and growth pattern, resulting in a three-dimensional flow structure, the evolution of three-dimensional flow fields accompanying vegetation has not been studied adequately. This research investigates, for cases of abrupt changes in vegetation density in the downstream direction, the three-dimensional structure of the flow field, its process of change, and the downstream distance required for the mean flow to develop.

2. EXPERIMENTAL PROCEDURES AND CONDITIONS

The cross-section and planform of the experimental waterway are shown in Figures 1 and 2, respectively. This single-sided compound straight waterway was 28 m long and 0.8 m wide, with a main channel width of 0.5 m, a floodchannel width of 0.3 m, and a floodchannel height of 0.057 m. The simulated vegetation was 0.035 m wide and was placed in a continuous strip along the main channel's bank.
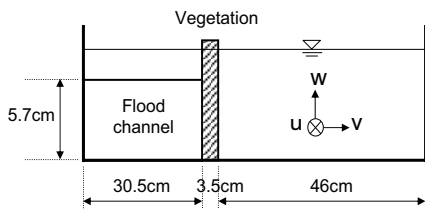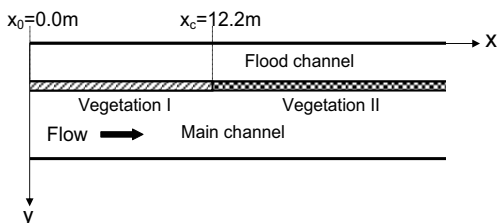

Fig.1 Cross-section of the experimental channel   Fig.2 Plan view of the experimental channel

Table 1 Experimental condition

Case	Vegetation I	Vegetation II	Discharge	Bed slope
Exp. D	dense			
Exp. N	no vegetation			
Exp. ND	no vegetation	dense		
Exp. SD	sparse	dense	23 (ℓ/s)	1/550
Exp. DS	dense	sparse		
Exp. DN1	dense	no vegetation		
Exp. DN2	dense	no vegetation	28 (ℓ/s)	
Exp. DN3	dense	no vegetation	30 (ℓ/s)	

D: Dense, S: Sparse, N: Nothing

To determine the effect of longitudinal changes in vegetation density, each experimental case (see Table 1) tested a different combination of vegetation conditions in the upstream and downstream sections of our experimental channel—dense (D) simulated vegetation, sparse (S) vegetation, or no (N) vegetation. The transition from one vegetation condition to another

occurred at the section where x_c = 12.2 m. Velocity through the vegetation can be expressed with the permeability coefficient K, which is defined as $\upsilon = KI_e^{1/2}$, where υ is velocity inside the vegetation and I_e is the energy gradient. K is 1.74 m/s for the sparse vegetation and 0.45 m/s for the dense vegetation.

Under uniform flow conditions, a depth of 6.5–9.9 cm was maintained throughout the entire watercourse so as not to completely submerge the simulated vegetation.

A Laser Doppler Velocimeter (LDV) with a 100-Hz sampling frequency and an I-type electromagnetic velocimeter with a 20-Hz sampling frequency were used to measure velocity.

3. RESULTS OF EXPERIMENT
3.1. Evolution of the Three-Dimensional Structures of Mean Flow and Turbulence Downstream from Abrupt Change in Vegetation
### 3.1.1. Longitudinal Change in Flow Structure in Experiment ND

Figures 3 (a), (b), and (c) respectively show mean velocity distribution ($\bar{u}$) and Reynolds stress distributions ($-\overline{u'v'}$, $-\overline{u'w'}$). Because flow field properties in a compound flow differ above and below the floodchannel bottom, the authors divided the channel into upper and lower layers and calculated the vertical mean for each. Because of flow field changes, the velocity distribution changes from one characterized by an inflection point roughly at the main channel–floodchannel boundary to one characterized by velocity reduction caused by the vegetation. At the section 1.4 m from the transition point, velocity had slowed primarily in the upper layer of the main channel, but by the point 2.2 m downstream, both the upper–lower layer differential and the longitudinal variation in velocity had diminished, indicating a nearly stable flow. Reynolds stress distribution ($-\overline{u'v'}$) is such that in sections upstream from the vegetation, a stress value was registered only in the upper layer. This is because of the mixing between the main channel and floodchannel flows in the upper layer. At points farther downstream, Reynolds stress ($-\overline{u'v'}$) in the neighborhood of vegetation increases in both the upper and lower layers, then changes to a negative value in the floodchannel. This is interpreted as follows: The flow around the vegetation is significantly slowed in the upper and lower layers by the strong resistance arising from the vegetation, so that mixing around the vegetation occurs uniformly in the vertical direction. Furthermore, mixing in the upper layer comprises not just mixing between flows inside and outside of the vegetation but also mixing between the main channel and floodchannel flows through the vegetation, which is why the value of $-\overline{u'v'}$ is larger than that for the lower layer.
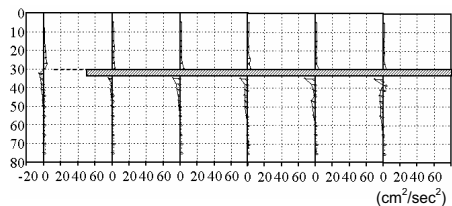
The value of $-\overline{u'w'}$ around the vegetation is small at the transition point but increases at points farther and farther downstream. This is due to the vertical difference in velocity that arises
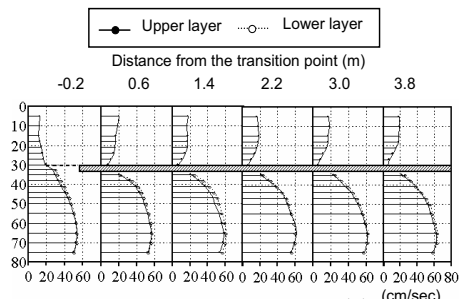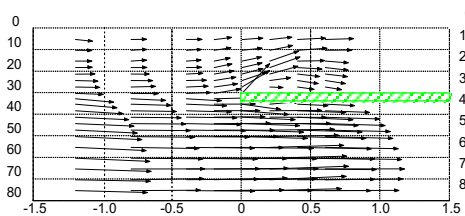
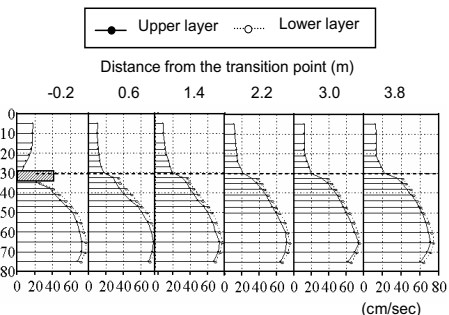(a) Mean velocity distribution $\left(u\right)$
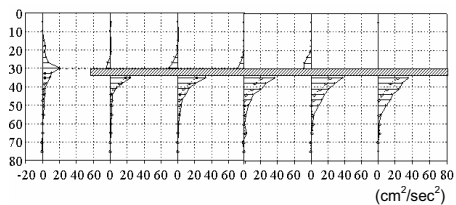
(b) Reynolds stress distribution $\left(-\overline{u'v'}\right)$
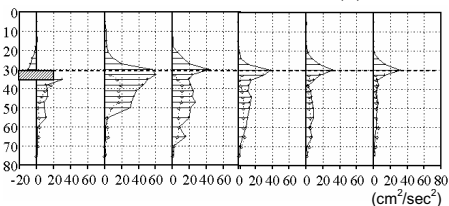
(c) Reynolds stress distribution $\left(-\overline{u'w'}\right)$

(d) Velocity vector distribution

Fig.3 Experiment ND

(a) Mean velocity distribution $\left(u\right)$

(b) Reynolds stress distribution $\left(-\overline{u'v'}\right)$
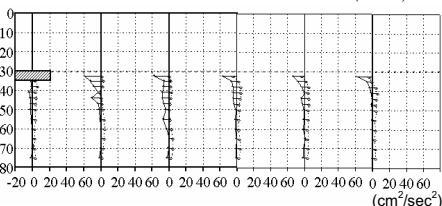
(c) Reynolds stress distribution $\left(-\overline{u'w'}\right)$
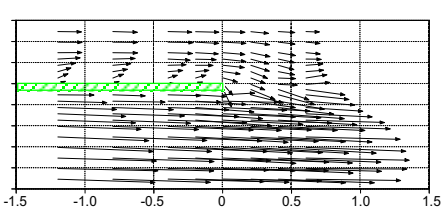
(d) Velocity vector distribution

Fig.4 Experiment DN

from the development of large-scale horizontal eddies. In the transition to a vegetation-affected flow, the mechanism of flow mixing changes extensively because of the abrupt onset of the effect of resistance at the upstream end of the vegetation. In addition, the main channel flow is accelerated when it strikes the upstream front of the vegetation and flow direction is bent. Large-scale horizontal eddies form and grow larger as the flow travels downstream, resulting in a flow characterized predominantly by horizontal mixing in the upper layer. The resultant upper–lower layer velocity differential in the main channel produces vertical mixing.

3.1.2. Longitudinal Change in Flow Structure in Experiment DN

Figures 4 (a), (b), and (c) respectively show mean velocity distribution ($\bar{u}$) and Reynolds stress distributions ($-\overline{u'v'}$, $-\overline{u'w'}$) for experiment DN. Here, at the transition from dense vegetation to an absence of vegetation, the velocity distribution changes from one characterized by deceleration at the main channel–floodchannel boundary to one characterized by acceleration of the floodchannel flow by the main channel flow. That $-\overline{u'v'}$ is significantly greater than $-\overline{u'w'}$ indicates the predominance of transverse mixing, and its high value also suggests vigorous mixing between the main channel and floodchannel flows in the upper layer.

As seen in Figures 4 (b) and (c), Reynolds stress downstream from the vegetation (both $-\overline{u'v'}$ and $-\overline{u'w'}$) exceeds that in the range of the vegetation. As Figure 4 (d) shows, this is due to the vigorous mixing that occurs when floodchannel flows that had been slowed by the vegetation abruptly enter into the main channel, and when very slow flows inside the vegetation exit the vegetation into the downstream waters. As the water travels downstream, the effect of this vigorous mixing is diffused transversely in the form of convection from the floodchannel and large-scale horizontal eddies. The structure of this mixing is evident in the longitudinal change in $-\overline{u'v'}$. Horizontal mixing at the boundary decreases farther downstream, and mixing gradually gives way to a structure characteristic of compound flows in a waterway lacking vegetation.

3.2. Downstream Distance Required for Flow Field Development

This section considers the downstream distance required for development of the mean flow field. Distance L from the flow field transition point to where mixing reaches equilibrium can be thought of as the flow field transformation distance. The change in mean flow field in this experiment is clearly apparent in the Reynolds stress distribution ($-\overline{u'v'}$); the change in $-\overline{u'v'}$ associated with this transformation is particularly great at the floodchannel–main channel boundary and the vegetation boundary. Therefore, development of the mean velocity field is determined as longitudinal change in the Reynolds number Re', which is calculated using a representative velocity defined as the square root of $-\overline{u'v'}$ acting on the upper layer at the boundary, and a representative length defined as the transverse width B over which $-\overline{u'v'}$ occurs

in the upper layer of the main channel. This value of Re' is referred to in this paper as the boundary Reynolds number.

Figure 5 (a) shows the longitudinal change in Re' for experiments DS, DN1, DN2, and DN3; Figure 5 (b), that for experiments SD and ND. The values of L (i.e., distance required for flow field development) were L_{SD} = 1.4 m, L_{ND} = 2.2 m, L_{DN1} = 4.4 m, L_{DN2} = 5.2 m, and L_{DN3} = 5.8 m (L_{DS} was not calculated because of the inability to determine a clear transition section). The results show that in cases of abrupt change in the flow field (as in DN and ND), the downstream distance required to reach equilibrium is longer. A comparison of L_{ND} and L_{DN1} shows that despite the considerable change in both flow fields, the transformation distance was longer in the latter case because of the considerable effects of mixing at the end of the vegetation. A comparison of L_{DN1}, L_{DN2}, and L_{DN3} reveals a relationship whereby transformation distance increases with discharge. This is because under these experimental conditions, an increase in discharge intensifies mixing at the end of the vegetation, requiring a greater distance to diffuse its effects.
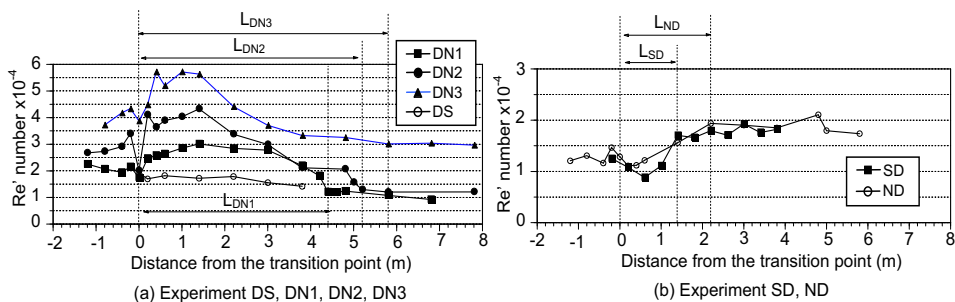

(a) Experiment DS, DN1, DN2, DN3

(b) Experiment SD, ND

Fig.5 Longitudinal change in boundary Reynolds number Re'

3.3. Deriving an Equation for Transition Distance

Distance L from the end of the vegetation to where mixing achieves equilibrium is considered the transition distance. An equation of motion for the transition section in the x- direction is derived thus:

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = gi - \frac{1}{2h}Fu^2 + \varepsilon\frac{\partial^2 u}{\partial y^2} \tag{1}$$

where u: main velocity, h: depth, F: friction loss coefficient ($F = 2gn^2/h^{\frac{1}{3}}$), ε: coefficient of eddy viscosity.

In equation (1), the hydraulic quantities for each point can be divided into equilibrium quantities and deviation thus

$$u(x, y) = u_\infty(y) + \tilde{u}(x, y), \ h(x) = h_\infty + \tilde{h}, \ \varepsilon(x) = e_\infty + \tilde{\varepsilon}$$

Separating equation of motions—one for the equilibrium flow field and another for the deviation from equilibrium, and giving following approximations

$$u_\infty \gg \tilde{u}, \ \frac{\partial^2 \tilde{u}}{\partial y^2} \approx 0, \qquad (h_\infty + \bar{h}) \approx h_\infty$$

thereby simplifying the equation of motion for the transition to derive the following equation:

$$u_\infty \cdot \frac{\partial \bar{u}}{\partial x} = -\frac{F}{h_\infty} u_\infty \cdot \tilde{u} + 2\varepsilon_\infty \frac{\partial^2 \tilde{u}}{\partial y^2} \tag{2}$$

Upon nondimensionalizing x and y in equation (2) with transition distance L and width of mixing in the equilibrium range ΔY

$$\bar{u} = X\left(\frac{x}{L}\right) \cdot Y\left(\frac{y}{\Delta Y}\right)$$

and realizing X, X', Y, Y' and Y" to be determined solely with respect x and y,
the following proportional relationships are valid.

$$\frac{\varepsilon_\infty}{(\Delta Y)^2} \alpha \frac{F \cdot u_\infty}{h_\infty}, \ \frac{u_\infty}{L} \alpha \frac{\varepsilon_\infty}{(\Delta Y)^2}, \ \frac{u_\infty}{L} \alpha \frac{F \cdot u_\infty}{h_\infty}$$

From this, the following relational equation is derived:

$$L = \alpha \cdot \frac{h_\infty}{F} \tag{3}$$

Transition distance L is proportional to (depth)/(friction loss coefficient), and proportionality constant α is a coefficient that is determined by the nondimensional quantities represented by $\varepsilon(x)$, ΔY, and equilibrium velocity u_∞, which depend on large-scale horizontal eddies and the vegetation permeability coefficient. Because of the pronounced effect of flow field transition in the main channel, the main channel friction loss coefficient F_m and mean depth h_m at equilibrium were substituted into equation (3), and proportionality constant α was determined so as to agree with measured transition distance L as determined from the longitudinal change in boundary Re number (Re'). Under these experimental conditions, the values shown in Table 2 were obtained

Table-2 Numerical values of Eq (3)

Case	hm	Fm	L	α
Exp ND	8.4	0.0050	220	0.130
Exp SD	8.43	0.0050	140	0.083
Exp DN1	6.97	0.0052	440	0.328
Exp DN2	8.01	0.0050	520	0.324
Exp DN3	8.61	0.0049	580	0.330

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for α. In all three DN cases, a value of 0.33 was obtained for α, indicating that under these conditions (i.e., a relative depth of 0.18–0.33), transition distance is proportional to (depth)/(friction loss coefficient) downstream at equilibrium.

4. CONCLUSIONS

This research elucidated the process of change in mixing mechanisms associated with change in vegetation density, as well as the process of change directly upstream and downstream from the vegetation, and considered flow field transition distance. It was found that immediately downstream from the vegetation, the abrupt inflow of the floodchannel flow into the main channel resulted in extensive horizontal mixing that exceeded the mixing between flows inside and outside of the vegetation. Another important characteristic was that the vigorous mixing immediately downstream from the vegetation is diffused by large-scale horizontal eddies. As with cases of density that is greater downstream, the process of mixing development is one in which the development of large-scale eddies changes the main channel layer's velocity distribution, resulting in vertical mixing.

Thus flows are three-dimensionally complex, with strong nonlinearity, at the points where vegetation permeability changes longitudinally and in the flow field transition areas that occur at the upstream and downstream ends of the vegetation. Consequently, numerical analysis methods are an effective means of predicting hydraulic phenomena in a channel having various types of vegetation growth. The next step is to develop a highly accurate three-dimensional analysis model capable of predicting the resistance properties and transition distance of a channel having varying vegetation permeability an d hydraulic conditions.

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