STUDY ON MIDDLE-CLASS FLOOD DISTURBANCE IN MIDDLE STREAM OF RIVERS AND SEDIMENTATION IN COMPOUND CHANNELS

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ABSTRACT

Although middle-class flood disturbance is highly correlated with diversity of vegetated area of river habitat, still it is not clearly defined due to its complexity. For describing flood disturbance characteristics, two indices, *BOI* and *WOI*, are used for expressing breaking condition of trees and washout condition of trees and grasses. The relationship between diversity index of vegetated area (*DI*); calculated using vegetation species maps, and flood disturbance index (I_i); which represents the expected value of different flood disturbances, was investigated on four gravel bars in the Karasu River, Japan. The flood disturbance indices in Region A (high possibility to be a forest) and Region E (high possibility to be a bare area, as defined in this study) are identified as indicators for middle-class flood disturbance in this study. Furthermore, based on the observed data and calculated results related to the possibility of vegetation and bare area on gravel bars in all investigated rivers, a range of flood return periods was defined for middle-class flood disturbance for habitat on gravel bars which is from 3 years to 12.5 years.

Second stage of this study was focused on determining a suitable cross section for compound channels of rivers. The turbulent flow structure of the compound channel was investigated with Particle Image Velocimetry (PIV) technique and results were further verified by comparing with sediment deposition profiles obtained with sedimentation experiments. According to the results, possibility of sedimentation on floodplain is increased with vegetation due to the momentum transport towards floodplain from the interface of low channel. Also it can be concluded that construction of middle water channel with inclined floodplain can be effective in minimizing sediment deposition on middle water channel bed in short term, but in long term when vegetation starts growing on it, it would become less effective towards that purpose.

KEYWORDS: flood disturbance, diversity of vegetated area, middle class flood disturbance, Reynolds stress, sediment transport

1. INTRODUCTION

Forestation in a river creates a valuable natural environment, which is mainly important in terms of bank stabilization and ecological restoration, but sometimes it can become a problem because it enhances flow resistance, reduces river flow downstream and accumulated debris of vegetation can increase the drag force around bridge piers while causing large scour holes around them. Furthermore, excessive forestation by a single species can sometimes affect the biodiversity of the river ecosystem.

Therefore, for proper rehabilitation and management of river environment, it is important to determine what kind of flood disturbance can increase the diversity of vegetation but control the rate of forestation in a river habitat. When the vegetation condition on the gravel bars of the river is considered, with the increase of flood disturbance, the possibility of washout of vegetation on gravel bars increases, but on the other hand, i.e., when the flood disturbance decreases, the possibility of vegetation existence on gravel bars will be increased. Moreover, it has been found that vegetation existence on gravel bars is affected mainly by flood intensity and frequency. Since flood disturbance is the combined effect of flood intensity and frequency, some indices are required to define middle-class flood disturbance for the above purpose.

The middle-class flood disturbance proposed in early studies have focused on tropical forests but did not define it for river habitat, and it was not included in previously defined biodiversity indices. In previous studies such indices have been derived to define middle-class flood disturbance based on investigations on Arakawa and Tamagawa Rivers, Japan, but the trend of diversity of vegetation with those indices was found to be different for the two rivers. Therefore the applicability of the flood indices needs to be verified with other rivers, while determining the reasons for the differences. In predicting the possibility of forestation in rivers, previous studies discussed mainly the washout condition of trees. However, the degree of damage on trees is also considered in this study because trees that were broken or bent down by a flood might regenerate after the flood, and the washout condition of grasses is also considered. Furthermore, middle-class flood disturbance was not clearly defined in terms of flood return period (frequency) in previous research, so this study was focused on defining a specific range of flood return periods for middle-class flood disturbance in rivers.

The second stage of this study was based on the sedimentation and flow structure in compound water channels. Compound water channels are one of the most important flood control methods used in river engineering since in many areas where flooding cannot be allowed because of infrastructure around the rivers. For the purpose of increasing flow capacity, extension of only low channel width would not be enough in some cases because with time, sand bars can be formed in the low channel due to reduction of flow velocity and cause the reduction of flow capacity. Therefore construction of middle water channel by excavating floodplain would be a better solution in this matter.

However, it also creates opportunity for frequent inundation on middle water channel bed due to lowered floodplain. Then due to the velocity difference between low channel flow and middle channel flow, complicated flow patterns are generated and the shear layer that develops at the interface between main channel and middle water channel (floodplain) affects the turbulent flow structure. This complex turbulent flow structure leads to generation of two types of vortices. One is horizontal vortices that are generated due to shear layer of the streamwise flow and other type is vortices with longitudinal axis called secondary currents due to anisotropy of turbulence. Since these vortices enhance lateral mass and momentum exchange, it causes a net transfer of sediment from the low channel to the floodplain. Moreover, sediment will tend to settle out once transferred to the floodplain region because of the reduced transport capacity of the flow. Therefore with time there is a possibility of increasing sedimentation on floodplain, which can promote the growth of vegetation and decrease of depth. This study hypothesized that the slope of the middle water channel in transverse direction could be an important factor to control the sedimentation on middle water channel bed so that vegetation growth also can be controlled on it. Although many studies have been conducted related to compound channel flow, the studies related to the effect of inclined floodplain on sedimentation and flow structure with physical simulation of sedimentation are still rare. Therefore this study was focused on turbulent flow structure and sedimentation on flat and inclined as well as smooth and vegetated floodplain. Two types of experiments (PIV-Particle Image Velocimetry to evaluate the change of the secondary flow, and the Reynolds stresses related to sediment transportation and sediment experiment to observe sediment deposition) were conducted for flat/inclined floodplain, plain/vegetated floodplain, and low/high water depths.

2. METHODOLOGY

2.1 Field investigation and River flow analysis

A field investigation was conducted on four gravel bars (1: 36^{0}17'26"N, 139^{0}4'28"E, 2: 36^{0}17'27"N, 139^{0}4'25"E, 3: 36^{0}17'26"N, 139^{0}4'11"E and 4: 36^{0}17'25"N, 139^{0}4'5"E) located at the Karasu River, Japan (Fig. 1).

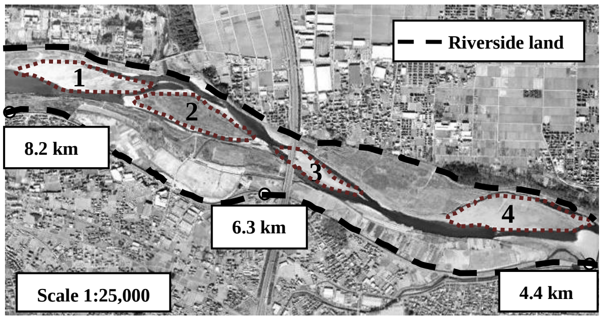

Fig. 1: Study area in Karasu River, Japan (distances at stations are measured from confluence with Tonegawa River)

Particle size distribution of gravel bed materials at each site was determined. $d50$ and $d90$ were estimated by an image analysis method since the particle size was found to be large at the sites where the sieve analysis test cannot be used. To simulate the river flow, a two dimensional (2D) hydrodynamic model was used. The basic equations used in the hydrodynamic model are the conservation of fluid mass equation and the momentum equations (Reynolds equation).

2.2 Definition of indicators for classifying the possibility of forestation in a river

Two indices are used to evaluate washing out trees and grasses and breaking or bending of tree trunks as proposed by Tanaka and Yagisawa (2012). For evaluating trunk breakage, *BOI* (Breakage or Overturning Index = d_{BHmax} / d_{BH}) and for washing out trees and grasses, *WOI* (Wash-Out Index $=\tau_{*90}/\tau_{*c90}$) are defined, where d_{BH} is the tree diameter at the flood event, d_{BHmax} is the maximum tree trunk diameter that the flood can break, τ_{*90},τ_{*c90} are non-dimensionalized shear stress and non-dimensionalized critical shear stress of d_{90} (grain size for which 90 % of the material weight is finer) respectively. Fig. 2 shows classification of possibility of plant removal or damages using the above two indices proposed by Tanaka and Yagisawa (2012).

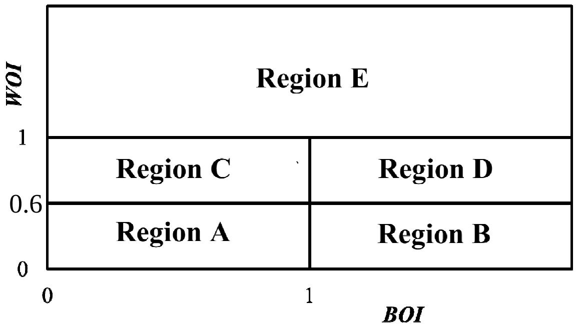

Fig. 2: Classification of tree damage and washout conditions (modified from Tanaka & Yagisawa (2012))

Region A-E are defined so that; when *BOI*>1 trees can be broken or bent down. When *WOI*<0.6 neither trees nor grasses will be washed out. For 0.6<*WOI*<1 only annual grasses will be washed out and when *WOI*>1 all types of vegetation can be washed out (for more details refer Tanaka and Yagisawa (2012)).

2.3 Definition of flood disturbance index (I_i) and diversity index of vegetated area (*DI*)

Considering flood disturbance and magnitude, flood disturbance index (I_i) is defined by Tanaka and Yagisawa (2012) as;

$$I_i = \int_{1/40}^{1/2} \frac{A_i(P)}{A_t} dP \tag{1}$$

Where, T is return period of flood (this study T = 2, 3, 5, 10, 20, 25, 40 years), A_i *(P)* is the area classified in Region-*i* (i = A, B, C, D or E) when flood return period is T ($P = 1/T$ is the probability of flood event), A_t is the total area of gravel bar. Diversity Index of vegetated area, *DI* is defined by Tanaka and Yagisawa (2012) as;

$$DI = -\sum_{i=1}^{ns} \frac{S_i}{A_t} \log \frac{S_i}{A_t} \tag{2}$$

Where, S_i is the area of vegetation-*i*, measured by the habitat distribution map of the gravel bar, *ns* is the number of representative vegetation species on the habitat.

2.4 Turbulent flow structure & sedimentation in compound channels

As explained earlier, due to the construction of middle-water channel on a river floodplain, frequent inundations occur on lowered floodplain and complicated flow patterns are generated and a shear layer is developed at the interface between low channel and middle-water channel (here after referred as floodplain).

For a single floodplain without middle water channel, these effects have been studied experimentally by Arnold (1989), Shiono and Knight (1991), Tominaga and Nezu (1991) and Naot et al. (1993). In addition to them, Prinos et al. (1985), Shimizu and Tsujimoto (1993), Lambert and Sellin (1996), and Sofialidis and Prinos (1999) have also studied the turbulence structure in compound channels. Among them, Shiono and Knight (1991) and Tominaga and Nezu (1991) have observed these effects using fiber-optic Laser-Doppler Anemometer (LDA) and Nezu et al. (1999) have conducted LDA and Particle Image Velocimetry (PIV) measurements on these effects. According to these studies two types of vortices have been identified which are called horizontal vortices (eddies) and secondary currents. These vortices enhance the lateral mass and momentum exchange which creates possibility of increasing sedimentation on floodplain, which can promote the growth of vegetation and decrease of depth with time.

Moreover, momentum transfer from low channel to floodplain on a vegetated floodplain becomes greater than that without vegetation on floodplain, since the roughness increases the resistance and enlarges the velocity difference between the channel sections, and therefore the shear layer in the interface becomes stronger (Sofialidis and Prinos 1999). In previous researches, Tominaga and Nezu (1991) and Tominaga et al. (1993) have conducted experiments with rough floodplain and found out that lateral turbulent shear stress was quite large near the interface and the turbulence level was increased in the main channel, indicating an increase of the turbulence production. In addition, Tominaga and Nezu (1991) have shown that effect of roughness on floodplain is not as predominant as the ratio between flow depth on floodplain to total flow depth on turbulent flow structure. The experimental results of Huang et al. (2002) have shown that velocity in the main channel increased significantly after the floodplains were covered in vegetation.

James (1985) and Chunhong et al. (2010) have investigated sediment transport on compound channel flow. James (1985) has developed a numerical model for simulating the transfer of suspended sediment from a channel to an adjacent floodplain and verified it with laboratory experiments. Chunhong et al. (2010) have obtained an analytical solution for the lateral distribution of the depth-averaged velocity and sediment concentration in a compound channel, which was proved with experiments.

Like wise, although many studies have been focused on different areas of compound channel flow, studies related to inclined floodplain with vegetation and physical simulation of sedimentation on compound channels are still rare. Therefore based on the hypothesis of this study (that the slope of the middle water channel in transverse direction could be an important factor to control the sedimentation on middle water channel bed) experiments were conducted in a flume for 8 cases, which included both flat and inclined floodplain, vegetated and plain floodplain, and low and high water depths. With the available facility, experiments were conducted within low water channel and middle water channel and for smaller water depths as shown in Fig. 3.

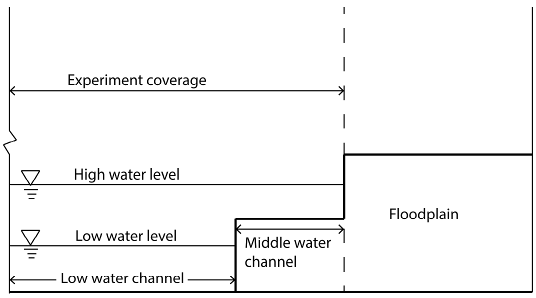

Fig. 3: Coverage of the experiments

Results are presented for secondary flow pattern, Reynolds stress distribution and sediment deposition profile for both flat and inclined vegetated floodplain.

In this study two types of experiments were performed in a flume, 1) Particle Image Velocimetry (PIV) technique was used to evaluate the change of the secondary flow, and the Reynolds stresses related to sediment transportation and 2) small diameter sand was added to upstream of flume and sediment deposition profile on channel section was measured after achieving equilibrium condition.

Both experiments were conducted maintaining two water depth ratios H_m/h (where H_m is water depth in low water channel and h is floodplain height); small H_m/h to simulate horizontal vortices (Nezu et al. 2000), and large H_m/h; that secondary currents could be apparently observed; for plain and vegetated, and flat and inclined floodplains. Experiments were conducted in a flume of 15m length, 0.5m width and 0.4m height.

The compound flow channel section was constructed over the length of flume with overall width (B) = 50cm, low channel width (b_f) = 22cm, middle channel width (b_m) = 28cm and floodplain height (h) = 6cm. Slope of the flume was set to 1:1000 and for inclined floodplain slope of floodplain was set to 3.5º.

For vegetated floodplain, floodplain height (h_v) was set to 6.5cm including 0.5cm vegetation height, made with the above selected artificial grass layer to represent grasses on floodplain. Accordingly, four cross sections constructed for the experiments series are shown in Fig. 4.

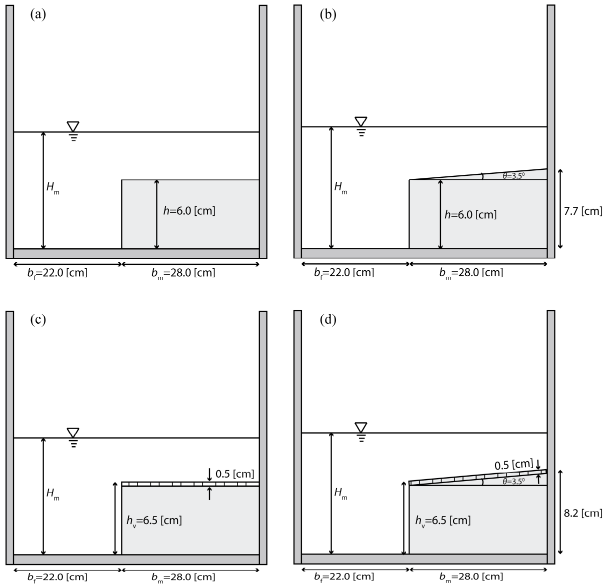

Fig. 4: Cross sections of experiment setup: (a) plain flat floodplain, (b) plain inclined floodplain, (c) vegetated flat floodplain, and (d) vegetated inclined floodplain.

To find water depth ratios (H_m/h) for low water depth cases, a series of experiments were conducted for each above section to check horizontal vortices (eddy) occurrence. For different water depths and velocities, horizontal vortices occurrence was checked by adding ink drops to water surface and taking video clips. Then H_m/h values were plotted vs Reynolds number of all cases and the ranges of clear occurrence of vortices were identified. Then the small H_m/h values were decided based on that. For high water depth cases, H_m/h ratios were decided based on results of previous researches (Nezu et al. 2000).

Accordingly, for sections with plain floodplain (sections (a) and (b) in Fig. 4.2), water depth ratios were set as H_m/h = 1.28 for low water depth; for occurrence of horizontal vortices and H_m/h = 2.00 for high water depth; for occurrence of secondary flow. For sections with vegetated floodplain (sections (c) and (d) in Fig. 4.2), water depth ratios were set as H_m/h_v = 1.26 for low water depth and H_m/h_v = 1.88 for high water depth.

Finalized experiment conditions are shown in Table 1 including representative Froude number; $Fr = U_m/\sqrt{gH_m}$ and Reynolds number; $R_e = U_mR/\nu$, where U_m = average cross sectional velocity, R = hydraulic radius and ν = kinematic viscosity, and g = gravitational acceleration. PIV and sediment experiments were conducted for these 8 cases.

Table 1: Experiment conditions for PIV and Sediment experiments

Condition	Non-vegetated floodplain				Vegetated floodplain ($h = h_v$)			
	Flat		Inclined		Flat		Inclined	
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Floodplain height h (cm)	6.0				6.5			
Low channel water depth H_m(cm)	7.7	12.0	7.7	12.0	8.2	12.2	8.2	12.2
H_m/h	1.28	2.00	1.28	2.00	1.26	1.88	1.26	1.88
Froude Number (Fr)	0.31	0.36	0.29	0.32	0.43	0.38	0.50	0.52
Renumber (R_e) x 10^4	0.9	2.3	0.9	2.3	1.3	2.4	1.4	2.5

2.4.1 PIV experiment

PIV experiment was conducted at nearly the middle of the flume (6.4 m from upstream). In the PIV experiment, fluid motion is visualized by mixing and circulating a tracer in water flow (Aluminum powder was used as tracer in this study). Then the velocity field is calculated by analyzing the digital videos captured using a High-Speed Digital Camera (High Speed Digital Camera K-II: Kato Koken Co. Ltd) and a Laser Sheet (Green Laser Sheet 200m/G: Kato Koken Co. Ltd). Measurements were taken at cross sections in both horizontal and vertical directions by changing orientation of high-speed digital camera and laser sheet for above 8 cases.

In horizontal direction measurements were taken at 1cm spacing while in vertical direction spacing was 2cm as shown in Fig. 5(a). Coordinate system for calculations was set as x, y and z in streamwise, vertical and transverse direction (Fig. 5(b)). Furthermore, velocity u, v and w were measured in streamwise, vertical, and transverse direction.

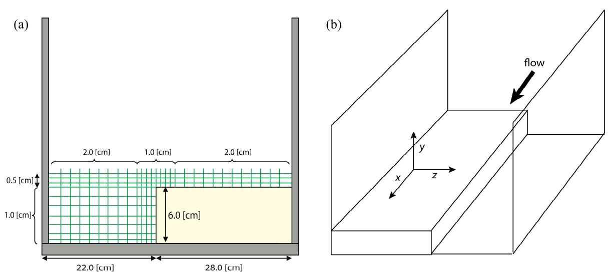

Fig. 5: (a) Horizontal and vertical measurement sections (Case 1), and (b) Coordinate system for calculations (x, y and z axes are in streamwise, vertical and transverse directions respectively)

2.4.2 Sediment experiment

The Sand used for the sediment experiment was comprised of about 30 % of 0.075 mm diameter sand, 40 % of 0.053 mm diameter sand and rest was under 0.05 mm. Sand was added with a known rate to the low channel side at upstream of the flume before the start of floodplain. In order to determine the equilibrium condition related to sediment deposition in the channel, suspended sand in the flow was collected using a sand trap (made with a net with sieve size of 0.05mm) at the downstream end at each hour.

Both sand input rate (Q_{in}) and sand output rate (Q_{out}) were plotted vs. time to check the equilibrium condition as shown in Fig. 6 for each case. When calculating Q_{out}, sand amount that can be passed through the sand trap was also considered. During the experiments, in some cases to achieve the equilibrium in a short period of time, at first a higher Q_{in} was maintained and later it was reduced (Fig. 6(b)).

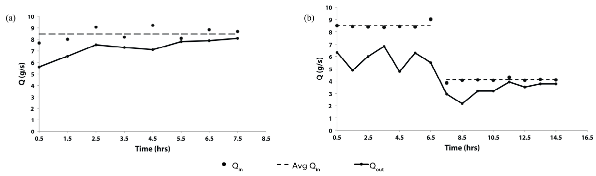

Fig. 6: Equilibrium condition for sediment experiment: (a) Case 3, and (b) Case 7

After sediment deposition become stable (for e.g. after around 11.5 hours in Fig. 6(a) and after 7.5 hours in Fig. 6(b)), sediment profile was measured at the same location using a laser profiler where PIV experiment was conducted.

3. RESULTS & DISCUSSION

3.1 Relationship between flood disturbance index (I_i) and diversity index of vegetated area (DI) for investigated gravel bars and comparison with results of previous studies (Tanaka and Yagisawa (2012))

Fig. 7 shows the relationship between flood disturbance index (I_i) and diversity index of vegetated area (DI) for Region A, D and E on the four gravel bars in Karasu River (1, 2, 3 and 4), together with three gravel bars of Arakawa River (KL, KR and AR) and Tamagawa River (TO, HL and HR) of previous studies. Since the values of Region B and C are found to be small, only trend of Region A, D and E is discussed.

The diversity of vegetation in Region A where plants are not washed out and trees are not broken, shows positive correlation with the increase of flood disturbance index in Karasu and Arakawa Rivers. On contrary, it is a negative correlation in Tamagawa River. On the other hand, the trend between DI and I_E is negative in Karasu and Arakawa Rivers, but for Tamagawa River it is positive. It can be noticed that the similar and different trends between DI and I_i in three rivers are due to the effect of flood disturbance that the investigated gravel bars have been subjected in previous years before 2006. (the vegetation maps used in this study were produced in 2006).

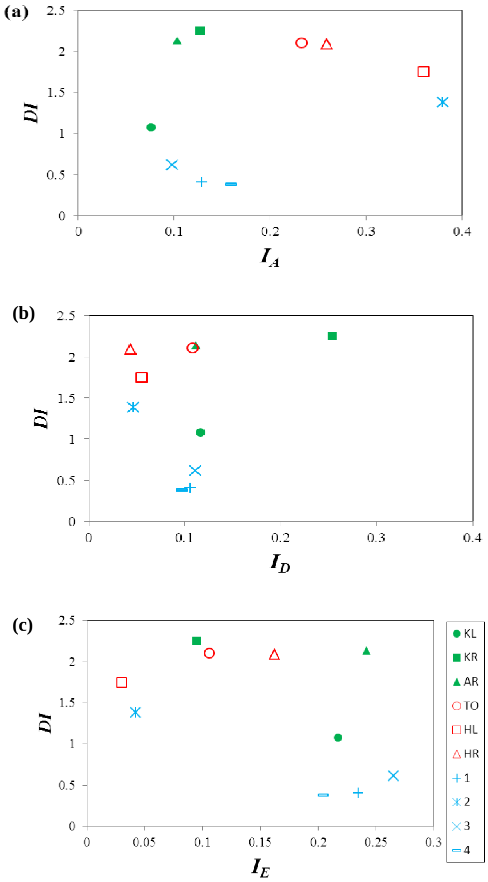

Fig. 7: Relationship between flood disturbance index (I_i) and diversity index of vegetated area (*DI*) for Reg. A, D and E

From the definition, with the increase of possibility of flood disturbance, I_E increases. On contrary, I_A increases when flood disturbance decreases. As this is the combined effect of flood magnitude and frequency, I_A and I_E can be defined as indicators for middle class disturbance as derived by Tanaka and Yagisawa (2012) in their previous studies on Arakawa and Tamagawa Rivers. The diversity of vegetation in Region D where 0.6<*WOI*<1, does not show much noticeable trend for all rivers. This can be because tree types of vegetation are found to be less on the investigated gravel bars since Region D is related to the possibility of breaking or bending of trees. So this study confirms the result of Tanaka and Yagisawa (2012) and the applicability of this to other rivers, although trend of *DI* with I_i could be different for each river depending on its flood and geographical characteristics.

3.2 Definition of middle-class flood disturbance in terms of return period of flood (flood magnitude)

In the previous section, relationships between the flood expectation value and diversity of vegetated area for floods with 2- to 40-year return periods were analyzed, and the indicators for middle-class flood disturbance were identified. However, it is important to find the range of flood return periods related to middle-class flood disturbance towards increasing the diversity of vegetated area more precisely. When the return period of a flood is smaller, the intensity of the flood is smaller but the flood frequency becomes higher. In that sense when the range of flood return periods related to middle-class flood disturbance is considered, the lower flood return period values can be related to the possibility of vegetation growth on gravel bars, and the upper flood return period values can be related to the possibility of bare area and plant removal. To determine these lower and upper return periods, the following analysis was performed using the simulation results of the four gravel bars in the Karasu River as well as of three gravel bars of the Arakawa River and three gravel bars of the Tamagawa River.

The definitions of Regions A and E in this study involve the possibility of vegetation growth and substrate removal (i.e., generation of bare areas) on gravel bars in a river, respectively. Therefore, the above-mentioned lower and upper flood return periods can be related to Regions A and E, respectively. Based on that, the total areas of Regions A and E non-dimensionalized by the total area of the gravel bar (Ai(P)/At) were calculated for each gravel bar for all flood return periods (2, 3, 5, 10, 20, 25, and 40 years). The same factor (Ai(P)/At) was also determined as an observed value considering the vegetated areas as Region A and the bare areas as Region E using data observed on the gravel bars based on the definitions of Regions A and E. Both calculated and observed Ai(P)/At values were plotted vs. the probability of flood return period (P=1/T), considering the average values for gravel bars of all three rivers. Fig. 8 shows the plot for Region A of Karasu River.

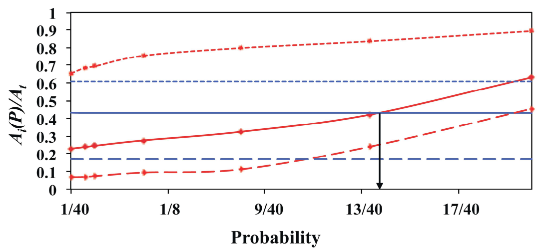

Fig. 8: Estimation of flood return periods for definition of middle-class flood disturbance using observed and calculated area of Regions A, non-dimensionalized by total area of gravel bar ($A_i(P)/A_t$): for Region A of Karasu River.

It is assumed that the interception of calculated and observed average lines represents lower and upper flood return period values related to vegetation growth and bare areas, respectively. Accordingly, lower and upper flood return period values were obtained to discuss middle-class flood disturbance, as shown in Table 2.

Table 2: Estimated return periods relevant to forest/bare area (in years)

	Karasu river	Arakawa river	Tamagawa river	For all
Lower value of return period*	3	2.5	3	3
Upper value of return period†	12.5	15	10.5	12.5

* related to region A according to definition

† related to region E according to definition

The lower and upper values of return periods are three years and 12.5 years, respectively, when the values for all rivers are averaged. This result is used to define middle-class flood disturbance as illustrated in Fig. 9.

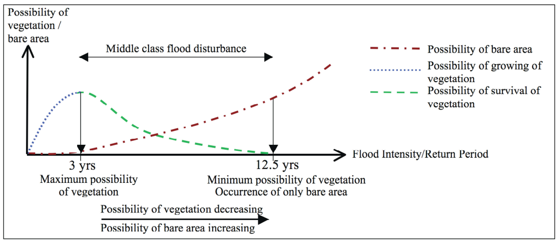

Fig. 9: Schematic diagram defining middle-class flood disturbance

As shown in Fig. 9, floods with higher return periods (lower frequency) have a higher intensity. A particular gravel bar with a three-year return period of flood has the maximum possibility of vegetation growth. When the flood frequency exceeds that (lower return periods), the possibility of the existence of vegetation is reduced due to frequent flood occurrences, which leads to the rise of water table of the area, thus reducing the possibility of vegetation growth on the gravel bar. On the other hand, a return period of up to three years allows vegetation to start growing on gravel bar due to low flood intensity. Therefore, a flood return period of less than three years can be considered to be related to the possibility of vegetation growth.

At return periods between three years and 12.5 years, the possibility of vegetation surviving on a gravel bar is reduced, where it reaches its minimum at 12.5 years due to the increment of flood intensity, although flood frequency is decreased. Thus, this period can be taken as related to the possibility of the survival of vegetation. On the other hand, the possibility of substrate removal (generation of bare area) increases with increasing flood intensity/return period. However, this condition can be different for some time after the flood because then the vegetation might start growing again. For example, after a nearly complete washout of vegetation in a 12.5 year flood or after partial washout of vegetation in between a three year to 12.5 year flood.

According to this, middle-class flood disturbance on gravel bars of the investigated rivers can be defined between 3–12.5 years return period.

3.3 PIV experiment results

3.3.1 Changes in non-dimensional flow velocity

In this section, change of stream-wise velocity profile in the cross section is analyzed with change of water depth H. Here surface velocity is selected as velocity profile and the difference between two water depths H=7.5 (for low water depths) and 11.5cm (for high water depths) is discussed for 8 experiment cases conducted.

Fig. 10 shows the surface velocity profile for the two water depths with horizontal axis, z/B (where z is the distance measured from low channel wall, and B is the total channel width), and vertical axis, u/u_{avg} (where, u_{avg} is the averaged velocity in cross section, and u is the surface velocity at each location). Vertical line at z/B = 0.44 shows the interface between low channel and floodplain. Fig. 10(a) and (b) represent plain flood plain cases and vegetated floodplain cases, respectively.

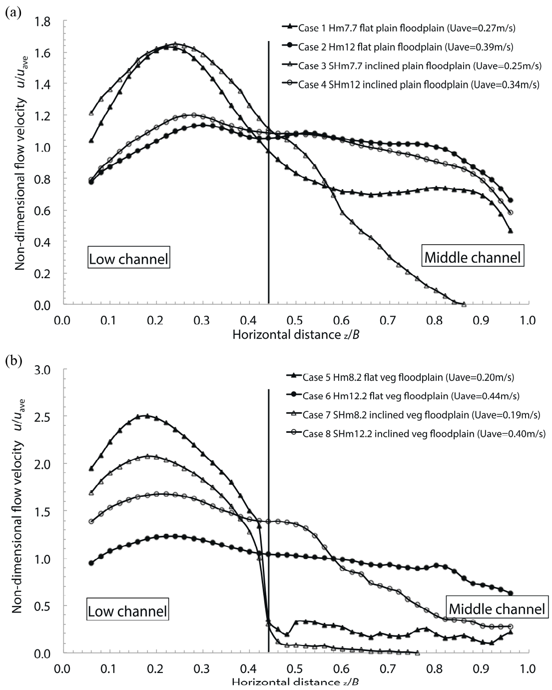

Fig. 10: Change of non-dimensional flow velocity over channel section: (a) for plain floodplain, and (b) for vegetated flood plain

For all water depths, velocity is larger in low channel due to the higher water depth. With the change of water depth in Cases 1, 3, 5, and 7 (low water depth cases) where large horizontal vortices are generated, have larger velocity difference between the low channel and floodplain. This difference can be clearly seen in vegetated floodplain due to the high friction occurred from vegetation layer. Moreover this becomes more significant for inclined floodplains with low water depths (Cases 3 and 7) where velocity reaches zero at z/B=0.86 and 0.76, respectively. The reduction of flow velocity also can be seen even for Case 8 with higher water depth and inclined vegetated floodplain.

This implies momentum exchange from low channel has a possibility to become larger for both vegetated and inclined floodplain, and specially in case of low water depths. In addition, for low water depths, peak value of the momentum transfer appears near the interface of the low channel and floodplain, which is similar to phenomenon observed by Chunhong et al. (2010).

3.3.2 Changes in secondary flow vector

Fig. 11 and 12 shows the distribution of velocity vector (secondary flow) in the cross section for the 8 cases with non-dimensional cross-stream length, z/B as x-axis and non-dimensional height, y/h as y-axis (where, h is the height of floodplain, and y is the water depth) for plain and vegetated floodplain cases, respectively. The secondary flow velocity $\sqrt{v^2+w^2}$ is non-dimensionalized by $u_{\max}$ (similar to the method of Tominaga and Nezu, 1991), the maximum stream-wise velocity in the cross section.

In Fig. 11 (plain floodplain cases), when secondary flow pattern in Case 1 and Case 3 is compared, where the hydraulic condition is related to large eddy formation; anti-clockwise secondary flow pattern in low channel at the interface can be clearly seen in Case 3. At the same time downward flow from floodplain towards low channel is at large scale for Case 3. In case of high water depths, Case 2 shows anti-clock wise secondly flow at around z/B = 0.4, and clock wise secondly flow at around z/B = 0.5. On the other hand Case 4 shows opposite, specially in low channel (because stronger secondary flow from floodplain suppress the upward flow from low channel).

In Fig. 12 (for vegetated floodplain cases), both Case 5 and 7 have anti-clockwise secondary flow in large vertical scale at around z/B = 0.4, so that upward flow from low channel at the interface can be clearly seen, and for Case 7, it becomes more clear. However, at the same time, downward flow from inclined floodplain is not so

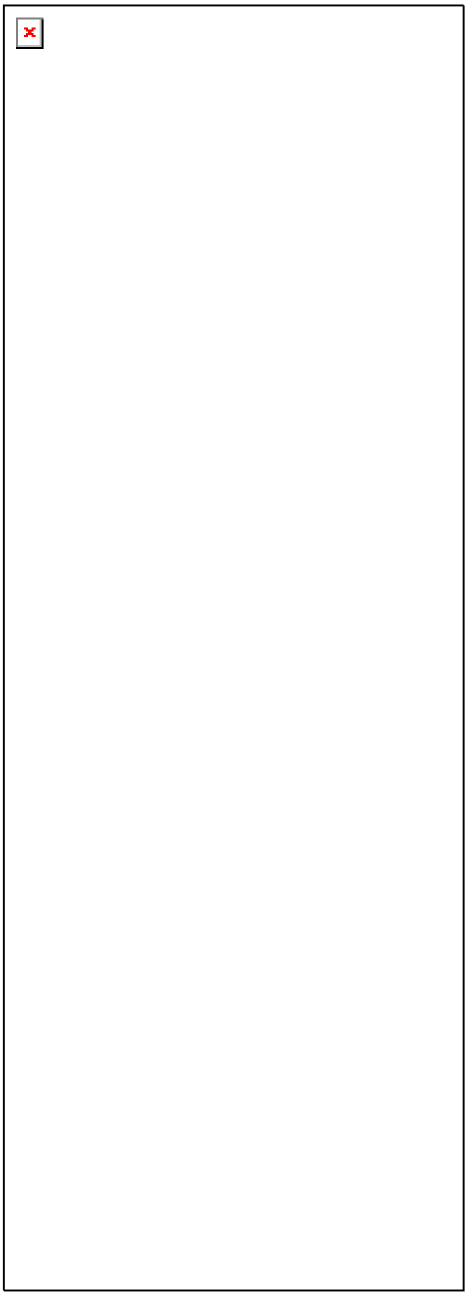

Fig. 11: Changes in secondary flow vector for plain floodplain cases: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4

clear in Case 7 as compared to Case 3, which is due to the friction force from vegetation layer. Moreover, formation of longitudinal vortex (also called free surface vortex) is clear around z/B = 0.18 in case 5 as also observed by Tominaga and Nezu (1991) which occurs due to the anisotropy of turbulence.

On the other hand, both case 6 and 8 show clockwise secondary flow pattern on the interface between low channel and floodplain (z/B = 0.5) while it becomes larger in case 8. Upward flow from low channel (anti-clockwise secondary flow around z/B = 0.4) is also comparatively large in case 8. Furthermore, the possibility of sediment

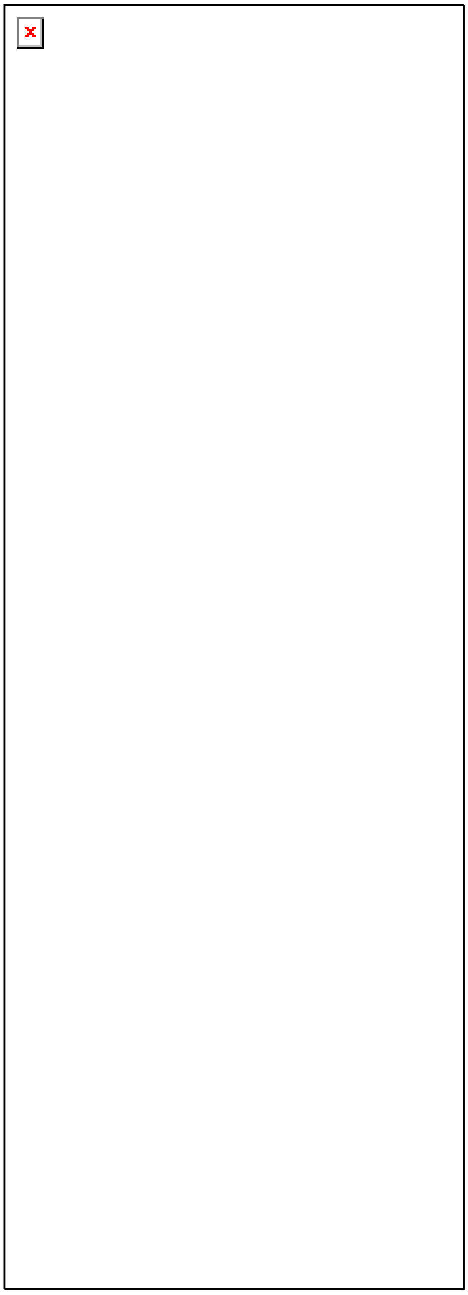

Fig. 12: Changes in secondary flow vector for vegetated floodplain cases: (a) Case 5, (b) Case 6, (c) Case 7, and (d) Case 8

deposition can be noted over the length of floodplain even in inclined floodplain.

When comparing this secondary flow data with similar previous experiments conducted by Tominaga and Nezu (1991) for single plain floodplain, for Case 1, the maximum magnitude of secondary currents, $\sqrt{v^2+w^2}$ was about 5% of $u_{\max}$, which is slightly greater than Tominaga and Nezu (1991) observed (2.5%) for a bit narrower channel with plain floodplain. At the same time, for Case 2 it was about 4% of $u_{\max}$, which is the same as observed by them for the similar plain floodplain condition with higher water depth. For Cases 3 and 4: with inclined floodplain, the maximum magnitude of secondary currents was about 5% and 6% of $u_{\max}$, respectively. Inclined upward flow at junction edge towards free surface can be seen in all cases similar to the observation by Tominaga and Nezu (1991).

3.3.3 Changes in Reynolds stress in the transverse direction

Here, transport of momentum related to sediment deposition is discussed with respect to Reynolds stress distribution in transverse direction at the same cross section. Transverse Reynolds stress $-\rho\overline{u'w'}$ is non-dimensionalized by representative shear stress $\rho u_*^{\,2}$, where u_* is the friction velocity. Friction velocity is calculated using;

$$\frac{u}{u_*}=\frac{1}{k}\log\frac{y\cdot u_*}{v}+A \qquad (3)$$

where, *u*: average flow velocity, *k*: Von Karman constant (=0.41), *v*: kinematic viscosity (=0.01007cm^2/s), and *A*: constant.

Distribution of transverse non-dimensionalized Reynolds stress $-\overline{u'w'}/u_*^{\,2}$ is shown in Fig. 13 and 14 for plain floodplains and vegetated floodplains, respectively. Black (positive) and white (negative) regions show that the momentum transport occurs from low channel to the floodplain, and the opposite, respectively. In general, momentum transport from the low channel towards floodplain can be identified for all cases as also shown by Tominaga and Nezu (1991).

According to Fig. 13, when comparing Case 1 and 3, Reynolds stress has higher negative peak value on flood plain at case 3 caused by large-scale horizontal vortices and return flow due to inclination. So that sediment deposition on floodplain will become less as also was evident by secondary flow pattern.

In case of high water depths also (Cases 2 and 4), inclined floodplain promotes increase of momentum transport from floodplain towards low channel but not so high as in low water depths. For Case 2 with flat floodplain, possibility of sediment deposition is also higher compared to Case 1 with low water depth.

When considering the vegetated floodplain cases (Fig. 14), Case 5 has positive Reynolds stress regions on floodplain near the interface and almost throughout the length due to flow towards floodplain. For Case 7 positive region is located near the interface followed by a negative region so that inclination increases the downward momentum transport but at the same time it is suppressed by vegetation layer as proved by secondary flow pattern. Comparing Case 6 and 8, positive Reynolds stress regions on floodplain in both cases express the flow towards floodplain.

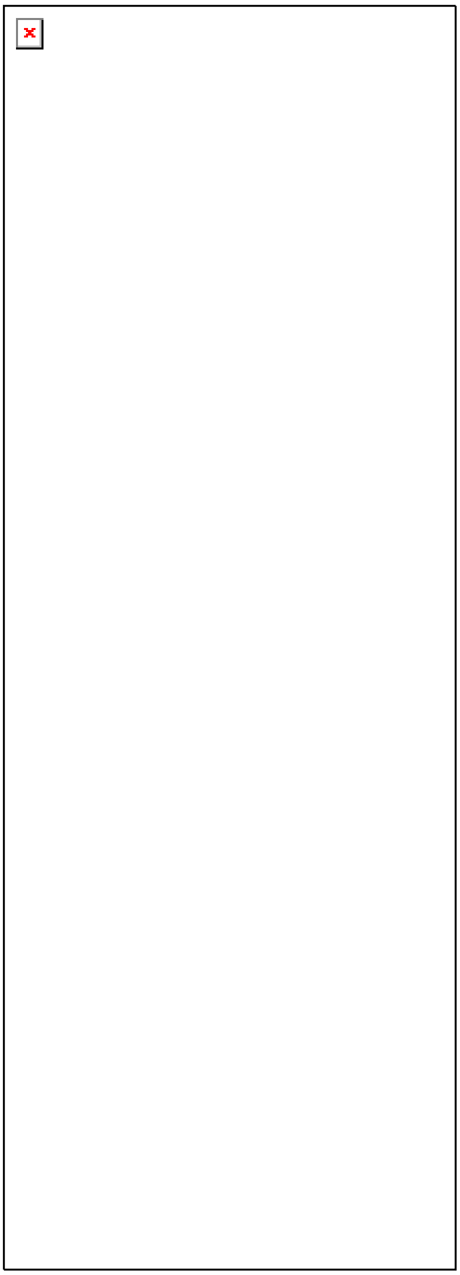

Fig. 13: Changes in Reynolds stress in the transverse direction for plain floodplain cases: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4

Furthermore possibility of sediment deposition around middle of the floodplain would be higher on Case 6 due to larger positive Reynolds stress region and, negative Reynolds stress region for $z/B > 0.76$. The possibility of sediment deposition over the length of floodplain becomes also evident in Case 8 as observed from secondary flow analysis.

3.4 Sediment experiment results

3.4.1 Sediment deposition profiles from sediment experiment

In this section, sediment deposition profiles measured at the same location of PIV experiment after achieving equilibrium condition for all 8 experiment cases are presented and discussed

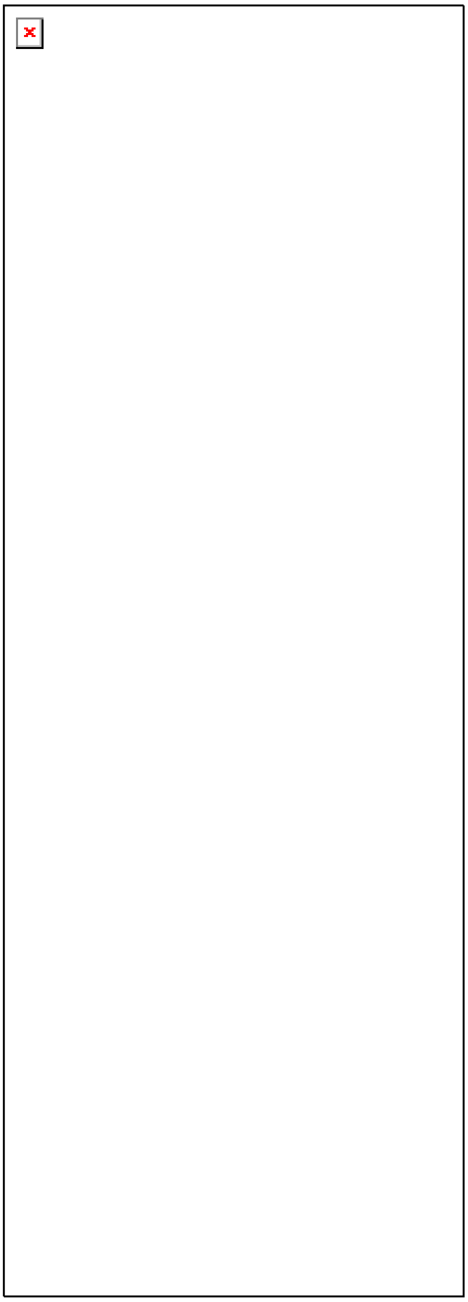

Fig. 14: Changes in Reynolds stress in the transverse direction for vegetated floodplain cases: (a) Case 5, (b) Case 6, (c) Case 7, and (d) Case 8

with PIV experiment results. Fig. 15 and 16 show sediment deposition profiles for plain floodplain cases (Cases 1, 2, 3, and 4), and vegetated floodplain cases (Cases 5, 6, 7, and 8), respectively.

When comparing Fig. 15 and 16, it is clear that sediment deposition is higher on vegetated floodplains and in case of high water depths as become evident by PIV experiment results also. In Fig. 15, between Case 1 and 3 with plain floodplain, effect of inclination of floodplain can be seen on Case 3 with least sediment deposition while Case 1 shows little deposition throughout the floodplain. For high water depth cases with plain floodplain (Cases 2 and 4), both show some deposition on floodplain even with the effect of sloped floodplain in Case 4.

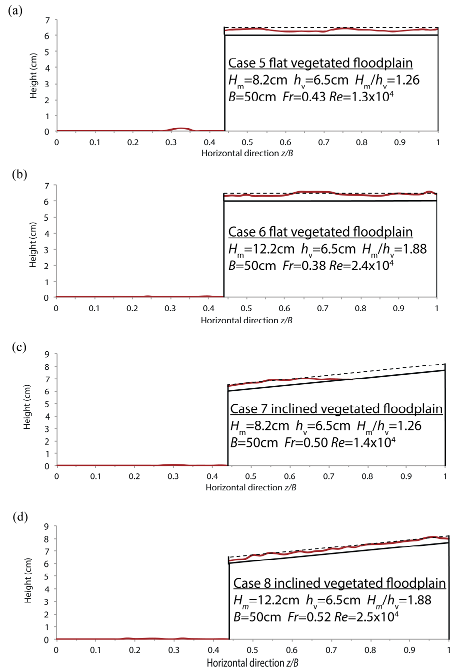

Fig. 15: Sediment deposition profiles for plain floodplain cases: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4

When considering vegetated floodplain cases (Fig. 16), sediment deposition in case 5 is distributed over the floodplain, while for case 7, momentum transport towards low channel is clearly evident but the inclination has become less effective towards reducing sediment deposition on floodplain due to effect of vegetation.

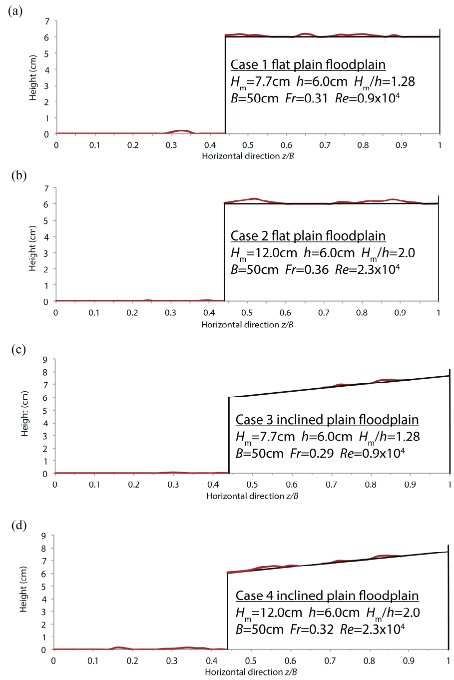

Fig. 16: Sediment deposition profiles for vegetated floodplain cases: (a) Case 5, (b) Case 6, (c) Case 7, and (d) Case 8

For inclined vegetated floodplain (Case 8) sediment deposition is lesser compared to Case 6 with flat floodplain that sediment was distributed over the length of floodplain. In case of Case 6 higher deposition of sediment is also visible around middle of the floodplain. Therefore it can be concluded that these sediment deposition profiles also verify the results of PIV experiment.

4. CONCLUSIONS

In the first stage of this study, the relationship between the diversity index of vegetated area calculated by the vegetation species map and flood disturbance index, a kind of expectation value of flood disturbance, was investigated for four gravel bars in the Karasu River and compared with the results of previous studies of the Arakawa and Tamagawa Rivers. The relationship between the diversity of vegetated area on gravel bars in the middle stream of a river and flood disturbance characteristics was investigated. The diversity of vegetated area was found to be correlated with the flood disturbance index in Regions A and E for the investigated rivers.

In addition, the diversity of vegetated area in Regions A and E showed the same trend for the Karasu and Arakawa Rivers and a different trend for the Tamagawa River, where the trend was affected by previous floods of the investigated gravel bars. However, this indicates the possibility of expressing middle-class flood disturbance of gravel bars in the middle stream of rivers and confirms the applicability of studies of other rivers investigated (Tanaka and Yagisawa 2012). Because the present study could not evaluate the trend of diversity of vegetation with flood disturbance in Regions B, C, and D, a future study should focus on gravel bars with smaller gravel size distribution and during the initial development of vegetation.

Furthermore, based on the observed data and calculated results of the investigated rivers, a definition of middle-class flood disturbance was presented in relation with the return period of floods for the investigated rivers.

The second stage of this study was based on the turbulent flow structure and sedimentation on compound water channels. Although middle water channels are constructed for the purpose of increasing flow capacity in rivers, due to the occurrence of complicated flow patterns it can create possibility of sedimentation on floodplain and with time it also leads to growth of vegetation on floodplain. This study focused about the effect of middle water channel towards reducing sediment deposition on floodplain while increasing the river flow capacity it was hypothesized that effect of inclination of middle water channel bed would be an important factor to control the sedimentation on middle water channel bed so that vegetation growth also can be controlled on it. For proving this PIV and sediment experiments were conducted for 8 cases covering plain, vegetated, flat, and inclined floodplains with low and high water depths.

From the results it can be seen that possibility of sedimentation on floodplain is increased with vegetation due to the momentum transport towards floodplain from the interface of low channel. Also it can be concluded that construction of middle water channel with inclined floodplain can be effective in minimizing sediment deposition on middle water channel bed in short term, but in long term when vegetation starts growing on it, it would become less effective towards that purpose. (Still it performs better than flat floodplain). Furthermore sediment deposition on inclined floodplain would be less for low water depths in comparison to high water depths with or without vegetation on floodplain. This situation in high water depth is similar also in case of flat floodplain. In addition, it can be concluded that on vegetated floodplain, for low water depths sediment deposition would be distributed over the floodplain while for higher water depths sediment deposition would be prominent in the middle of floodplain.

Finally, this information on river cross-section shape can be used to discuss the relationships between flood indices of middle class flood disturbance and diversity of vegetation of first part of this study. In future studies, it needs to be checked with different river channel morphologies, with different flood disturbance effects and vegetation conditions. So that it will lead for more effective and economical river bed design with increased diversity of vegetation and proper management of river habitat.

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