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FLOW STRUCTURE THROUGH GROINS IN THE KISO RIVER DURING A FLOOD EVENT

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ABSTRACT

In the downstream segment of the Kiso River, the groins were constructed about one hundred years ago. Since the installation of these groins, the back marsh, which was frequently inundated and is now used for cultivation and human habitation, has been successfully protected from the inundation. Over the last fifty years, the flow regime and the dynamics of the sediment have been changed by the human activities, and altered the bed topography. Sediment has been deposited around the groins, the accumulated sediment has changed the topography around the groins, and an embayment has formed around the groins. In this study, a one-dimensional flow model and a horizontal two-dimensional flow model are used to investigate the flow structure around the groins, and the stability of the characteristic topography around the groins during a flood is investigated. The results show that during the medium water stage of the flood, the flow meanders with following the low-flow channel topography (bars), and the densely vegetated regions in the groin section are associated with the flow structure during the medium water stage periods. Then, in the peak discharge period, the flow shows a larger structure, following the meandering of the river course, and the small channels in the groin section is parallel to the flow pattern in the peak period. This means that the ribbed topography is formed during the peak discharge period. Finally, from the result of the movable-bed calculation, it is found that the topography in the groin section is stable because the intense flow resistance due to dense vegetation reduces a velocity of the flow and the bed shear stress in the groin section , hence the topography of the embayment formed in the groin section is stable due to the flow regulation function, one of the ecological functions, provided by the riparian vegetation.

Keywords: groin, spur dike, embayment, flow structure, flood, river environment.

1 INTRODUCTION

In the downstream segment of the Kiso River, the groins were constructed about one hundred years ago. Since the installation of these groins, the back marsh, which was frequently inundated and is now used mainly for cultivation and human habitation, has been successfully protected from the inundation. Over the last fifty years, the flow regime and the dynamics of the sediment have been changed by the human activities, such as the construction of the dams, and these changes in the flow and sediment conditions have also altered the bed topography. Sediment has been deposited around the groins, the accumulated sediment has changed the topography around the groins, and an embayment has formed around the groins (see Figure 1.)

The relationship between the flood flow and the embayed topography has been discussed in

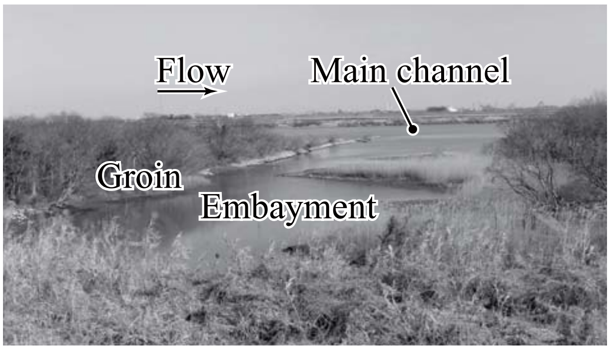


Figure 1: Landscape of the embayment formed around the dike section. The photo was taken from 18.6 km from the mouth of the Kiso River on the right side bank in winter.

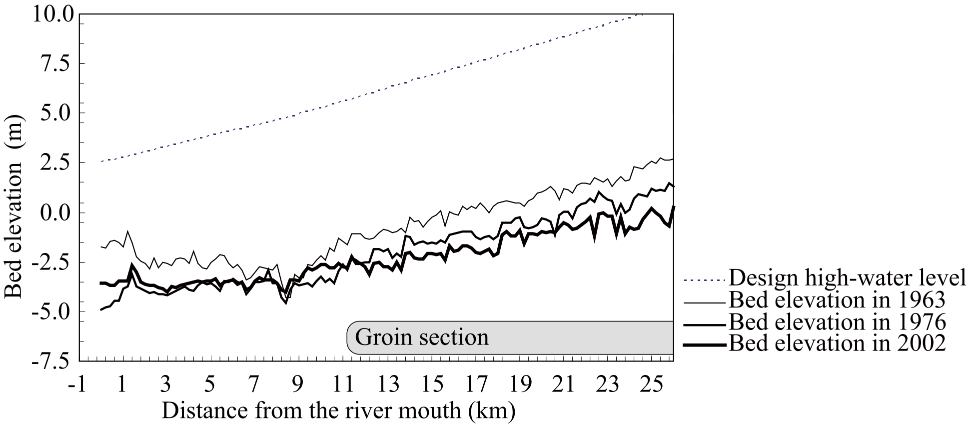


Figure 2: Historical changes in the longitudinal profile of the Kiso River.

previous works. For example, Kitamura et al. [1] categorized the embayed topography found in the downstream of the Kiso River from the view point of vegetation density and the shape of the embayment, and discussed the transition of the categorized topography. The river round table of the Japan Society of Civil Engineers discussed the morphological changes observed around the groins using a vertical two-dimensional numerical model [2]. The flow conditions and the mode of the sediment transport in the low-flow channel and in the groin section were examined in the following literatures [2, 3]. Tominaga et al. [4] and Nezu et al. [5] investigated the difference in sedimentation patterns relative to the angle of the groins to the direction of the main channel. However, the interactive mechanism of the sedimentation between the groins and the profile of the bed of the low-flow channel is not understood, and the flow structure around the small channels within the groin section is still unknown.

In this paper, the mechanisms of the formation and the maintenance of the embayment during the flood are discussed from the viewpoint of the fluid and sediment dynamics during the flood, using a numerical flow model.

2 STUDY AREA

Figure 2 shows the historical changes in the longitudinal bed elevation profiles of the channel in the study section from 1963 to 2002. In this area, the degradation is observed the entire region, and the reasons for this degradation consists of a ground sinkage due to overpumping in the surrounding area, a decrease in the supply of sediment from upstream due to the construction of the dams and the weirs, and the mining of bed material [2]. The first dam, constructed in the Kiso River system, is the Oh-i dam; it was constructed in 1924 for the purpose of electricity. The discontinuous structure of the river nearest to the study area is the Magai weir located in 26 km from the river mouth; it was constructed between 1970 and 1974.

A comparison of the degradation of the low-flow channel and the groins area, reported by Kitamura et al. [1], reveals that degradation had been occurred mainly in the low-flow channel, but the elevation of the groins area was almost maintained. This means that the elevation of the groins became relatively high in comparison to the elevation of the main channel, and this led to the formation of the embayment. Consequently, it can be said that the formation of the embayment between the groins was triggered mainly by the mining of the bed materials and the reduction in the supply of sediment from upstream.

Figure 3 shows a historical translation of bed topography regime plot of the main channel in the downstream of the Kiso River. The diagram was derived from the two-dimensional flow equations and the bed-load transport equation (Kuroki and Kishi [6]). This diagram has been used to verify the bed topography regimes of meso-scale structure of the bed topography, namely the alternate bar, the double-row bar and the no bars regimes, corresponds to the fundamental flow parameters. One-dimensional steady flow equations are solved to calculate the flow condition, such as cross-sectional averaged water depth H and velocity U, at each transect located at one kilo-meter intervals for longitudinal. For the in-flow boundary condition, discharge of 6000 m^3/s, order of the averaged annual maximum high water, is used. For out-flow boundary condition, constant water stage is imposed. In Figure 3, in the reach upstream of the Magai weir (section between 26 km to 40 km), the topography regime has been positioned in the double-row bar regime at 1963 and still located in almost same position at 2002. The plots of two reaches located in the downstream of the Magai weir, were located in the boundary between the alternate bar and the double-row bar regime. These positions had been shifted to the center of the alternate bar regime between the periods of 1967 to 2002.

In this section, the one-dimensional flow estimation is used to understand the historical changes in the topography around the groin section. In the following section, a horizontal two-dimensional flow model is used to investigate the flow structure around the groins, and the formation mechanism of the characteristic topography around the groins is discussed.

3 FLOW STRUCTURE THROUGH THE GROIN SECTION DURING A FLOOD EVENT

3.1 Numerical model

A numerical model is used to solve the shallow water equations discretized with the finite difference method and an unstructured triangular grid system [7]. The fundamental equations used here are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y} = 0, \tag{1}$$

$$\frac{\partial uh}{\partial t}+\frac{\partial u^2h}{\partial x}+\frac{\partial uvh}{\partial y}+\frac{g}{2}\frac{\partial h^2}{\partial x}-gh\frac{\tau_{sx}-\tau_{bx}}{\rho}-h\frac{F_x}{\rho} = -\frac{\partial h\overline{u'^2}}{\partial x}-\frac{\partial h\overline{u'v'}}{\partial y}, \tag{2}$$

$$\frac{\partial vh}{\partial t}+\frac{\partial uvh}{\partial x}+\frac{\partial v^2h}{\partial y}+\frac{g}{2}\frac{\partial h^2}{\partial y}-gh\frac{\tau_{sy}-\tau_{by}}{\rho}-h\frac{F_y}{\rho} = -\frac{\partial h\overline{u'v'}}{\partial x}-\frac{\partial h\overline{v'^2}}{\partial y}, \tag{3}$$

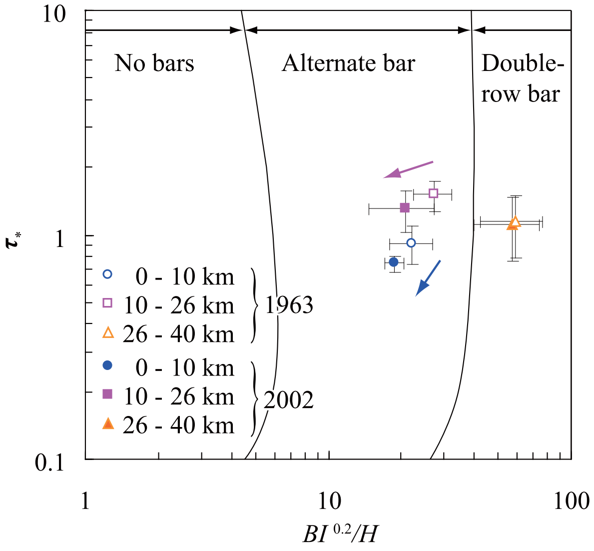


Figure 3: Historical change in bed topography regime plot (Kuroki and Kishi [6]) of the downstream area of the Kiso River. Error bars indicate standard deviation calculated from the values of transects at longitudinal intervals of one kilo-meter within the each reach. τ_* is the non-dimensional tractive force. B is the width of the channel. I is the bed slope. H is the water depth.

where h is the water depth, u and v are the horizontal velocity components, g is the acceleration due to gravity, τ_{bx} and τ_{by} are the gradient slopes, and τ_{sx} and τ_{sy} are the bed frictions, calculated using a Manning's roughness parameter n. The drag due to the vegetation is estimated as follows [8, 9];

$$F_x = \frac{C_d \rho \lambda_v \min(l,h) u \sqrt{u^2+v^2}}{2h}, \tag{4}$$

$$F_y = \frac{C_d \rho \lambda_v \min(l,h) v \sqrt{u^2+v^2}}{2h}, \tag{5}$$

where C_d is the drag coefficient, λ_v is the cover rate of vegetation, and l is the vegetation height. Horizontal Reynolds stress tensors, e.g., $-\overline{u'v'}$, are

$$-\overline{u'v'} = D_h \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right), \tag{6}$$

$$-\overline{u'^2} = D_h \left(2\frac{\partial u}{\partial x} \right) - \frac{2}{3}k, \tag{7}$$

$$-\overline{v'^2} = D_h \left(2\frac{\partial v}{\partial y} \right) - \frac{2}{3}k, \tag{8}$$

where D_h is estimated as $\alpha h u_*$ [10, 11]; k is the horizontal turbulence energy, α is a constant, and u_* is the bed friction velocity.

The numerical domain is as shown in Figure 4. Total number of triangles used for the grid is 35438. The size of triangles varies from 43 m^2 to 4300 m^2 (10 m and 100 m in the length per side, respectively). Small-sized triangles are used around the groins section, and large-sized triangles are used in the main channel. The calculation domain represents the topography

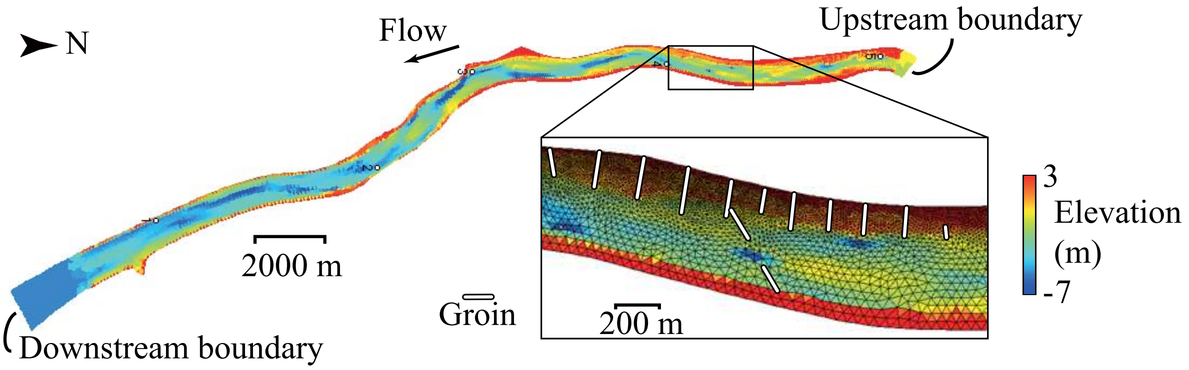


Figure 4: Computational domain and bathymetry.

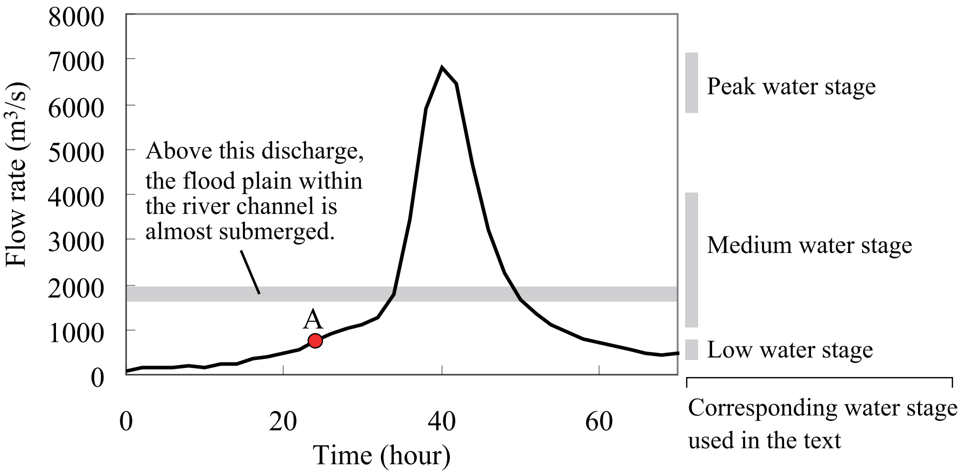


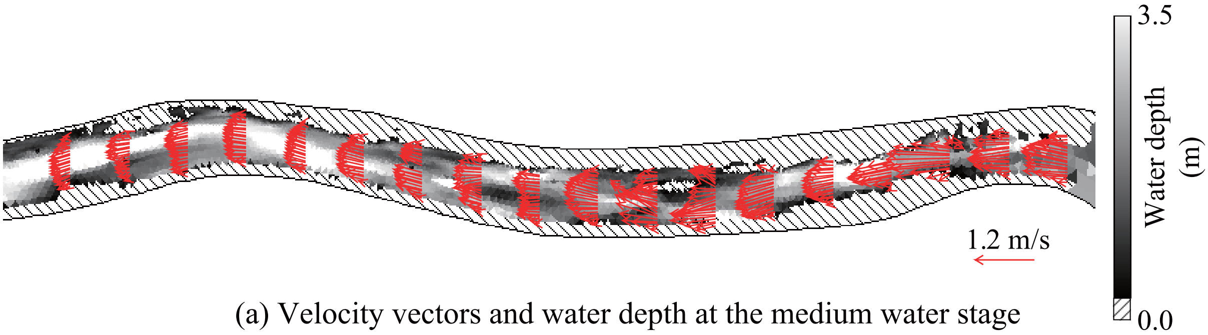
Figure 5: Hydrograph.

of the section of the Kiso River from 0 km to 25 km from the river mouth. The Manning's roughness parameter is set at $n = 0.02$ for the whole region [3]. The height distribution is based on the Airborne LiDAR (Light Detection and Ranging) data measured in 2007 for the ground surface above the water surface at the observation time, and the results of the latest cross-sectional surveying conducted in 2003 at longitudinal intervals of 200 m are used for the height distribution under the water surface. The cover rate of the vegetation, λ_v, is set at 0.025 m^{-1} [8], and the vegetation height is calculated by the LiDAR results.

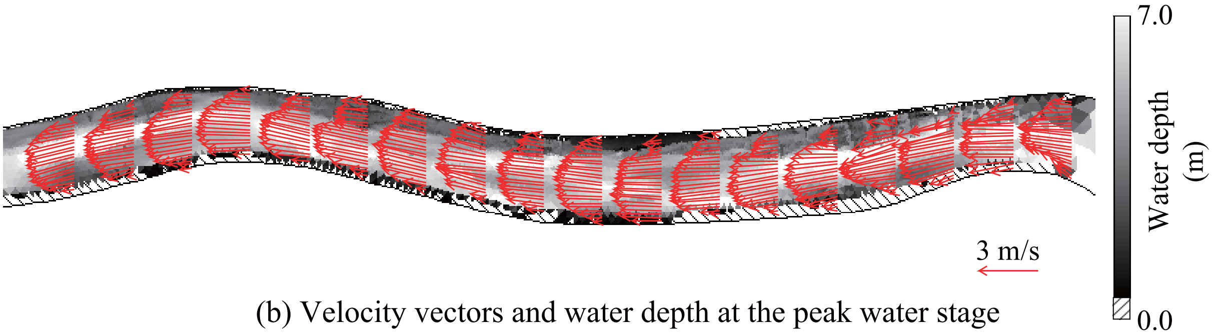
For the upstream boundary condition, the hydrograph shown in Figure 5 is used. The peak discharge of 6820 m^3/s was the average annual maximum discharge from 1976 to 2005. For the downstream boundary condition, a constant water depth, which was set as the mean tide level at the river mouth, is imposed.

3.2 Investigation of flood flow structure using fix-bed calculation

To investigate the flow structure in the main channel and in the groin section, a fix bed calculation is imprimented. Figure 6a shows the velocity distribution at the time instant A shown in Figure 5. In Figure 6a, the flow goes along the low-flow channel topography well, and meanders along the alternate bars in the low-flow channel. In Figure 6b, the velocity profile at the



(a) Velocity vectors and water depth at the medium water stage



(b) Velocity vectors and water depth at the peak water stage

Figure 6: Velocity distributions and the segmentation of the sediment movement types.

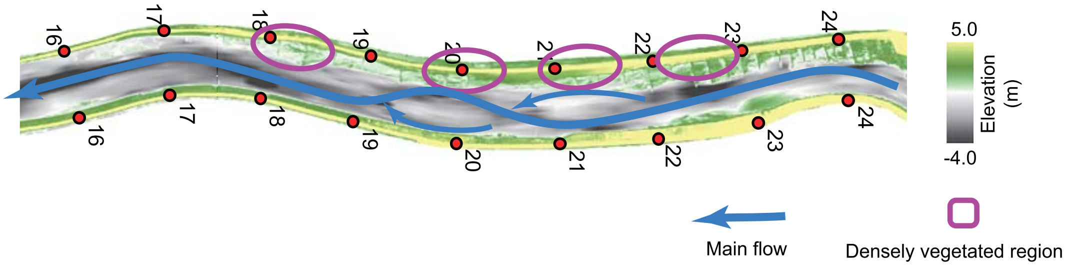
peak discharge period is shown. During this period, the flow structure follows the large-scale meandering of the river channel, and the bed-profile of the low-flow channel (bars) has little impact on the flow (c.f. Figure 6a.)

The interactions between the flow structure and the topography in the medium water stage, and in the peak water stage, are discussed using Figure 7. Figure 7a shows the location of the main stream and the vegetated regions in the initial and the decaying periods. The densely vegetated regions depicted with purple circles in the figure are adopted from the investigative work consisting of the aerial photographs reported by Kimura et al. [12]. In Figure 7a, it can be seen that the densely vegetated regions are located along the edge of the meandering profile of the low-flow channel, and that the interval between the densely vegetated regions corresponds to the wavelength of the meander of the low-flow channel.

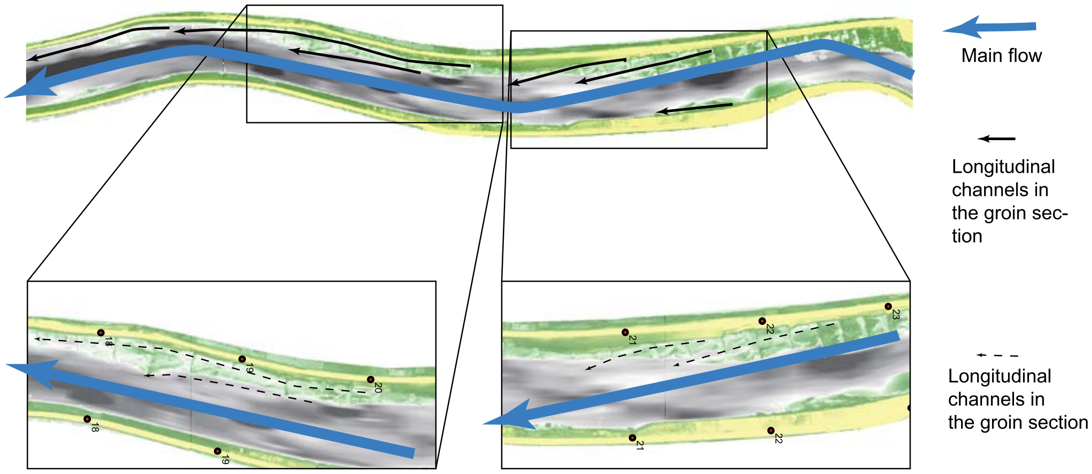
In Figure 7b, the flow structure during the peak discharge and the ribbed-shaped topography in the groin section are shown. It is seen that the small channels of the ribbed structure, indicated with black arrows in the figure, are parallel to the flow direction of the main stream during the peak discharge. This means that the formation of the ribbed topography is associated with the large-scale flow structure in the peak discharge period.

3.3 Estimation of topographical change using movable-bed calculation

In the section 3.2, a fix-bed calculation is carried out to understand fundamental flow condition and structure during the flood. In this section, the movable-bed calculation, modeling the bed-load transport of sediment, is implemented to investigate the morphological change of the topography around the groin section. The flux of bed-load transport is calculated using the Ashida and Michiue formula [13]. For upstream boundary conditions, a hydrograph shown in Figure 5 is used for flow condition and equilibrium sediment feeding (constant bed elevation)



(a) Flow structure in the medium water stage and densely vegetated regions



(b) Flow structure in the peak water stage and the location of the longitudinal channels

Figure 7: Relationship between the flow structures and the topographical characteristics in the groin section under different water stages. The red points with numbers indicated the distance from the river mouth in kilometers.

is used for sediment condition. For downstream boundary, a constant water surface elevation is imposed.

Figure 8 shows the topographical change after passing the model flood. The initial bed topography is as same of the bed using in the section 3.2. In Figure 8, a deformation of the river bed is observed mainly in the main channel. Periodical degradation and aggradation alternation are observed in the main channel, and this result indicates that the bars on the river bed migrates to the flow direction during the flood. In the groin section, the displacement of the bed elevation is quite small. This is because the shear stress for the bed is quite small due to the intense flow resistance from groins and vegetation.

The topographical change in the groin section is quite small, compared with that in the main channel. The channel model used in this section represents the detail of the topography and the vegetation arrangement. These detail also affect the topographical change so that it is difficult to identify the the fundamental structure of the formation of the topography of the groin section.

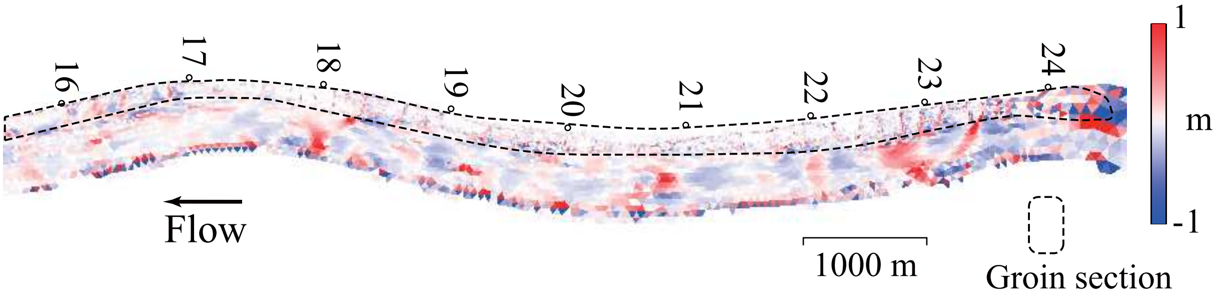


Figure 8: Displacemene of bed elevation after passing the model flood.

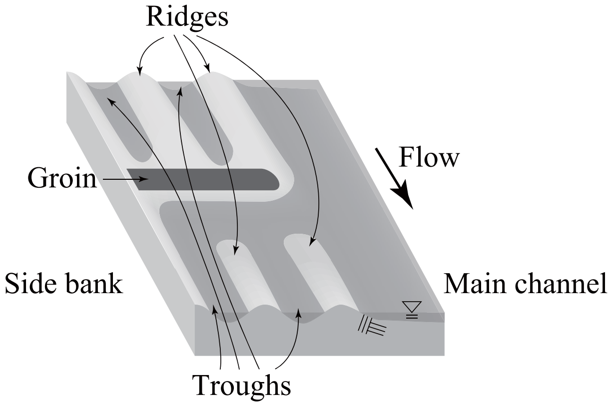


Figure 9: Scheme of the ribbed structure formed around a groin.

4 CONCLUSIONS

In this study, the flow structure during a flood, the modeling of a typical annual flood event, and the interaction between the flood flow and the topography around the groin section have been investigated. The results show that during the medium water stage of the flood, the flow meanders with following the low-flow channel topography (bars), and that the densely vegetated region in the groin section is associated with the flow structure during the medium water stage periods. From this insight, it is possible to predict the locations where sedimentation and vegetation expansion are likely to be active by investigating the low-flow channel topography. Then, in the peak discharge period, the flow shows a larger structure, following the meandering of the river course, and the small channels in the groin section is parallel to the flow pattern in the peak period. This means that the ribbed topography is formed during the peak discharge period.

From the result of the movable-bed calculation, it is found that the topography in the groin section is stable because the intense flow resistance due to dense vegetation reduces a velocity of the flow and the bed shear stress in the groin section , hence the topography of the embayment formed in the groin section is stable due to the flow regulation function, one of the ecological functions, provided by the riparian vegetation.

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