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Experimental Investigation of Flow in Embayment

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This study reports the results of flow visualization and velocity mea-
surements in embayment. Flow visualization was done using aluminum
powder as tracer and velocity measurements were carried out with elec-
tromagnetic velocitymeter. Visualized flow shows the formation of large
organized eddies at the embayment-main channel interface and the exis-
tence of primary recirculation, secondary recirculation and flow separa-
tion. Measured velocity reveals that the mean velocities vary little with
depth for low flow condition. Flow becomes more complex for flood flow
condition and then, depth averaging is meaningless.
Keywords: embayment, flow visualization, organized large eddy, recir-
culation, flow separation, mass transfer

1. Introduction

Natural riparian areas are usually rich in aquatic plants and wide variety of alignment and bed topography
exists. Such parts of the riparian area are source of nutrition and support wide variety of fauna and flora.

River improvement is essential for the purposes of flood control, drainage improvement, maintenance of
navigation and reduction or prevention of bank erosion. But if revetment works and utilization of flood
plain are done by conventional engineering methods [1], natural riparian areas tend to be lost. In order to
avoid monotonous artificial environment and to preserve high level of natural condition in riparian areas,
construction of embayments along the shore which are able to provide shelters, foods and nutrients for eco-
system is highly needed.

When there are embayments along a river bank, the water quality of the river depends on the mass
exchange between the embayments and the river. The net exchange of a specific property is affected by its
distribution both in the river and the embayments.

Prior to actual construction of man-made embayments, quantitative evaluations of sedimentation patterns
and distribution of specific properties in an embayment are essential. These require a sufficient knowledge of
the flow characteristics in the embayment and its entrance.

The flow in an embayment is complex because of separation, recirculation, complex eddy structures, high
turbulence intensities and forced oscillation for low flow condition. Evidently, the complexity increases for
flood flows. Due to the complexity of the flow in an embayment, detailed measurements have been rarely
reported in the literature. Booij [2] presented the measurements of horizontal velocity field and turbulence
energy in a scale model of a square harbour along a river. Tingsanchali & Chinanont [3] measured the
horizontal velocity in a channel side pool only at a few points. To the knowledge of the authors, measurement
of flow characteristics for flow past over embayment has not yet been reported.

The present paper describes the results of flow visualization for low flow condition and measurement of
horizontal velocity field for both low flow and flood flow cases. Flow visualization technique was used to
clarify the basic flow characteristics in embayment and its entrance. Velocity measurement was carried out
to provide reliable quantitative data on turbulent flows with complex geometry. Such information is essential
to test and develop mathematical models for flow predictions.

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2. Experimental Investigations

Experimental investigations consisted of two phases. Phase I was flow visualization using aluminum powder as tracer. Phase II was point velocity measurement with electromagnetic velocitymeter.

2.1 Flow Visualization - Experimental Apparatus and Procedure

Flow visualization was carried out in the hydraulic laboratory of the University of Tokyo. Boxes were placed in a tilting flume of 40.2 cm wide to form an embayment as shown in Fig. 1. The length of the flume is 20 m and the embayment was located at the middle length of the flume. The boxes and part of the flume bed were painted in black to minimize reflection. To take photograph of flow visualization, camera was mounted on a platform adjacent to the embayment so that it covered the whole embayment and part of the main channel.
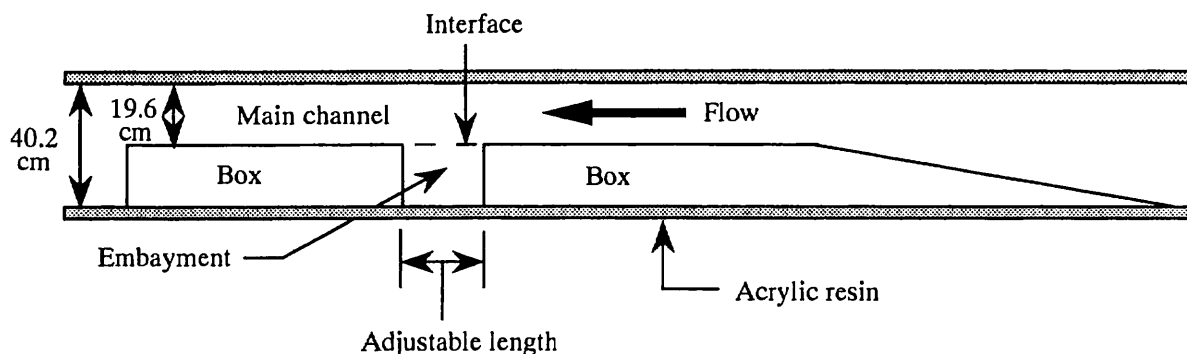

Fig. 1. Plan of the test section for flow visualization

Three experiments were conducted in case of flow visualization. The first experiment was done to observe the formation and movement of large eddies on water surface. The second and third experiments were performed to produce path lines of tracers with the purpose of demonstrating certain flow features which are not clear from the first experiment. In each experiment, steady state flow condition was confirmed before any measurement. The flow depth was controlled by a tail gate when required. Upstream to the embayment, the uniform flow depth in the main channel was measured at the center. The water depth in the embayment was measured at its center. The experimental conditions are listed in Table 1.

To capture eddy structure, aluminum powder was sprayed more or less uniformly on the water surface of the embayment. One 500W lamp was used as light source. Photographs were taken at 1/3 s interval for exposure time 1/60 s and 1/30 s.

Light Sheet Technique was used to achieve the goals of the second and third experiments. An arrangement was available in the laboratory to make a sheet of light from one 500W light source. The thickness of the sheet of light could be suitably changed. Solution of aluminum particles was prepared by adding small amount of liquid soap such that the particles could remain in suspension. For experiment no. 2, a sheet of light of 4 mm thickness was projected horizontally from transparent side wall of the embayment. The light sheet was located at 2 cm below the water surface level. Two slide projectors (150W each) were placed at the opposite wall of the flume to produce sheet of light at the same level in order to make the embayments corners, which were in the plane of embayment-channel interface, clearly visible in photographs. Solution of aluminum particles was added continuously through a nozzle on the water surface of the main channel at sufficient upstream of the embayment so as not to disturb the flow in the embayment. The discharging point was very close to the channel bank along which the embayment was located. Pictures were taken for

Table 1: Experimental conditions for flow visualization

Expt. no.	Embayment size, cm²	Bed slope	Water depth in channel, cm	Water depth in embayment, cm	Velocity in channel, cm/s	Reynolds number
1	20.6 × 20.6	1/1000	3.6	3.57	34	9000
2	20.0 × 20.6	1/5000	7.7	7.68	24	10300
3	20.0 × 20.6	1/5000	11.5	11.48	18	9500

different exposure time ranging from 1/30 s to 1/2 s . It was observed that the path lines of particles were clear on photographs only when the exposure time was long enough and number of particles was large. Thus, experiment no. 3 was performed using high concentration of aluminum particle. For this experiment, the thickness of sheet of light was 5 mm and was set at 5 cm below the water surface level and photographs were taken for exposure time 1/4 s, 1/2 s and 1 s.

2.2 Velocity Measurement - Experimental Apparatus and Procedure

Velocity measurement was conducted in a 100 cm wide tilting flume located at Oomiya campus of Shibaura Institute of Technology. The length of the flume is 25 m. The discharge and slope are easily adjustable. The flume is fitted with a weir tank at the upstream end. Rails are fixed along the flume for carriage in which point gauge and velocitymeter can be mounted. The carriage can be moved longitudinally and laterally to any desired position. Perforated plates, wire nets and wave suppressor are set in the flume to minimize the disturbances resulting from the weir discharge.
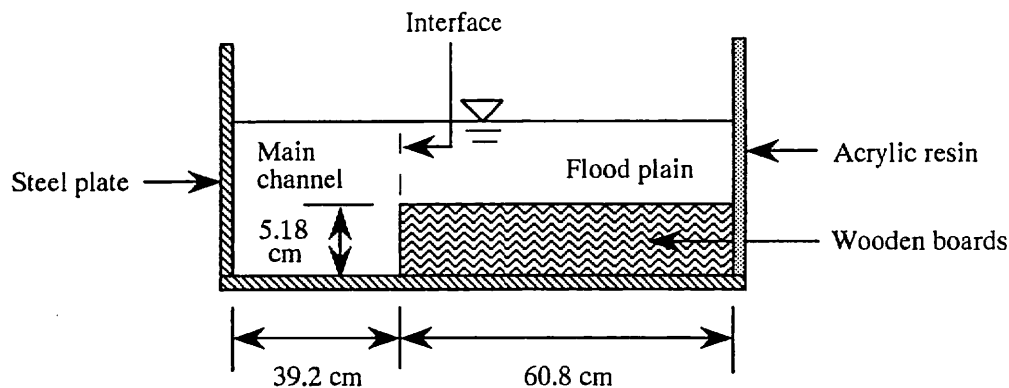

Fig. 2. Cross-section of the compound channel

Originally, the flume had rectangular cross section. But in natural rivers, embayments are located in flood plains. So, the flume was converted to a compound channel by placing wooden boards in part of the cross-section. The boards were glued to the flume bed and side wall. The resulting cross-section is shown in Fig. 2. An embayment of size 20 cm × 20 cm in plan and depth equal to the height of the flood plain was cut in the flood plain. The embayment was located at 9.5 m away from the upstream end of the flume. A perspective view of the experimental section of the flume is shown in Fig. 3.

Water depth was measured by point gauge and discharge was measured by V-notch fitted with the weir tank. Since the flow in an embayment is predominantly recirculating, two component electromagnetic velocitymeter was used for point velocity measurement. The probe is 5 mm in diameter and 1.8 cm in length.
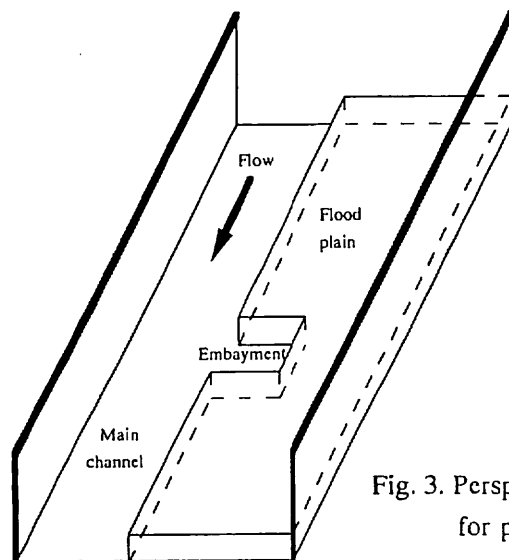

Fig. 3. Perspective view of the test section for point velocity measurements

Table 2: Experimental conditions for low flow depth velocity measurement

Bed slope	= 1/2000
Discharge	= 5.93 l/s
Average velocity in the main channel	= 32.28 cm/s
Flow depth in the main channel	= 4.69 cm
Water depth at the embayment center	= 4.63 cm
Reynolds number	= 12200

It is to be inserted vertically into water and gives the point velocity in two horizontal directions corresponding to the position 1 cm above the bottom of the probe. This type of velocitymeter has certain advantages over other types. Its response is linear, can work in dirty water, measure simultaneously the longitudinal and transverse velocity components, easy to calibrate and can measure very low velocity.

For velocity measurement, the electromagnetic velocitymeter was properly grounded and was connected to an A/D converter. The A/D board was then connected to a personal computer for automatic data acquisition.

Two experiments were run for velocity measurements. The first experiment was conducted for low flow condition while the second experiment was performed for flood flow. Measurement was started after establishment of steady state flow in the channel. The velocitymeter was calibrated before the measurement. The probe was oriented to give longitudinal and transverse velocity components. For low flow depth, uniform upstream flow depth in the main channel was measured at the channel center and water depth in the embayment was measured at its center. For flood flow case, uniform flow depths were measured at the center lines for both the main channel and the flood plain. The experimental conditions for low flow case are shown in Table 2 .

For low flow depth, velocity measurement was done at three different levels on the vertical of a measuring station. They were 30%, 50% and 80% of the water depth when measured from the bed level and the corresponding horizontal planes are termed as z_1, z_2 and z_3 planes respectively.

Table 3 shows the experimental conditions for flood flow case. Velocity was measured at five different levels on the vertical of a measuring station in the main channel or the embayment. They were 20%, 40% , 60% , 77% and 89% of the water depth in the main channel from the bed level. The corresponding horizontal planes are termed as z_1, z_2 , z_3, z_4 and z_5 planes respectively. In the flood plain, velocity was measured at two different levels, namely 40% and 70% of the flood plain flow depth when measured from the flood plain level. These two levels correspond to z_4 and z_5 planes respectively.

For low flow case, velocity measurement was continued for 600 samples for each measuring point. The sampling rate was 10 samples per second. For flood flow case, 300 samples were taken for each measuring point at the same frequency. Measuring stations were mainly concentrated in and around the embayment. Measurements were also taken at sections much upstream and downstream of the embayment. All the data were stored in floppy disks for later analysis.

3. Results and Discussion

3.1 Formation of large eddies and their movement

Photographs of experiment no. 1 of flow visualization reveals the mass exchange mechanism between the embayment and the channel. Figure 4 shows 3 consecutive pictures taken at 1/3 s interval for exposure time 1/60 s. A mixing layer is formed at the interface. For the flow direction shown in the figure, anti-clockwise rotating eddies of different sizes form continuously one after another just at the downstream of the origin of the

Table 3: Experimental conditions for flood flow velocity measurement

Bed slope	= 1/2000
Discharge	= 17.16 l/s
Average velocity in the compound main channel	= 32.87 cm/s
Flow depth in the main channel	= 8.37 cm
Flow depth in the flood plain	= 3.19 cm
Reynolds number	= 14700

mixing layer (Fig. 4(a)). The large eddies of them may develop into bigger size while advecting downstream and envelope surrounding smaller eddies - thus increasing the width of the mixing layer considerably. At the same time, the large eddies may breakdown into smaller eddies.

For the experimental conditions, fairly organized large eddies form irregularly at the interface. Fig. 4(c) clearly shows the existence of a large organized eddy on the water surface at the interface. Complete clipping of the large eddies are predominant. One part of the mixing layer goes directly into the channel. The remaining part impinges on the downstream cross wall with high velocity, generating high degree of turbulence. The striking mass then divides into two parts. One part leaves the embayment and joins the main flow while the remaining mass enters the embayment (Fig. 4). After entering the embayment, the large eddies move mainly parallel to the impinging wall and then parallel to the side wall. While convected, they are diffused and merging of two large eddies can occur (Fig. 4(b)).
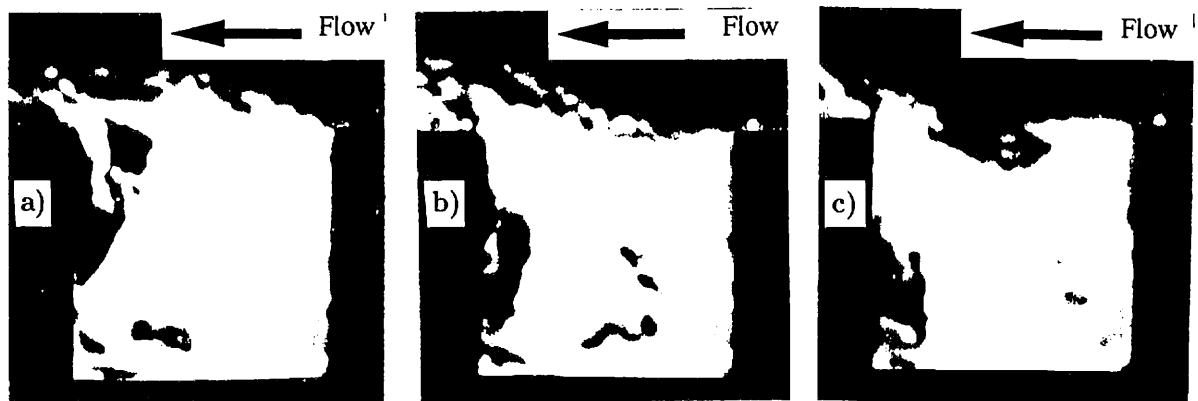

Fig. 4. Large eddies on water surface and mass exchange between
the channel and the embayment (f2.8, exposure 1/60 s).

3.2 Flow characteristics in embayment by flow visualization

The second and third experiments of flow visualization produced path lines of tracers. Figure 5 shows one photograph of path lines for 1/2 s exposure time of the second experiment. From the photographs of the third experiment, one picture having 1 s exposure time is presented in Fig. 6. When the exposure time is small, the path lines of tracers can be interpreted as instantaneous velocity in broad sense. Both figures show a large recirculation filling the whole embayment. It is noted that the center of the recirculation is not at the embayment center but is located at the downstream of the embayment center. This is contrary to the finding
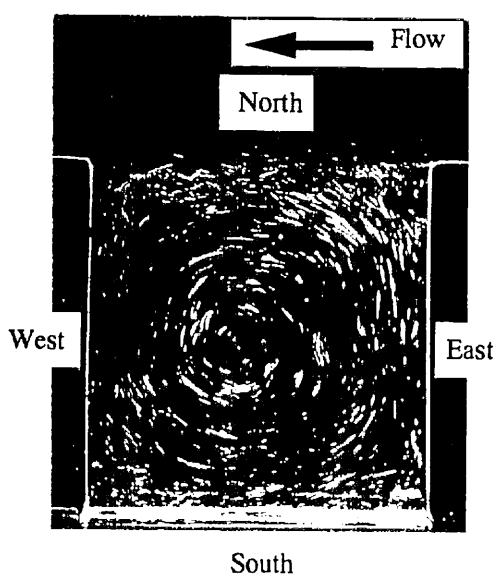

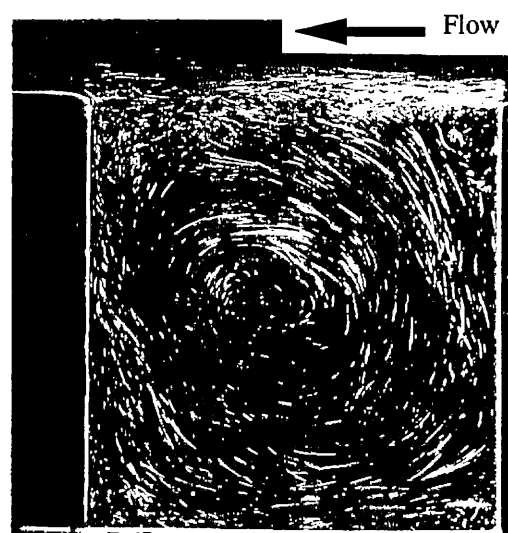Fig. 5. Path lines of tracers in experiment
no. 2 (f2.8, exposure 1/2 s).

Fig. 6. Path lines of tracers in experiment
no. 3 (f2.8, exposure 1 s).

of Tinsanchali & Chirananont [3] who found in their numerical calculation that the center of flow circulation is always upstream of embayment center and nearer to the channel. It is difficult to locate the exact position of recirculation center in the results presented by Booij [2]. Other photographs, not presented in this paper, give the impression that the recirculation center may not be fixed in position but is usually located downstream of the embayment center and closer to the channel. It is also found that the shape of the recirculation pattern may change continuously especially when the water depth is high.

In Fig. 5, the path lines adjacent to the middle part of the downstream cross wall are not clearly visible. The main reason of this is small concentration of tracer in an organized large eddy due to entrainment of tracerless water from the main flow. When the number of aluminum particles is small, sharp path lines are not obtained by the weak lighting system. The second probable reason is three dimensionality of large eddy. The thickness of the sheet of light was only 4 mm. So, it can be assumed that the movement of particles was not confined within that thickness.

When the path lines of Figs. 5 & 6 are judged carefully, very short path lines are found at the south-east and south-west corners of the embayment. These are secondary recirculation zones where velocity is very small. When the exposure time is very long, clear path lines can be found at those corners. Also at the north-east corner, a small region, where the path lines are very short, can be noticed. This is the evidence of flow separation which occurs due to abrupt change in flow geometry.

3.3 Velocity field in the embayment for low flow depth

All the data for low water depth are analyzed for mean longitudinal and transverse velocity components. From the analysis, point velocities at z_1, z_2 and z_3 planes are obtained. It is observed that the mean point velocities vary a little from plane to plane for most part of the embayment and the main channel i.e., the flow is nearly two dimensional. So, only the point velocities in z_3 plane are reported in Fig. 7. It is seen that a recirculation is developed in the embayment, filling it completely. The velocity at the embayment center is not zero which means that the recirculation center and the embayment center are not at the same position. The recirculation center is located at the downstream of the embayment center and nearer to the main channel. This is identical to the observation in flow visualization. Flow separation and secondary recirculation are absent in Fig. 7 , because the size of the measuring probe is too large to capture them.

If we notice the velocity vectors at the embayment-channel interface, we can see that the transverse velocity component has small magnitude throughout the length of the interface and has the same direction. Figures 8 and 9 show the transverse turbulence intensity and the average Reynolds stress respectively along the interface in z_3 plane. We see that both the turbulence intensity and the Reynolds stress have high values which are due to the generation of large eddies at the interface. So, we can conclude that the exchange of mass through the interface is greatly caused by large eddies and can not be explained as the action of only depth averaged mean transverse velocity component. At this point, it is appropriate to mention that the treatment of mass transfer through the interface by Christensen [4] considering only the mean transverse velocity component and assuming its linear variation along the interface with magnitude zero at the center and with reverse direction in the upstream and downstream of the center may not be fully correct.
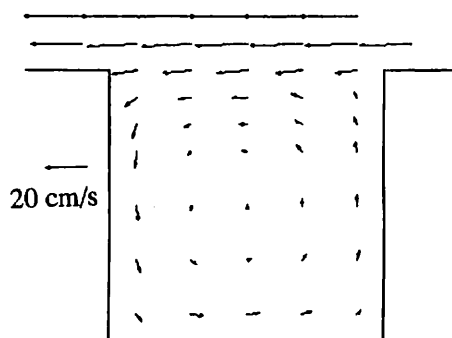
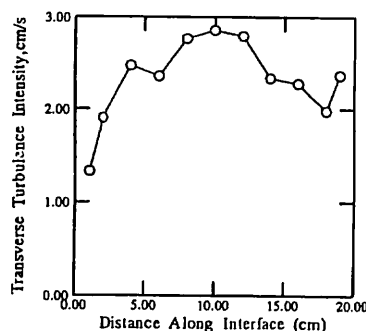Fig. 7. Velocity field in z_3 plane for low flow condition.

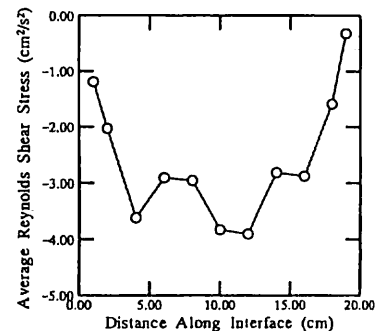Fig. 8. Transverse turbulent intensity in z_3 plane along the interface.

Fig. 9. Average Reynolds shear stress in z_3 plane along the interface.

3.4 Velocity field in the embayment for flood flow case

By analysis of the data of flood flow case, mean point velocities are obtained at five different horizontal planes. It is seen that the flow behaviour in z_4 and z_5 planes are quite similar and the flow pattern in other planes are different from one another. So, the velocity vectors in z_1, z_2 , z_3 and z_5 planes are presented in Figs. 10, 11, 12 & 13 respectively. From these figures, it is clear that the flow in the embayment is very complex. The complexity arises from the fact that the resulting velocity field is the superposition of two recirculating flows - one is horizontal recirculation similar to low flow depth case and the other is vertical recirculation as seen in case of backward facing step flow (The upstream cross wall of the embayment acts as a backward facing step in case of flood flow). The complexity is further increased by the presence of the forward facing step (the downstream wall of the embayment) due to which the backward facing step flow can not fully develop, flood plain-main channel interaction and flood plain-embayment interaction.
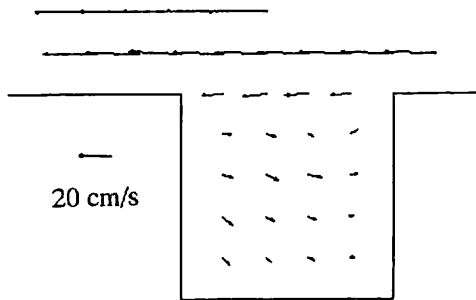

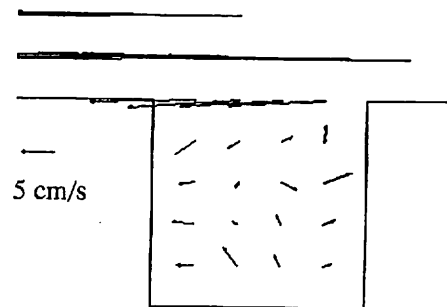Fig. 10. Velocity field in z_1 plane for flood flow condition.

Fig. 11. Velocity field in z_2 plane for flood flow condition.

The flow structures in the embayment mainly depend on the relative strength of the two recirculating flows as mentioned earlier. For this experiment, the vertical recirculation is dominant over the horizontal recirculation. So, all the velocity vectors in the plane close to the bed of the embayment (Fig. 10) are nearly in the opposite direction as compared to the main flow direction. Fig. 11 shows the most complex pattern and suggests the existence of vertical motion. The velocitymeter employed can not measure the vertical velocity component. The horizontal recirculation has little effect on the velocity distribution in z_3 plane (Fig. 12). In this plane, the velocities are predominantly in the main flow direction and the magnitudes are quite high. The velocities in z_2 plane are very small, because the plane lies in the transition zone where the longitudinal velocity component changes its direction from positive to negative or vice versa. Figure 13 shows that the mean velocities above the flood plain are affected very little by the presence of the embayment and the velocity vectors are more or less parallel to the main flow direction.
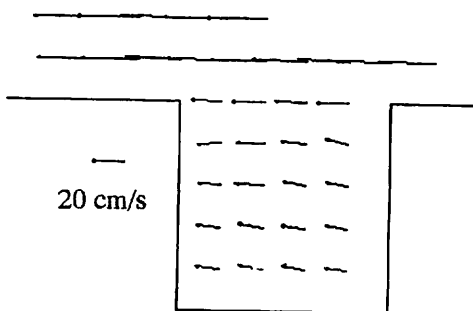

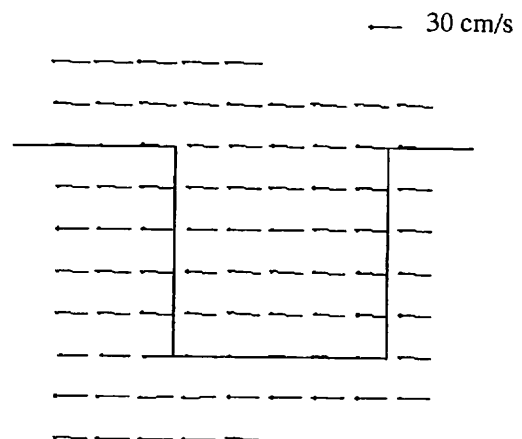Fig. 12. Velocity field in z_3 plane for flood flow condition.

Fig. 13. Velocity field in z_5 plane for flood flow condition.

4. Summary and Conclusions

In this study, flow visualization and velocity measurement were carried out to identify the basic flow features in embayment. Based on the results of the experiments, following conclusions can be made:

(1) Large organized eddies develop at the embayment-channel interface for low flow condition. These eddies are largely responsible for mass exchange through the interface.

(2) Low flow case shows the existence of primary recirculation, secondary recirculation and flow separation. The primary recirculation center is downstream of the embayment center and nearer to the channel.

(3) For low flow condition, the mean flow is nearly two dimensional over a large portion of the embayment when the water depth is small and depth averaged calculation is justifiable.

(4) When the embayment is overflowed, the flow in the embayment becomes very complex and depth averaged calculation has no meaning.

(5) For flood flow case, the flow is more complex below the flood plain level and the embayment has very little influence on the mean point velocities above the flood plain.

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