FLOOD FLOW CHARACTERISTICS IN NON-VEGETATED MEANDERING CHANNEL: A FLUME SIMULATION

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Global warming has been a major crisis discussed in many forums all over the world. Flood as one of its related effects is a frequent event occurs in the continents of Asia, Europe, America and Australia. The recent floods in countries like Thailand, China, Japan, Australia and the states of Perak, Johor, Pahang, Kelantan, Sabah and Sarawak in Malaysia have damaged the buildings, infrastructures and crops. Floods also created social problems to the affected population. Once the flow exceeds the river bank, a compound channel is formed. A lot of researches on compound meandering channels hydraulics have been carried out for many years. The hydraulics of flow in meandering channels is more complex than in straight channels. The behaviour of overbank flows in a non-vegetated meandering channel has been investigated using a physical model in the laboratory. The experimental study is focussed on stage-discharge relationship, flow resistance, stream-wise velocity and secondary flow. This paper discusses the hydraulics of shallow and deep flood flow inundations in a non-mobile bed meandering channel.

Keywords: meandering channel, overbank flow, flow resistance, stream-wise velocity, secondary flow

Introduction

Overbank flow is much related to the flooding event. According to the International Disaster Database from research on the epidemiology of disaster statistics in Malaysia between 1980 and 2010, floods took higher percentage in which 85.4% of people were affected by disaster followed by storm and epidemic of about 7.5% and 5%, respectively (*www.preventionweb.net/english/countries/statistics).*

Rivers can be classified as straight, meandering and braiding (Leopold and Wolman, 1957). Meandering is the most common planform acquired by natural rivers hence meandering rivers have received a lot of attention by many researchers (Shiono and Muto, 1998; Shiono *et al*., 1999; da Silva *et al*., 2006). A compound channel consists of a main channel and one or two floodplains. It is one the interesting subjects being studied in the field of hydraulic engineering. Nezu (2005) listed that the effects of complex geometry including curved and meandering channels on open channel turbulence as required research prospects in the 21st century. Field work is difficult partly because compound geometries typically occur under flood conditions when data acquisition is difficult and sometimes dangerous (Myers *et al*., 1999).

An experimental research has been conducted to study the flood flow characteristics in a non-vegetated non-mobile bed meandering channel in the Hydraulics Laboratory, Universiti Teknologi Malaysia (UTM). This research is aimed to enhance knowledge on the non-vegetated meandering river hydraulics during flooding. The main objective of the laboratory study is to investigate the flow characteristics including stage-discharge, flow resistance, stream-wise velocity and secondary flow pattern and bed shear stress in the channel. This study is concentrated on the shallow and deep flood flow conditions.

Experimental Research

The experimental research is carried out in a non-vegetated meandering channel constructed in a 12 m long and 3 m wide flume in the Hydraulics Laboratory, UTM. It consists of main channel and two floodplains on each side (Figure 1). A 0.5 m wide meandering channel with sinuosity of 1.54 is constructed in the flume. The channel wave length and meander belt width are 3.4 m and 2.2 m, respectively. The geometrical parameters are main channel width, B_{mc} = 0.5 m and depth, H_{mc} = 0.09 m. The channel is made of rigid boundary type of cross section. The flume bed is set at a gradient of 1/1000. The bed of main channel is filled with uniform graded sand layer and lined with cement to form a non-mobile bed (fixed boundary) channel.

The re-circulating water system in the laboratory supplies the water from a sump to the channel using a centrifugal pump. The flow rate or discharge is measured by a Portaflo 330 flow meter. A digital water surface profiler or point gauge is used to measure flow depth along the main channel. The water depth is controlled by tailgates located at downstream. Measurements are carried out once the water surface slope and bed slope are almost equal to each other. This flow condition is known as “quasi-uniform” (Sun and Shiono, 2009; Ismail, *et al*., 2009).

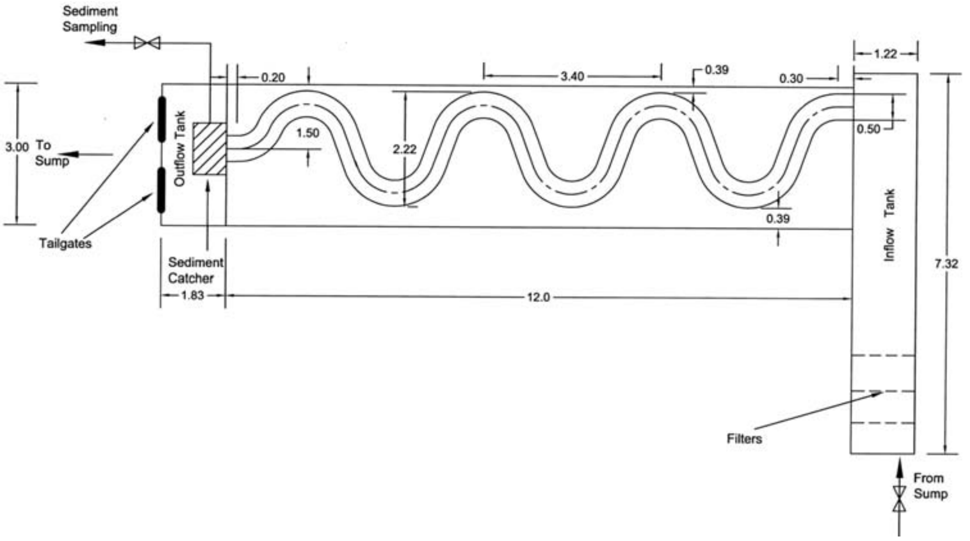


Figure 1: Plan view of meandering compound channel

The 3-dimensional velocity is measured using Nortek Vectrino$^+$ Acoustic Doppler Velocimeter (ADV) with a sampling rate of 100 Hz. Each point velocity is measured at least for 60 s. The equipment is placed on a mobile carriageway for data collection along the flume. Principally, the ADV measures the 3D velocities (U, V, W) of water particles located 5 cm below its probe.

The measurement sections are located 7 m downstream of channel inlet with a longitudinal distance of half wave length, namely sections S1, S4, S8, S12 and S15. Figure 2 shows the location of measurement sections in the channel. The sections S1 and S15 are the upstream and downstream apices and S8 is the crossover section. Meanwhile, S4 and S12 are the transition sections. The velocities are measured every 2 cm in transverse direction at several vertical layers.

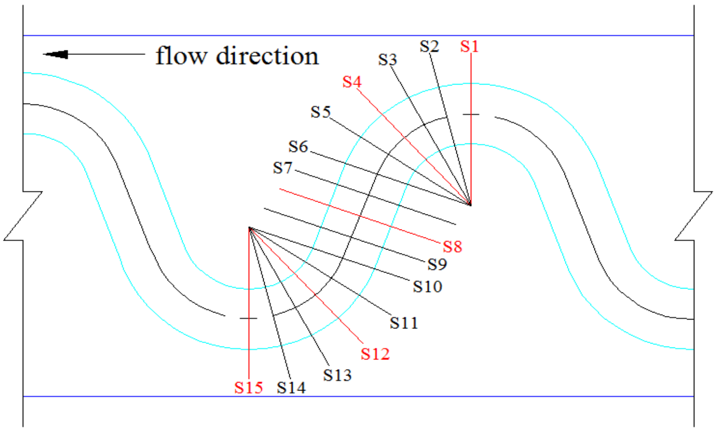


Figure 2: Layout plan of data measurement sections

Results and Discussions

Stage-discharge

The flooding flow velocities are measured at relative depths (DR) of 0.30 (shallow) and 0.45 (deep). The relative depth, DR is calculated as:

$$DR = \frac{(H - H_{mc})}{H} \qquad (1)$$

in which H is total flow depth and H_{mc} is the floodplain height (or depth of main channel). Using maximum velocities recorded at apices sections gives the experimental Reynolds numbers greater than 18,000. Meanwhile, the Froude number ranges from 0.10 to 0.36. This indicates that turbulent subcritical flows take place in this study.

Figures 3a and 3b show the stage-discharge and DR-discharge relationships. The inbank, bankfull and overbank flow conditions are clearly labelled. When the flow depth exceeds 90 mm, the overbank takes place in the meandering channel. The measured discharge to initiate overbank flow in the channel is about 17 L/s.

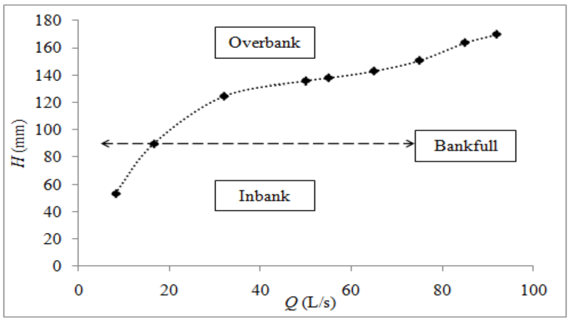


Figure 3a: The stage-discharge relationship

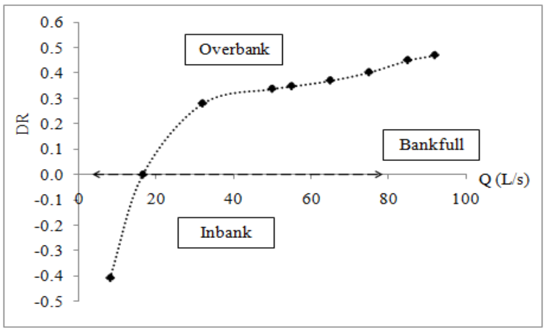


Figure 3b: The relative depth and discharge relationship

Manning's n

The Manning's roughness coefficients are calculated based on the stage-discharge data. The Manning's equation is applied to determine the Manning's *n* of compound meandering channel which is:

$$n = \frac{A\,R^{2/3}\,\sqrt{S_o}}{Q} \qquad (2)$$

For the non-vegetated meandering channel, the roughness value represents the resistance due to the surface of the channel. The finding shows the Manning's *n* increases with the flow depth, discharge and also relative depth, DR (Figures 4a and 4b). The n values for inbank and bankfull flows are lower compared to values for overbank flows. Manning's n value increases from 0.012 (inbank) to 0.013 (bankfull). Then, Manning's n value increases as overbank flow occurs in the channel. The roughness coefficient increases to 0.188 and it is almost uniform for overbank cases. This means that the main channel and floodplain boundaries increase the resistance to the water flow during flooding. In the case of overbank flow, Manning's *n* varies and becomes constant as flow depth, discharge and DR reach 0.14 m, 0.065 m^3/s and 0.40, respectively. It is common to think that the channel having a single value of *n* for all occasions. In reality, the value of *n* is highly variable and depends on a number of factors including surface roughness, vegetation, channel alignment and channel irregularity (Chow, 1959).

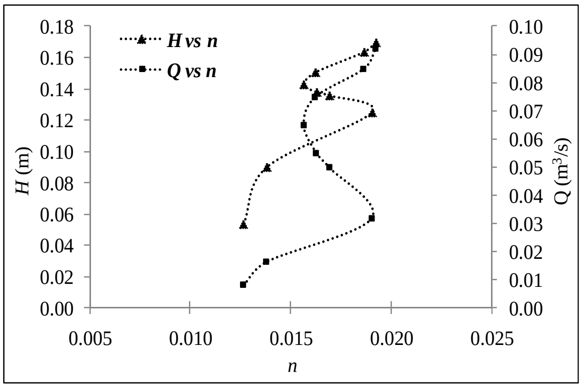


Figure 4a: Water Depth, *H* and Discharge, *Q* against Manning's *n*

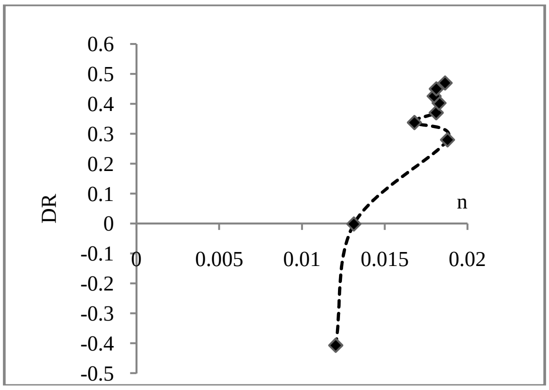


Figure 4b: Relative Depth, *DR* against Manning's *n*

Streamwise velocity distribution

In order to understand the flow characteristics in a meandering channel, velocity measurements are performed across sections S1 to S15. The 3D (streamwise, transverse and vertical) velocities are measured using the ADV. The method of point velocity measurement has been discussed earlier. The time-averaged velocities are used to plot the spatial distribution across each section. The temporal-averaged velocity components are analysed and plotted using ExploreV and Tecplot 360 softwares.

Figures 5a and 5b display the streamwise velocity distributions for sections S1 to S15 for DR = 0.30 and DR = 0.45, respectively. The plots are visualised from upstream. At Section S1 (upstream apex), maximum velocity cell presents close to inner bend (left). The phenomenon of "velocity dip" in which maximum velocity occurs below water surface does happen in the main channel. This phenomenon occurs in narrow channels, where aspect ratio, B/H is less than 5. Therefore, the flow is classified as 3D (Nezu, 2005; Rodriguez and Garcia, 2008; Kironoto and Graf, 1994). As the water flows downstream, the maximum velocity cell shifts toward another inner bend at S15. This is due to the centrifugal force effect at the channel bend. Prandtl's first kind secondary currents are produced by centrifugal forces. Meanwhile, Prandtl's second kind is turbulence-driven secondary currents (Nezu, 2005; Rodriguez and Garcia, 2008). The distribution of stream-wise velocity, U in the compound channel exhibits the transfer of momentum between main channel and floodplains. In general, the velocity in main channel and floodplains for DR = 0.45 is higher than DR = 0.30 case. It is noticed that the magnitude of U decreases toward downstream direction due to the resistance of channel and floodplains. Knowledge on velocity distribution in a channel also helps to determine the energy expenditure, bed shear stress distribution, and the associated heat and mass transport problems (Patra *et. al.*, 2004).

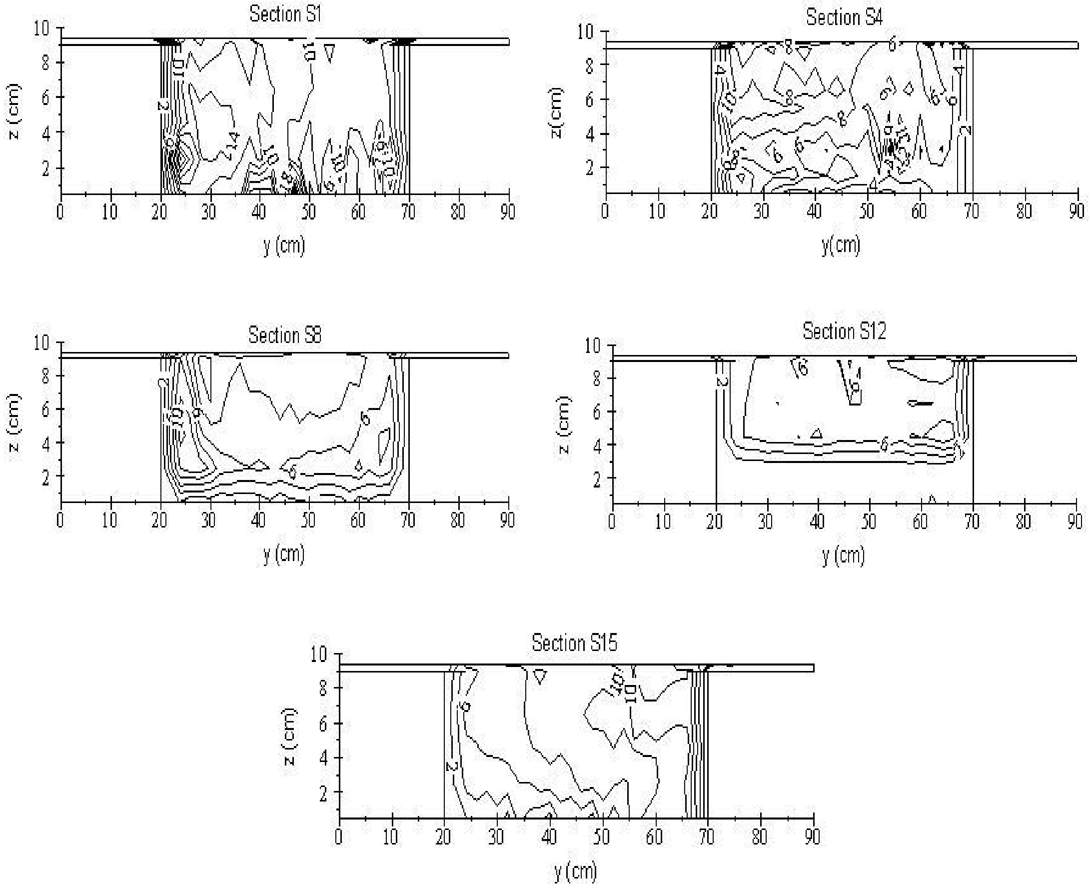
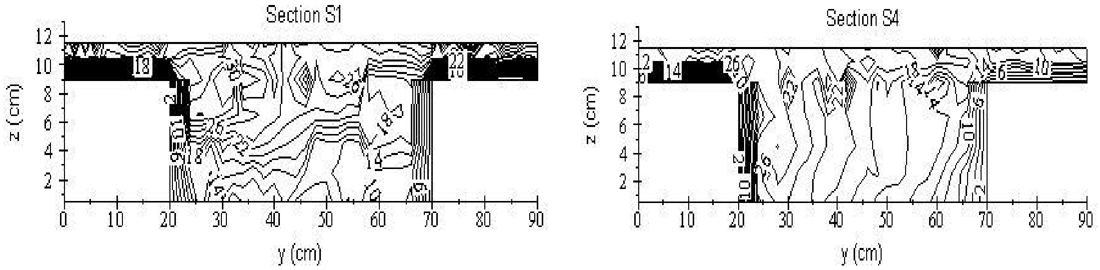


Figure 5a: Streamwise velocity, U at sections S1, S4, S8, S12 and S15 for DR = 0.30



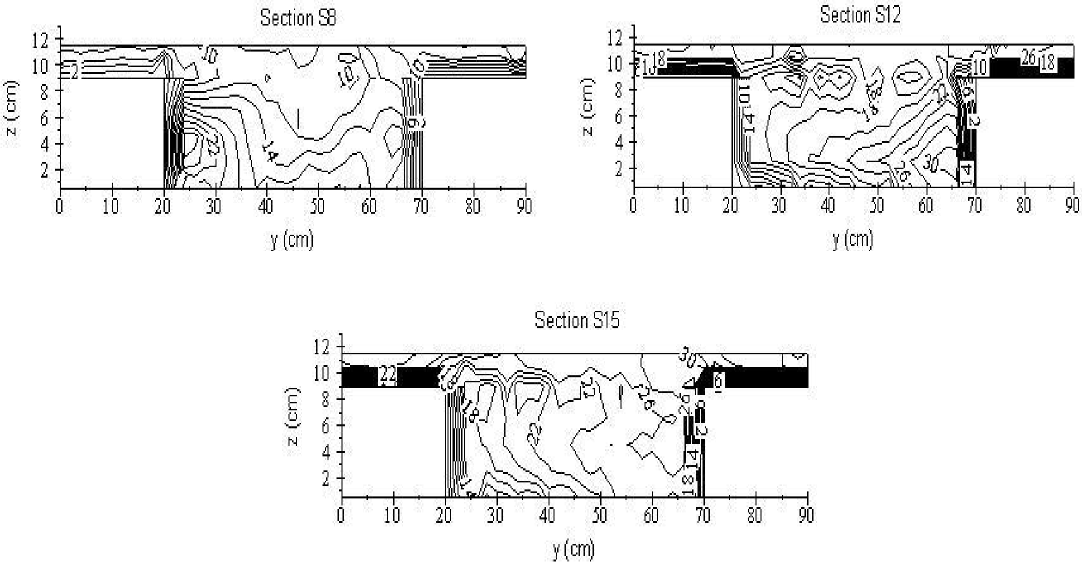


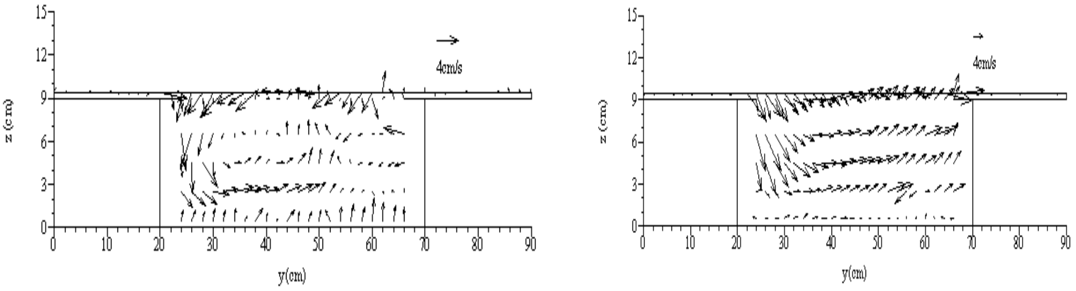
Figure 5b: Streamwise velocity, U at sections S1, S4, S8, S12 and S15 for DR = 0.45

Secondary flow

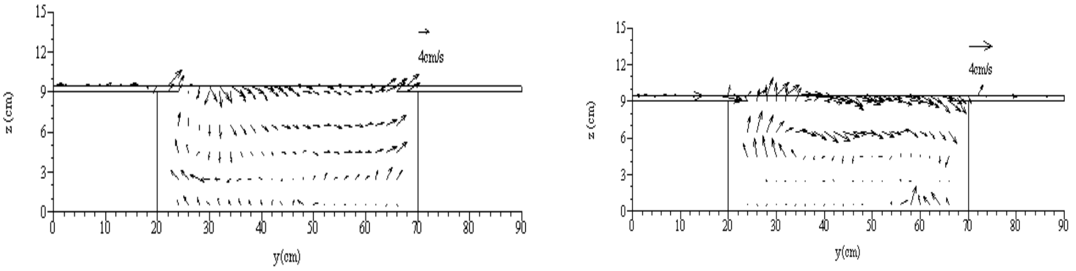
Narrow channels present strong secondary circulation patterns which resulted “velocity dip” in the channel (Chow, 1959; Rodriguez and Garcia, 2008). This horizontal secondary flow is also known as “stream-wise vorticity” (Tang and Knight, 2009; Sanjou and Nezu, 2009; Tominaga and Nezu, 1991). These secondary currents play important roles in erosion and sedimentation processes in natural rivers. To further understand the interaction between floodplain and main channel flows, secondary flow or circulation patterns are plotted. The secondary flow is generated by turbulence and centrifugal force in the channel. The circulation vector is the resultant of transverse (V) and vertical (W) velocity components.

Figures 6a and 6b illustrate the secondary current patterns at the measured sections for shallow and deep flow flows. In Figure 6a, the circulation pattern at section S1 does not clearly show the interaction between main channel and floodplain flows due to low overbank flow depth. The internal circulation is in counter clockwise direction. The flow from left floodplain enters the main channel, as visible in top layers of sections S4 to S12. In contrast, the flow direction changes at section S15 where flow from right floodplain enters the main channel. This result is similar to Shiono *et al.* (2008) for a non-mobile bed meandering channel. The secondary flow is generated by turbulence and centrifugal force in the channel.

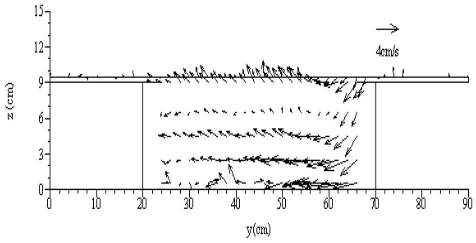
For DR = 0.45 flood case (Figure 6b), stronger circulation currents take place between floodplains and main channel especially in top flow layers at sections S4, S8 and S12. This clearly shows the plunging of floodplain flow into main channel and expulsion of main channel flow into floodplain, mentioned as flood mechanism in Willetts and Hardwick (1993). The internal circulation in counter clockwise direction presents at the upstream apex section S1. Meanwhile the internal circulation in opposite direction is observed at downstream apex section S15. Again, this is due to the centrifugal force effect at the channel bend which is known as Prandtl’s first kind secondary currents.



Section S1 Section S4

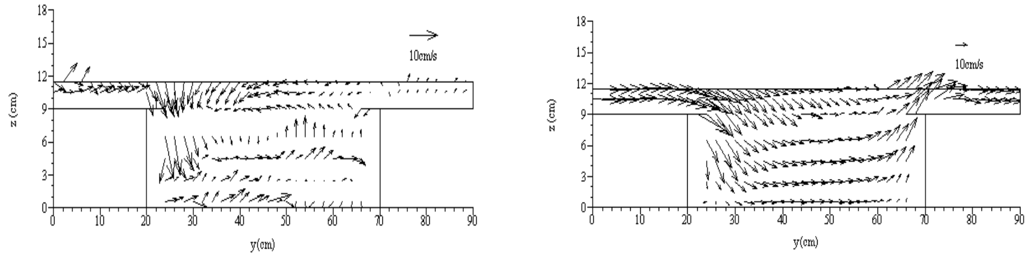


Section S8 Section S12

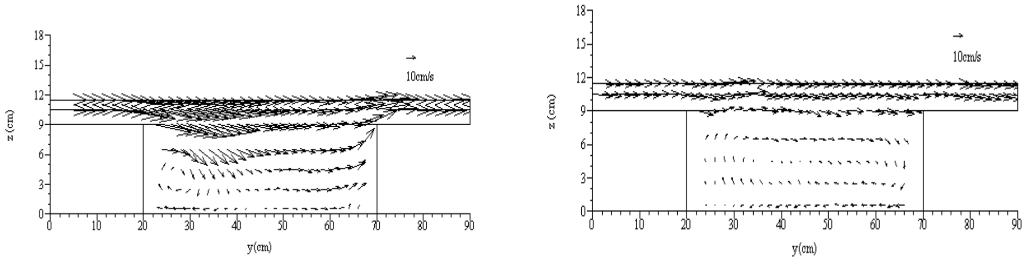


Section S15

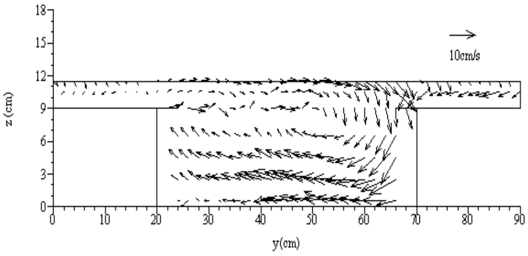
Figure 6a: Secondary flow pattern at sections S1, S4, S8, S12 and S15 for DR = 0.30



Section S1 Section S4



Section S8 Section S12



Section 15

Figure 6b: Secondary flow pattern at sections S1, S4, S8, S12 and S15 for DR = 0.45

Conclusions

The hydraulics of a non-vegetated meandering channel for shallow and deep overbank flows have been studied in the laboratory. The study is focussed on stage-discharge relationship, flow resistance, velocity distribution and secondary flow. The findings of the study are: (i) flow depth (H or DR) in the main channel and physical properties of channel influence the flow resistance, (ii) 3D flow takes place in the main channel due to its low aspect ratio, (iii) greater momentum transfer takes place between floodplain and main channel flows during high flooding, and (iv) the generation of secondary flows is stronger during high flood due to centrifugal force and turbulence in main channel.

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