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Depth-averaged modelling of vegetated meandering compound channel

Depth-averaged modelling of vegetated meandering compound channel

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Abstract. Advances of computing capabilities have increased the interest of using computational fluid dynamics to simulate more complex flow structures in open channel. A two-dimensional model, Telemac-2D was used to simulate flows with the presence of vegetation on the floodplain along the main channel inside a meandering compound channel. The simulation was done for two different relative depth for both non- and vegetated floodplain cases. The measured and simulated depth-averaged velocities were compared at the bend apex cross-section of the meandering compound channel for validation. Vegetation reduced the magnitude of the overbank flows and directed most of the overbank into the direction of the main channel. The effects of the vegetation on the overbank flows are more significant at low relative depth. The model shows good simulating capabilities of the depth-averaged velocities for the vegetated meandering compound channel and the numerical results also capable to generally capture the complex interaction between the overbank and inbank flows due to the presence of vegetation.

1. Introduction

An alternating green flood control engineering approach of using two-stage meandering channels are considered in this paper. Flow behaviours and mechanisms in meandering compound channels are complex and highly turbulent. Presences of vegetation on the floodplains inside the meandering compound channel increase the complexity of the hydraulic properties. Modelling these complex flows physically required large sums of money and very time-consuming, resources that most researchers and river engineers not available for. This raises the need for the flows to be modelled computationally for a better understanding and cost-effective method in studying the nature of the compound channel.

Research on meandering compound channel have been continuous further for a better understanding of their complex flows behaviours. These research fields have taken a big leap with the capabilities of this complex flows to be model computationally with the advanced of numerical modelling. The accuracy of the simulations depends on the governing equations, the numerical schemes and their solvers. A two-dimensional model gives the transverse distribution of water depth and primary flow velocity inside the model domain.

Bates et. al. [1] have used TELEMAC-2D to simulate overbank flows of a natural river and gives satisfactory numerical results. Works by Rameshwaran and Shiono [2], Rameshwaran and Naden [3] and many others have shown the capabilities of this two-dimensional model to simulate the flows inside meandering compound channels. Simulation of the depth-averaged model for flows inside open channel with or without vegetation by Spooner and Shiono [4], Langendoen et. al. [5], Zhou et. al. [6], Patra [7], Stoesser et. al. [8] and Xie et. al. [9] also makes use of the computational fluid dynamics model.

TELEMAC-2D is a finite element model that solved the depth-averaged continuity and Navier-Stokes equations or also known as Shallow Water Equations or Saint-Venant equations to gives the values of water depth and velocities. This model is an open source model that was developed at Laboratoire National d'Hydraulique, Electricite de France [10]. It used unstructured triangular mesh to solve for the variables inside the domain. A pre-processor tools known as MATISSE was used to generate the mesh used in the computation.

Investigation the effect of vegetation inside compound has becomes important and come to light nowadays. Thus, increase the needs for a better understanding of the flows behaviours with their presence inside this compound channel. Jumain et. al. [11] and Ibrahim [12,13] used the same arrangements of vegetation for straight compound channel and meandering compound channel for the latter in their physical experiments. Ismail and Shiono [14], Sun and Shiono [15] and Jahra et. al. [16] were among researchers that focused on experimental studies of overbank flows in meandering compound channel.

Sun et al. [17] have used TELEMAC-2D as the numerical model to simulate the effect of vegetation inside a natural meandering compound channel. Langendoen et al. [5] simulate meander channel with different sinuosity using this numerical model. These researchers continue the works of Ismail [18] where geometry blocks were placed along the meander main channel for different overbank flows.

The use of an existing two-dimensional finite element numerical model, TELEMAC-2D were considered here to simulate different depth of overbank flows inside the meandering compound channel with vegetation on the floodplains. This paper will assess the capability of the two-dimensional model in reproducing the depth-averaged velocities inside the vegetated meandering compound channel. The two-dimensional results were expected to give first insight and understanding to the behaviour of the complex flows before the needs of a more complex model were considered.

2. Methodology

The two-stage meandering channels consist of a meander main channel and floodplains in both sides were modelled numerically based on an actual physical model available in the Hydraulics and Hydrology Laboratory, Universiti Teknologi Malaysia, Skudai, Johor. Numerical simulation using TELEMAC-2D were used to simulate the overbank flows of non-vegetated floodplain (NVF) and vegetated floodplain (VF) for different overbank cases.

The model consists of a three and quarter wavelength of meander main channel with sinuosity of 1.374 and floodplain on both sides as shown in figure 1. The main channel is rectangular channel with 50 cm wide and 9 cm in height with an aspect ratio of 5.56. The length of the whole model is 1200 cm and 300 cm wide from one floodplain wall to another. The model was built with a gentle slope of 0.001 to closely resemble the natural conditions of meandering compound channel.

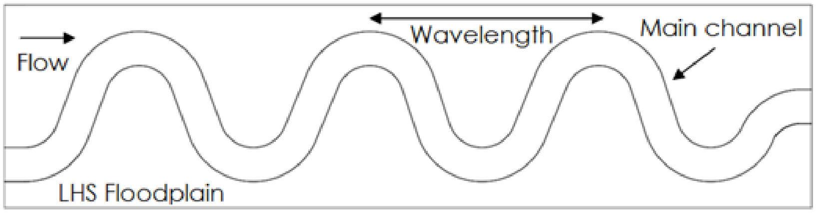

Figure 1. Meandering compound channel model.

Vegetation represented by a staggered two-line 0.5 cm diameter steel rod with a distance of two times the diameter from centre to centre along the left-hand side (LHS) of the floodplains viewing from the downstream end looking to the upstream end. The first line of the vegetation located 5cm from the interface of the main channel and the LHS floodplain as shown in figure 2. These lines of vegetation cover for a complete one wavelength of the meander main channel starts from the one and half wavelength. Meanwhile, the measurements sections only start at bend apex in the second half of the vegetated floodplain meandering following the same physical measurement sections in the experiment by Ibrahim [12] as shown in figure 3.

These overbank flows were modelled numerically as physical measurements can be very costly and time-consuming. Simulation done on two overbank flows of relative depth (DR) 0.30 and DR 0.45 for both NVF and VF conditions. Details of the flow properties of simulated cases are shown in table 1.

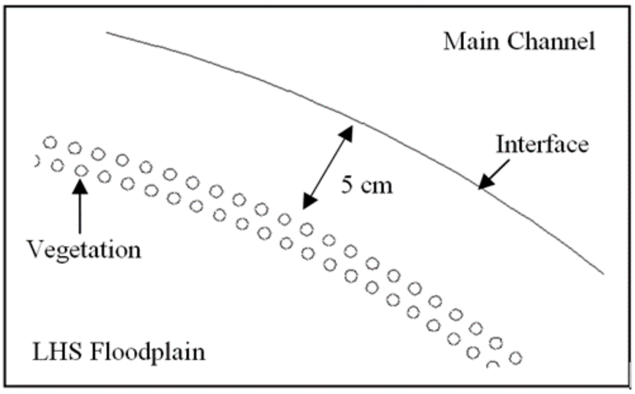

Figure 2. Staggered vegetation locations on LHS floodplain along main channel.

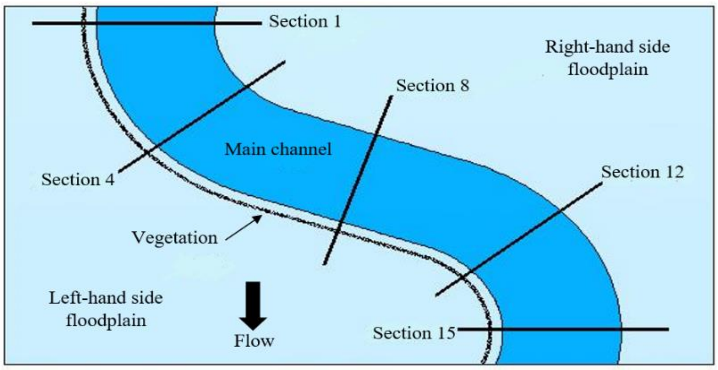

Figure 3. Measurements sections on the meandering compound channel.

Table 1. Flow properties.

Case	Discharge, (l/s)	Water Depth (cm)	Relative Depth, DR	Manning's n	Sectional-average velocity, U_s, (cm/s)
NVF DR0.30	38.0	12.86	0.30	0.0142	23.6
NVF DR0.45	85.0	16.36	0.45	0.0180	28.1

VF DR0.30	30.0	12.86	0.30	0.0190	18.7
VF DR0.45	48.7	16.36	0.45	0.0320	18.3

The relative depth of the overbank flows can be calculated using:

$$DR = (H - h_{mc})/H \quad (1)$$

where, H is total water depth and h_{mc} is depth of the main channel.

The details of the computational properties of the two-dimensional cases of the NVF and VF are summarised in table 2. Spatial resolution of the meandering compound channel is made fine around the vegetated floodplain area and coarser for the rest of the floodplains to keep in mind the overall computational economy in terms of computational time. The resolution of the meshes decided based on the Courant number and the time step criteria.

Table 2. Computational properties.

Case	Total nodes	Total elements	Time step (sec.)
NVF DR0.30	22915	42246	0.0100
NVF DR0.45	22915	42246	0.0100
VF DR0.30	86826	166136	0.0075
VF DR0.45	86826	166136	0.0075

The computational domain is bounded by open boundaries like inlet, outlet, sidewalls, bottom and free surface. These boundary conditions are to be predetermined and specified for the computational. As for the initial conditions, the water surface profile was set to be parallel to the channel bed to match the uniform flow profile that being simulate. The discharge was set to be constant at the inlet and fixed water depth at the outlet. Slip boundary condition is used for the bottom and sidewalls, meanwhile, for the free surface; zero gradient boundary conditions were applied. Initials and boundary conditions were set and predetermined to closely represents the uniform flows of the experiment.

Computational simulations started with the initial conditions above. The governing equations are split based on the fractional step techniques into advection and dispersion terms before being solved following the finite element method of streamline upwind Petrov-Galerkin. The maximum number of sub-iteration allowed was set to 100 which never exceeded for any of the simulation cases except for few initial iterations. The standard default solvers and preconditioning options available within TELEMAC-2D were used.

The simulations were carried out with an assumption of roughness and adjustments being made to the roughness to make the flow uniform. The calibrated roughness for each flow cases represents by Manning's coefficient, n summarised in table 1. The free surface profile at the centre and outside of the meander belt at every apex sections then compare with the experimental free surface to ensure the establishment of the uniform flow. The solutions were assumed to converge when the mass balance between two-time steps is within 1 % and increment values of the simulated variables at all nodes were below 0.001.

The simulated depth-averaged velocities were normalised to the sectional-average velocity, U_s where $U_s = Q/A$. Q is the discharge and A is the cross-sectional area of the meandering compound channel at bend apex. Normalisation of the depth-averaged velocity helps to compare the flows of different discharge for the same depth. More details and further explanations on the computational sequence can be found in the works by Sukla [19] and Sukla and Shiono [20].

3. Results and discussion

3.1 Validation

Figure 4 and 5 shows the validation of the simulation of the normalised streamwise depth-averaged velocities with the measurements by Ibrahim [8] for DR 0.30 and DR 0.45 respectively inside the main channel at bend apex of the meandering compound channel.

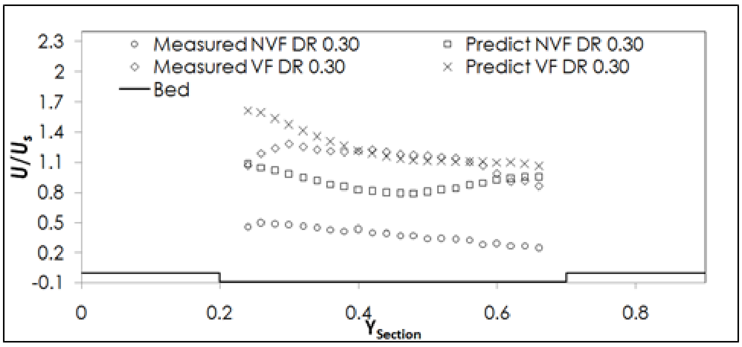

Figure 4. Validation of normalised streamwise depth-averaged velocity, U/U_s for DR 0.30 at apex cross-section.

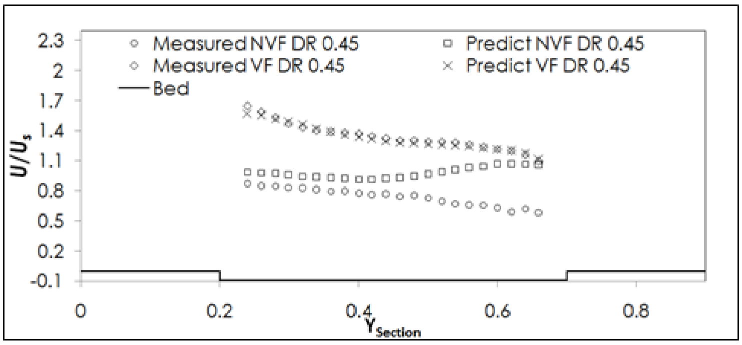

Figure 5. Validation of normalised streamwise depth-averaged velocity, U/U_s for DR 0.45 at apex cross-section.

3.2 Layered normalised streamwise depth-averaged velocity of compound channel

Analysis on layered normalised streamwise depth-averaged velocities, U of meandering compound channel can be divided into three main area; main channel, floodplains area inside the meander belt and floodplains area outside the meander belt. Generally, the streamwise velocity inside the main channel near the vegetation was reduced significantly especially at Section 1, but this is not true for Section 15 of both relative depth cases. Streamwise velocity reduction were up to 69.9% for DR 0.30 and 71.4% for DR 0.45 inside the main channel near the vegetated floodplain. Significant reduction of velocity inside the main channel was recorded near the vegetated main channel floodplain interface until the middle of the main channel before the depth-averaged velocity starts to follow the conditions without vegetation. These conditions start to differ as the flows move from Section 1 towards Section 15 as the flows been directed by the vegetation.

Vegetation placed along the LHS floodplain from Section 1 to Section 15 have directed the flows of the overbank towards the next bend apex at Section 15. Directed flows towards Section 15 increase the depth-averaged velocity of the flows as it passed to the downstream. The increase in velocity were up to 51.4% for DR 0.30 and 58.4 % for DR 0.45 at the bend apex Section 15. The increases were expected as the series of vegetation acts as vertical wall that reduces the volume of flows that can past through them especially with the smaller distance between the vegetation. The computational results generally gives higher values of the depth-averaged velocity for flows with NVF inside the main channel. In case of flows with VF, the computational result gives satisfactory results for velocity at bend apex Section 15 for both relative depth cases but differently for bend apex Section 1 were the flows gives high values for low relative depth but lower values for the case with high relative depth.

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Layered normalised streamwise depth-averaged flows were shown in figure 6 to 9 of NVF and VF for low and high relative depth cases. Depth-averaged velocity over the floodplains was significantly reduced in the area beyond the vegetations. This was due to the limited volume of flows that can pass through the vegetation. The vegetation increases the resistance to the flows and diverts most of the overbank flows to follow the direction of the main channel to the next bend apex. Flows that pass through the vegetation gains a slight increase of velocities at some distance from the vegetation as it goes downstream. The vegetation also affects the expansion and conviction from the upstream overbank flows into the main channel and downstream floodplain.

Increases of depth-averaged velocity on the floodplains outside the meander belt area were significant for both relative depth due to the diversion of flows by the presence of vegetation inside the first half of vegetated meander in the upstream. Directed flows by those vegetation increases the depth-averaged velocity of flows outside the meander belt for the vegetated floodplain between 20-35% inside the area. Normalised depth-averaged velocity contours seem to increase significantly as the flows past bend apex, Section 1 but starts to decrease due to the expansion of flows on the floodplains.

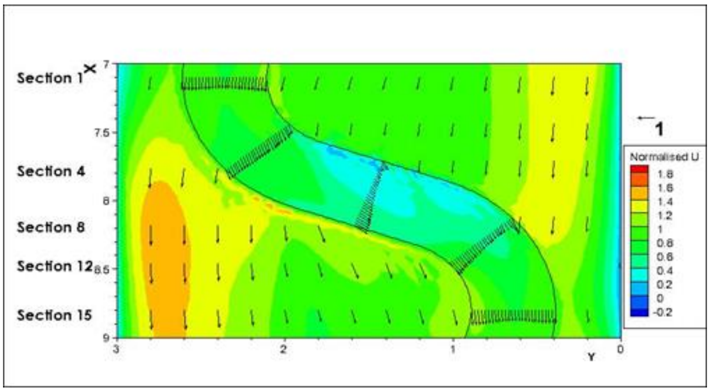


Figure 6. Layered normalised streamwise depth-averaged velocity for NVF DR 0.30.

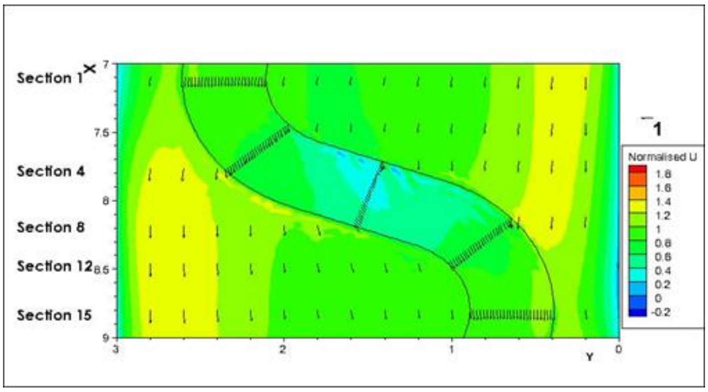


Figure 7. Layered normalised streamwise depth-averaged velocity for NVF DR 0.45.

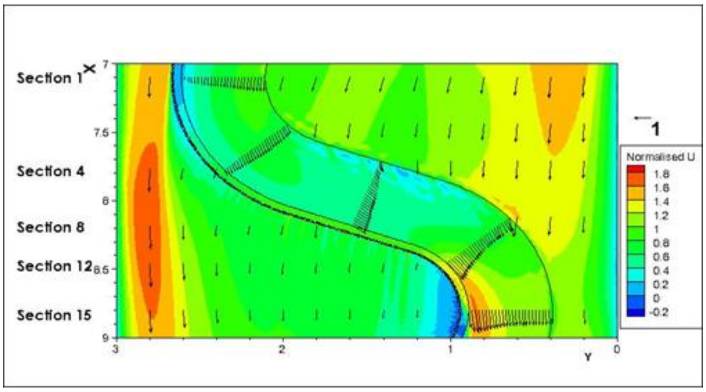


Figure 8. Layered normalised streamwise depth-averaged velocity for VF DR 0.30.

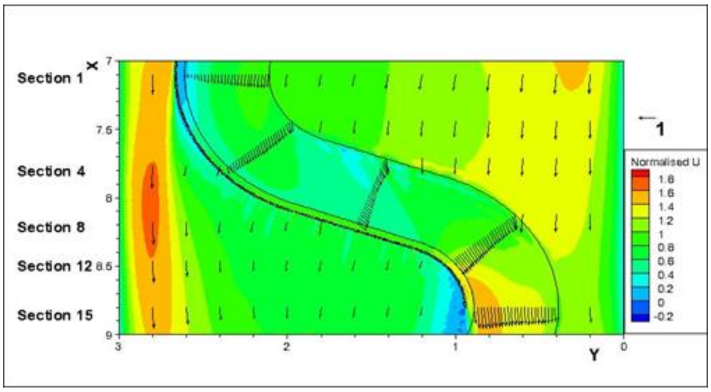


Figure 9. Layered normalised streamwise depth-averaged velocity for VF DR 0.45

3.3 Layered normalised lateral depth-averaged velocity of compound channel

The normalised lateral depth-averaged velocities of the meandering compound channel were shown in figure 10-11 for NVF and in figure 12-13 for VF cases. Generally, the lateral depth-averaged velocities of the meandering compound channel are significant inside the main channel especially in the cross-over region and in the area near the main channel and floodplain interface. The cross-over region is the area where overbank flows crossing the main channel between two bends. The lateral velocity becomes less significant on the flows over the floodplains and much lesser outside the meander belt area.

The overbank flows inside the main channel tend to follow the direction of the main channel for low relative depth but changes to follows the direction of the compound channel at higher water depth. This is due to the loss of the inbank flows dominance to the overbank flows inside the main channel. The compound channel likely to becomes a straight rectangular channel as the water depth increases due to the less significant effect of the main channel. The magnitudes and directions of lateral velocities near the interface area are likely to be affected by the expansion and contraction of overbank flows and become more visible at low relative depth.

Directed overbank flows by vegetation along the main channel greatly affected the lateral velocity of the main channel and in the floodplain area near the vegetation. The magnitude of lateral velocities inside the VF cases increases inside the main channel cross-over region near the vegetation with maximum velocity located in the inner bend between Section 12 and Section 15 for both cases. The locations of the maximum lateral depth-averaged velocity for both vegetated cases moved further downstream from Section 8 to Section 12 when compared to the NVF cases. Significant reduction of the lateral depth-averaged velocities magnitude of higher relative depth cases were recorded for both

NVF and VF cases inside the main channel and in the area near the main channel and the left-hand side floodplain interface but not true in any other areas on the floodplains.

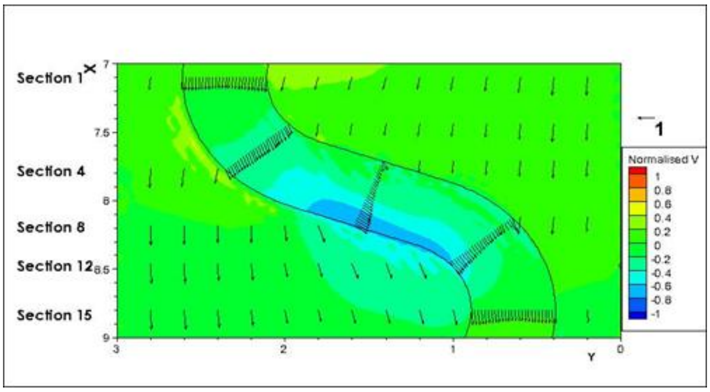


Figure 10. Layered normalised lateral depth-averaged velocity for NVF DR 0.30.

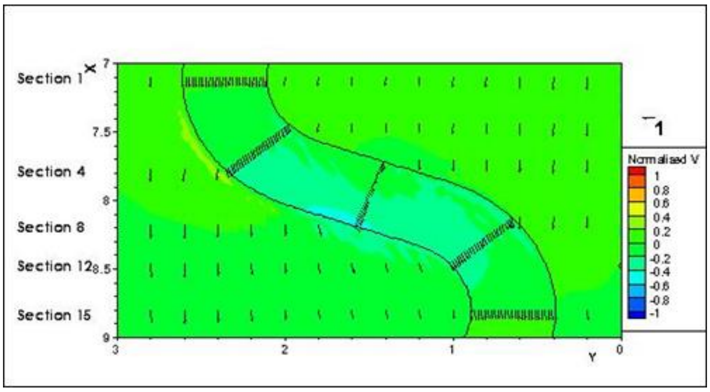


Figure 11. Layered normalised lateral depth-averaged velocity for NVF DR 0.45.

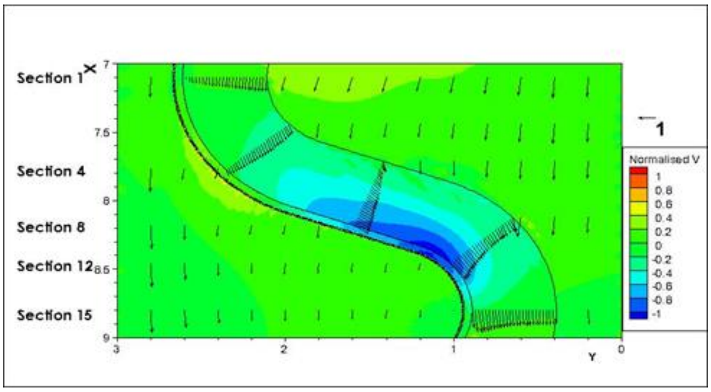


Figure 12. Layered normalised lateral depth-averaged velocity for VF DR 0.30.

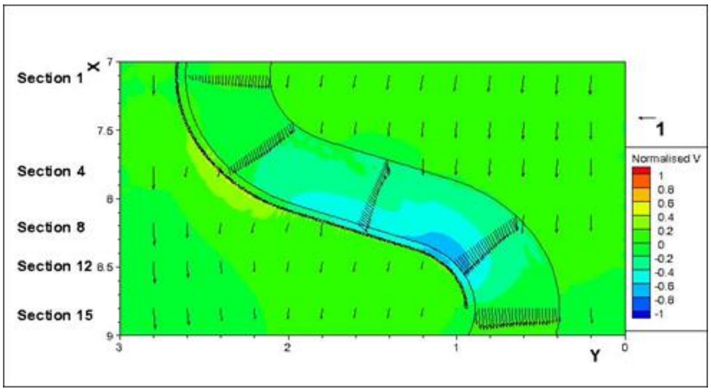


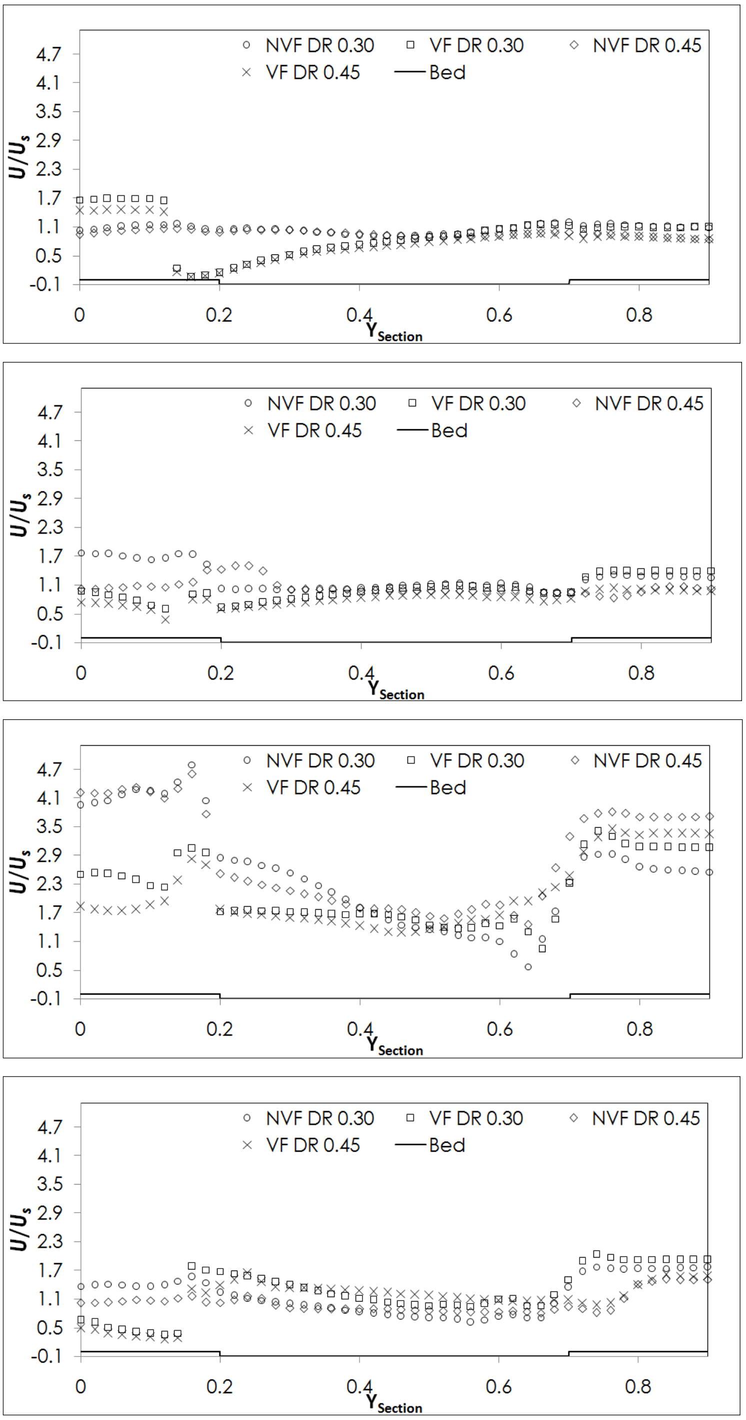
Figure 13. Layered normalised lateral depth-averaged velocity for VF DR 0.45.

3.4 Sectional normalised streamwise depth-averaged velocity along the main channel

Sectional depth-averaged velocity looks into the streamwise depth-averaged velocity across the main channel and on the floodplains in the direction of the main channel where the locations of depth-averaged values on the floodplains are perpendicular to the main channel as shown in figure 14. Distances of 20 cm from the interface on both floodplains were considered at the sections in main channel streamwise direction. Discussion of sectionals depth-averaged can be divided into three; floodplain on LHS, inside the main channel and right-hand side floodplain.

Generally, the pattern and magnitude of the streamwise depth-averaged velocities are nearly the same for both relative depths of NVF and VF cases in all the sections for right-hand side floodplain except at Section 12. Reduction of streamwise velocities near the interface were recorded for high relative depth of non- and vegetated cases as high as 53 % compared with the low relative depth cases. The presence of vegetation affected the strength of the overbank expansion into the main channel thus reduced the magnitude of the streamwise depth-averaged of DR 0.45 but increased the velocities for DR 0.30 on the right-hand side floodplain. This can be clearly seen in Section 8 that located inside the cross-over region where most of the expansion and contraction of the overbank flows take places.

The effect of vegetation to the streamwise depth-averaged velocities inside the main channel varies at different cross-sections. Vegetation reduced the velocities near the vegetated floodplain at the upstream cross-sections; Section 1, Section 4 and Section 8 but increased the velocities at downstream cross-sections; Section 12 and Section 15. Vegetation increased the flow resistance, therefore, reduces the velocities near the vegetated area for Section 1, 4 and 8. Vegetation limited the overbank flows that can pass through and directed most of the flows in the direction of the main channel thus increase the velocities for Section 12 and 15. Significant reduction of velocities for vegetated cases can be seen from the floodplain interface, $Y_{section}$ = 0.2 up to $Y_{section}$ = 0.48, near the middle of the main channel. Highest percentage of velocity reduction were recorded at the main channel and vegetated floodplain interface, $Y_{section}$ = 0.2 of Section 1 with values of 87.1 % for high relative depth and 86.4 % for low relative depth cases. Maximum increase of 51.3 % at $Y_{section}$ = 0.26 for DR 0.30 and 58.3 % at $Y_{section}$ = 0.24 for DR 0.45 were recorded at Section 15 that marks the highest velocity increase inside the main



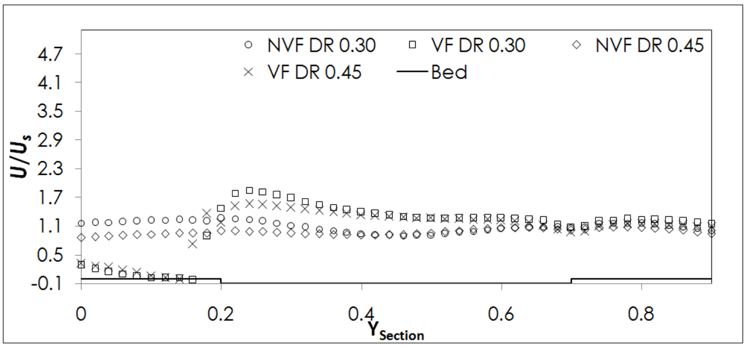
(a) Section 1

(b) Section 4

(c) Section 8

(d) Section 12

Figure 14. Normalised sectional streamwise depth-averaged velocity at (a) Section 1; (b) Section 4; (c) Section 8; (d) Section 12 and (e) Section 15.



(e) Section 15

channel. These increases were recorded in the main channel of Section 12 and Section 15 for both relative depths of the vegetated case.

Streamwise depth-averaged velocities on the LHS floodplain depends on the locations of the cross-sections and vegetation protection from the overbank flows. Directed overbank flows from the upstream increased the magnitude of the streamwise depth-averaged flows of Section 1 for both vegetated cases. Maximum increase of 64 % for DR 0.30 and 53.3 % for DR 0.45 at $Y_{section}$ = 0 of Section 1 were recorded. On most of the others sections, only reductions of streamwise depth-averaged velocities were recorded as these regions were protected by the vegetation from the upstream overbank flows. Highest reductions of velocities were recorded at $Y_{section}$ = 0.16 for DR 0.30 and at $Y_{section}$ = 0.14 for DR 0.45 of Section 15 for vegetated cases. In these regions, protection by the vegetation generate vortexes that can be clearly seen through the changes in directions of the streamwise velocities near the vegetation.

4. Conclusion

Presence of vegetation significantly affects the magnitude and direction of the depth-averaged velocity flows inside the main channel and floodplains area of the meandering compound channel. The effect much more significant for low relative depth cases of the compound channel. Streamwise depth-averaged velocities in the main channel were reduced at the outer bend of upstream bend apex mainly due to the protection of the vegetation. The flows inside the main channel near the vegetation later increase in magnitude as it goes downstream to the next bend apex due to the directed overbank flows. Vegetation limited the available cross-sectional area for the flows thus increase the depth-averaged velocity in the area that water can pass through. Downstream floodplain reduced the depth-averaged velocity outside the meander belt area by acting as wide channel through flows expansion for the vegetated cases.

Expansion and contraction of overbank flows were clearly disturbed by the presence of vegetation thus increase the complexity of the interaction between the inbank and overbank flows. A more complex numerical model will be needed for further understanding this complex flow behaviour due to the presence of vegetation. The two-dimensional model, TELEMAC-2D is capable to simulate the depth-averaged velocity for vegetated floodplains for both relative depth but gives more higher values of velocities for cases without vegetation for the same relative depth.

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