Hydraulic Resistance Characteristics of Riparian Reed Zone in River

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Abstract: The riparian vegetation zone plays an important role in river ecosystems, flow resistance, water velocity distribution, and water level variation. In this paper, the impacts of riparian reed zones on river flow and water level were studied by comparing measurements in river reaches with or without riparian reed zones in the Chaodongweigang River of Taihu Lake Basin, China. The effects of the density, stem diameter, and rigidity of reeds on flow regime, water velocity, and water level were investigated. Subsequently, flow resistance on the river's longitudinal water level caused by the riparian reed zone was studied. The results showed three water velocity zones in the river reach where there were riparian reeds, including the slack water zone, the transition zone of flow velocity, and the river's main flow zone. The water velocities in the three zones were related to reed density, diameter, and rigidity. The water-surface slope in the river reach with a riparian reed zone was larger than that without a reed zone. It showed that the riparian reed zone influenced the river flood discharge to some degree and resulted in increased water level upstream. Additionally, the water level of the river cross section exhibited a concave shape that the water level was higher in the riparian reed zone than in the center of river midstream, section with a riparian reed zone exhibited a concave shape; the water level was higher in the riparian reed zone than in midstream, and the water level difference was influenced mainly by the reed density.

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Introduction

Understanding the hydraulics of over vegetation is important to support the management of fluvial processes. Increasing attention has recently been paid to the effect of vegetation zones in the river channel on flow characteristics. Vegetation along the beds and banks of rivers plays an important role in hydrodynamic behavior, the purification of pollutants, and the ecological equilibrium (Carpenter and Lodge 1986; Sabbatini and Murphy 1996; Sand-Jensen 1998; Milsom et al. 2004). It has been reported that river riparian vegetation is an important factor retarding flood discharge. The hydraulic aspects of the vegetation concern some general features of the flow, such as turbulence, mixing, and resistance to the flow (Righetti and Armanini 2002).

Most of the previous studies (Fenzl and Davis 1964; Kao and Barfield 1978; Kouwen et al. 1981; Chiew and Tan 1992; Bakry et al. 1992; Carollo et al. 2002) have paid considerable attention to flow resistance. Flow resistance caused by submerged vegetation determines velocity profiles (Kutija and Hoang 1996; Righetti and Armanini 2002; Carollo et al. 2002). The flow drag varies according to the plant's form, dimensions, rigidity, the plant population per unit area, the spatially heterogeneous distribution of vegetation, and the degree of submergence. The stem spacing and Reynolds number of the plant are important parameters for the determination of the vegetation drag coefficient (Jonathan et al. 2004). Furthermore, vegetation density is considered to be one of the most important parameters for drag control. Increase in vegetation density leads to an increase in flow resistance and a reduction of the drag coefficient (Ming and Shen 1973; Petryk and Bosmanjian 1975; Kutija and Hoang 1996; Nepf 1999). A number of models have been used to describe the flow velocity profile and the hydraulic roughness of submerged vegetation (Lopez and Garcia 1998; Righetti and Armanini 2002). Most studies mainly focused on submerged vegetation, describing the effects of submerged vegetation on flow and obtaining the main influencing factors and range of values for drag coefficients. These research results supported the predictive computation of mathematical models. However, fewer studies have been conducted on rivers with riparian vegetation on both sides.

Advances in understanding the behavior of flow over vegetation provide us with more useful informations of flow-velocity profiles and flow resistance and the design of vegetated channels. The Chaodongweigang River located in Zhangjiagang, Taihu Lake Basin, China was selected as the test field in this study. By comparing research towards the river reach with or without riparian reed zones, the effects of riparian reed zone on river water velocity and water level were investigated, and the impacts of different reed densities, diameters as well as rigidities, on water velocity were analyzed.

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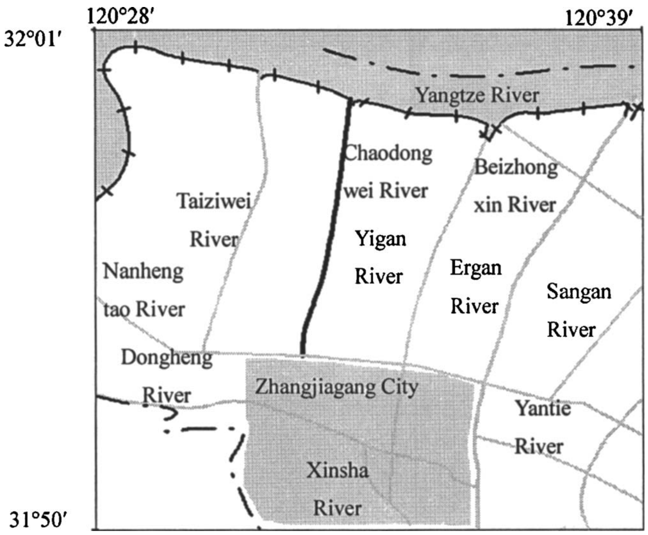

Fig. 1. The Chaodongweigang River and its geological location

Field Measurements

Study Area

The experiments were carried out in the Chaodongweigang River in the city of Zhangjiagang, Jiangsu Province, Eastern China. The total length of the river is 24.7 km (Fig. 1). It runs from the Dongheng River in the south to the Yangtze River in the north. The cross section is approximately a multiterrace shape. The bottom and top widths of the major river canal are 20.0 and 30.0 m, respectively, with 1:2 m of side slope and 2.5 m of water depth. The top width of the multiterrace riverway is 62.0 m with 1:3 m of side slope, and 10.0 m of platform width on each bank. The river cross sections are shown in Fig. 2. During floods, the water surface becomes up to 56.0 m wide, of which 30.0 m is not vegetated. During other periods, the water surface is at least 29.0 m wide, and the platforms on both sides are higher than the river water level. The total length of measured river reach is 16.2 km, with a longitudinal gradient $i_0=0.0001$. There are no drain entrances, tributary inlets, or diversion gaps in this river reach, indicating a basically equivalent water flow through each cross section.

The riparian vegetation zone is 13.0 m wide on each side in the upstream 8.1 km river reach, accounting for the platforms and parts of the composite slopes. Twelve surveys were carried out to investigate the density and species of riparian plants in this zone. Reeds had a density of 33.12 stems/m^2, accounting for 92% of the emergent vegetation in this zone. Other species found in the area included cattail (2.16 stems/m^2, accounting for 6% of the emergent vegetation) and some weeds (0.72 stems/m^2, accounting for 2% of the emergent vegetation). The downstream river reach is also 8.1 km long. However, flood discharge in this river reach has been severely affected by long-term silting and invasion of weeds. When a catastrophic flood occurred in Taihu Lake Basin in June 2001, the serious water retardance in this river reach led to large-scale submergence of the farmland and urban area and caused enormous economic loss. In order to improve the flood carrying capacity of the Chaodongweigang River, the local government conducted a dredging project in the downstream river reach at the end of 2001. As a result of the project, the riparian reed zone vanished. Subsequently, the differences in river vegetation between the upstream and the downstream river ecosystems provided a perfect comparative study area for this research.

Research Methods for Field Measurements

Ten cross sections for field measurements were designed in the above mentioned river reach. Section A (0.0 m), Section B (2,000.0 m), Section C (4,000.0 m), Section D (6,000.0 m), and Section E (8,000.0 m) were set up in upstream river reach with riparian reed zones on both sides. The reeds above water were artificially reaped along the river breadth, with an area of 13.0 m × 1.2 m on each side, in order to build board bridges spanning the sections for water level and velocity measure. Correspondingly, Section F (8,200.0 m), Section G (10,200.0 m), Section H (12,200.0 m), Section I (14,200.0 m), and Section J (16,200.0 m) were set up in the newly dredged downstream river reach without reeds.

Nine observation points for water level and nine measurement points for flow velocity were set up at each section in the downstream and upstream respectively. These points were set up at the midstream line and 10.0, 15.0, 18.5, and 22.0 m symmetrically away from the line on both sides. In addition, particular cross sections were selected as the main ones measured, with individual reed density shown in Table 1. Nine to twelve measurement points for water velocity were set up at half-width of the selected sections in order to analyze the effects of reed density, diameter, and flexibility on water velocity. The velocity was measured by using a SONTEK velocity meter, which produces data in three orthogonal directions aligned with compass points. Using these measurements, the principal direction of flow was derived and three velocities (the velocity in the principal direction, the velocity orthogonal to the principal direction, and the upward velocity) were reported. With the aid of national vertical control points, a level gauge was used to measure the elevation of the surveying rod for water level observation.

Periods of high water level and heading up in the bilateral riparian reed zone were chosen to study the impact of the riparian reed zone on flood carrying capacity according to the rainfall of Zhangjiagang City and the hydrologic properties of the Cha-

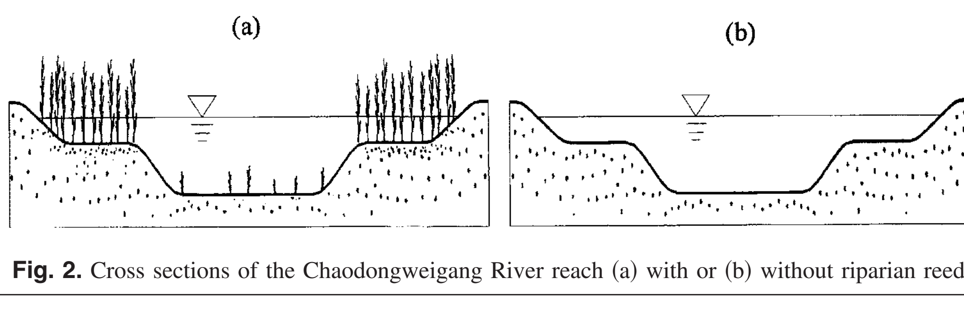

Fig. 2. Cross sections of the Chaodongweigang River reach (a) with or (b) without riparian reed

Table 1. Reed Densities in the Selected Sections of Half–Width River

Date	Cross sections				
	A (0.0 m)	B (2,000.0 m)	C (4,000.0 m)	D (6,000.0 m)	E (8,000.0 m)
June 4, 2003	18	27	33	42	52
June 7, 2004	20	29	34	43	53

Note: Unit in (stems/m^2)

odongweigang River in 2003 and 2004. Monitoring was performed on May 8, June 3, and June 28, 2003, as well as on May 12, June 6, and June 30, 2004. Water velocities were measured at the cross sections with different reed densities on June 4, 2003 and June 7, 2004. Seven measurements for water velocity were carried out on each monitoring date with an interval of 1 h between measurements.

Results and Discussion

Distribution of River Water Velocities

Previous studies have shown that vegetation influences the resistance of a watercourse and consequently the water velocities (Kutija and Hoang 1996; Carollo et al. 2002). However, the effects of vegetation, particularly grown vegetation in the river on both sides, are not yet fully understood. In the present study, water velocities were measured at different cross sections of measured river reaches with or without riparian reed zone. A significant difference was found between the vegetated zone and the unvegetated zone (see Fig. 3, in which each point is the mean value of the seven measurements).

In the vegetated part of the river, the water velocity was relatively larger in the 20.0 m width at the center of the river without reeds, but much smaller in the 10.0 m of reed zone on both sides at the measured cross sections of Sections A, B, C, D, and E [see Fig. 3(a)], due to the impact of emergent vegetation on the reeds. An obvious transition zone of flow velocity existed between the midstream main flow and the riparian reed zones on both sides [see Fig. 3(a)]. Three water velocity zones, including a slack water zone in reeds, the transition zone of flow velocity, and the river's main flow zone, could be distinguished in the vegetated river reach. This indicated that the riparian reed zones could significantly resist water velocity.

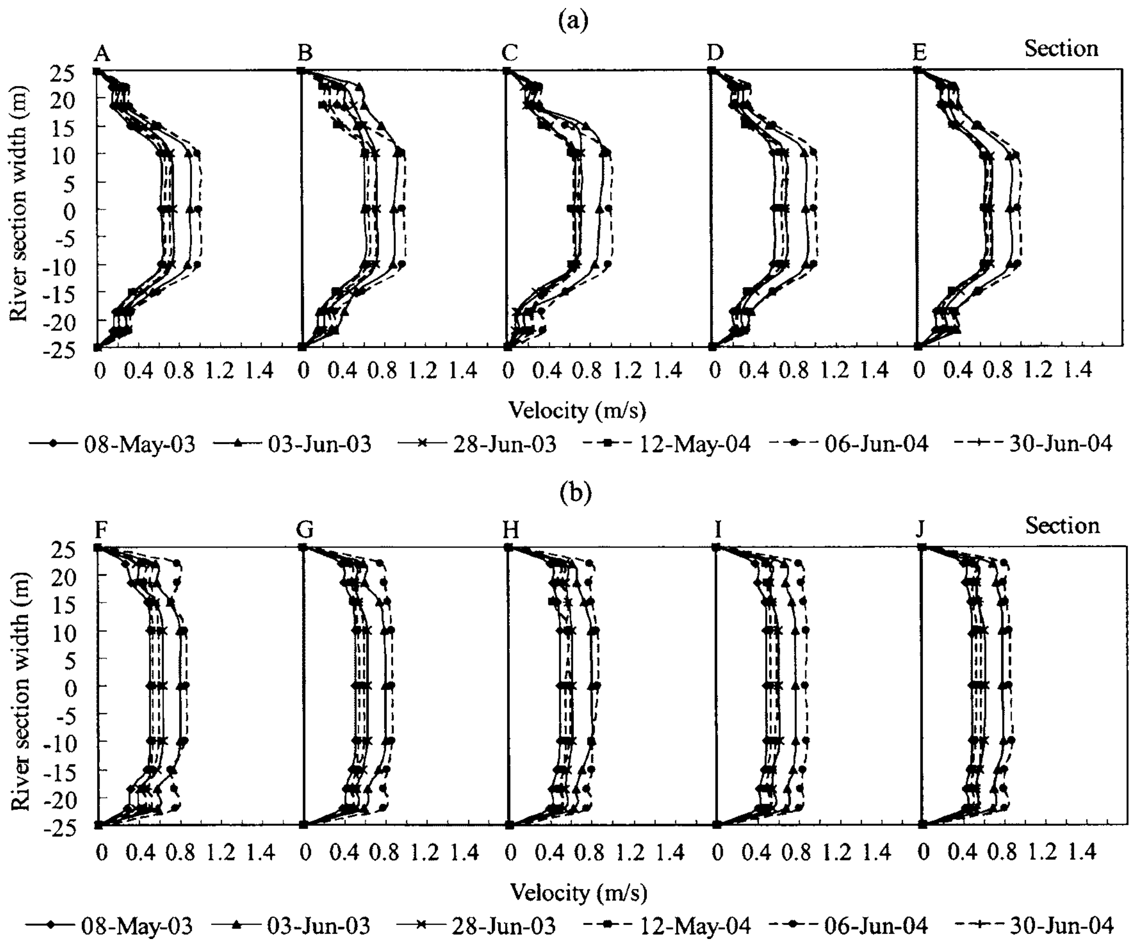

Fig. 3. Water velocity profiles during different periods at different cross sections of the Chaodongweigang River reach (a) with or (b) without riparian reed zone

Table 2. Reed Densities, Water Velocities, and Water Levels at Different Points of the Chaodongweigang River

Measurement point (m)	B′(2,050,20)	C′(4,050,−20)	C″(4,500,−20)	D′(6,050,20)	D′(6,050,−20)	E′(8,050,20)	E(8,050,−20)
Measurement date	June 7, 2004	June 4, 2003	June 4, 2003	June 4, 2003	June 7, 2004	June 4, 2003	June 7, 2003
Reed density (stems/m^2)	20	42	52	33	29	27	34
Velocity (m/s)	0.197	0.088	0.025	0.151	0.181	0.183	0.151
Water head[a] (cm)	4.5	9.4	10.2	6.8	5.6	5.5	6.8

[a]Water level of measurement point subtracts that in the middle of the measured cross sections.

In the unvegetated river reach, the water velocity was distributed uniformly in the measured cross sections of Sections F, G, H, I, and J [see Fig. 3(b)]. The flow velocity in the center zone of the river was approximately equivalent to that on both sides. Own to the effect of shoal roughness, water velocity at the composite platforms was slightly smaller than main flow velocity.

By comparing the water velocity in the vegetated and unvegetated zones (see Fig. 3), we can see that the main flow zone velocity in the vegetated river reach is larger than in the unvegetated reach at the same fluid flux, and the water velocity on both riversides with reeds is significantly smaller than without reeds. This suggests that the bilateral riparian reed zones have an important influence on the distribution of water velocities.

Impacts of Different Reed Densities on Water Velocities

It has been reported that stem concentration affects the shape of the velocity profile (Lopez and Garcia 1998; Nepf 1999; Carollo et al. 2002). Therefore, the effect of reed density on water velocity was investigated in this study. In the reed zones with densities of 20 and 27 stems/m^2 on the left-hand side of Sections B′ and E′, which were lower than the mean reed density (33.2 stems/m^2), the flow velocities are larger; correspondingly, in the reed zone with a density of 42 stems/m^2 on the right-hand side of Section C′, which was denser than those at other cross sections, the flow velocity was smaller (see Table 2). Further, the reed zone with a density of 52 stems/m^2 on the right of Section C″ had nearly stationary river flow. There were similar water velocities at the other sections with reed densities of nearly 33.2 stems/m^2 (the mean reed density).

In an area with relatively lower reed density upstream of the higher-density zone, a lateral flow of river water appeared, since the flow velocity changed from large to small. This made the flow regime more complicated.

Fig. 4 exhibits the influences of different reed densities on water velocity distribution in the river reach with riparian reed zones. The abscissa is $y/(0.5B)$, where y=distance from the measurement point to the midstream line and $0.5B$=half the width of the river water. The ordinate is $u(y)/u_{\max}$, where $u(y)$=field-measured water velocity and $u_{\max}$=maximum water velocity at midstream. The relative velocities at these river cross sections could be divided into three zones (see Fig. 3).

The first is the slack water zone in reeds with a relative width of Y_1. In this zone, different reed densities corresponded to different relative water velocities. For example, the maximum reed densities of 52 and 53 stems/m^2 corresponded to the minimum relative velocities of 0.105–0.205. In contrast, the minimum reed densities of 18 and 20 stems/m^2 corresponded to the maximum relative velocities of 0.625–0.678. These relationships reflect significant effect of riparian reed density on water velocities, consistent with the results of Kutija and Hoang (1996), Carollo et al. (2002), and Jonathan et al. (2004). When the reeds are too dense, the river flow is blocked. Consequently, in the high-density reed area, the river flow is almost stationary, and the lateral flow occurs in the upstream of the highly dense area.

The second is the transition zone of flow velocity, with a relative width of Y_2. Water velocities in the transition zone were larger than those in the slack water zone in reeds, but smaller than those in the river main flow zone. And the rate of change of relative water velocities in the transition zone was related to reed densities; an increase in reed density resulted in an increased rate of change of relative water velocity.

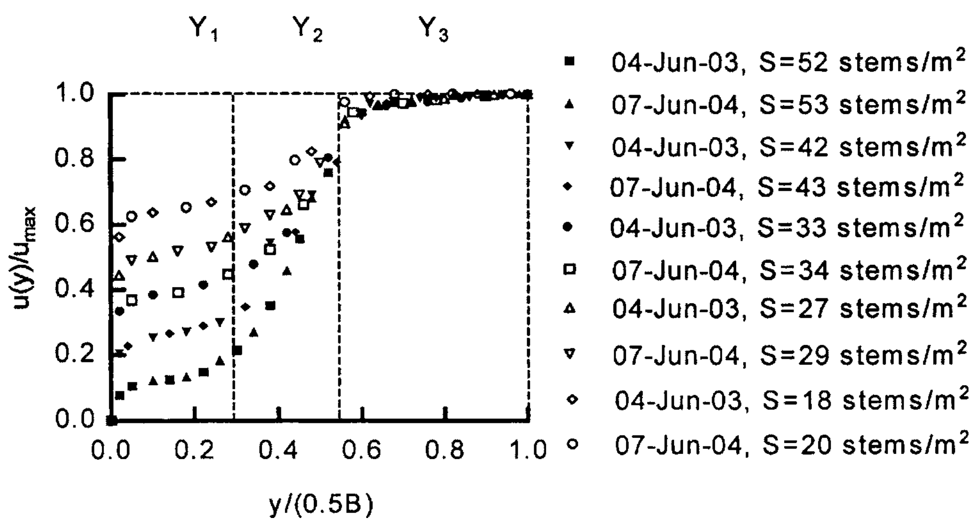

Fig. 4. Relative water velocity profile under different reed densities at the measured cross sections

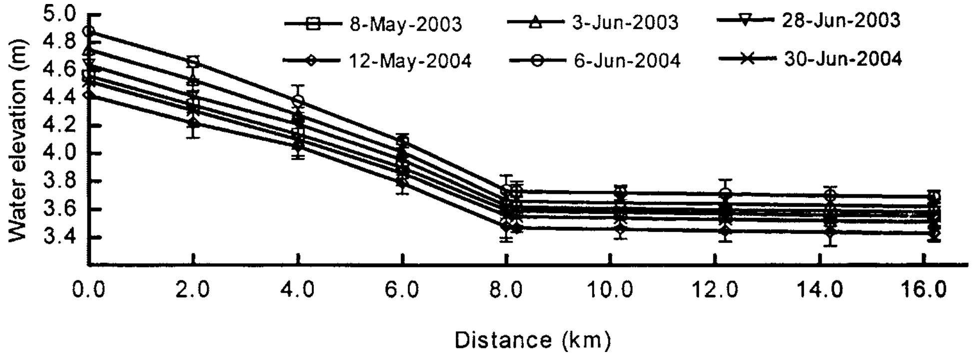

Fig. 5. Water-surface slope during different periods at different cross sections in the center of the Chaodongweigang River reaches

The third zone is the river main flow zone, with a relative width of Y_3. The relative velocity here was approximately 1.0, which shows that the reed zone does not directly influence this area. From the point of flow flux in the river, the water velocities measured in this zone were also larger than those measured in the main flow zone of the river reach without reeds.

Since the measured velocity distributions showed that the relative widths Y_1, Y_2 and Y_3 do not vary with reed densities, the locations of the three velocity distribution zones do not depend on reed densities.

Impacts of Reed Diameters and Rigidities on Water Velocity Distribution

The process of vegetation growth is dynamic, so flow in a vegetated channel is movable. It has been shown that different reed diameters and rigidities at different measurement dates affect water velocities to a certain degree (Jonathan et al. 2004). When the reed densities are lower than 29 stems/m^2, because the reed diameter and the rigidity are smaller in May than in June, the reeds are readily bent by flow. Consequently, the flow resistance is smaller in May than in June. When reed densities are higher than 34 stems/m^2, the effects of reed diameter and rigidity on river flow are not obvious. As shown in Fig. 3(a), the reed densities were lower on the left of Section B′ and the water velocity variation rates were observed to be larger in June than in May, whereas on the right of Section C′, the reed densities were higher and the rates were almost the same in May and in June.

Impacts of Riparian Reed Zones on the Water-Surface Slope along the River

Fig. 5 shows the water-surface slope in the center of the measured river reaches at different cross sections during different periods. The water-surface slope dropped greatly in the upstream river reach with riparian reed zones, whereas it only dropped slightly in the downstream reach without reeds. For example, on June 6, 2004, there was a 1.7 m difference in water level between Sections A and E in the upstream river reach with riparian reed zones. Excluding the elevation difference of 0.8 m (for the riverbed longitudinal gradient $i=0.0001$), the additional difference in water level was 0.9 m and the additional water-surface slope caused by the reed zone was 0.0001125. In contrast, there was a 0.8035 m difference in water level between Sections F and J in the downstream river reach without reed zones, which approximates the elevation difference of 0.8 m introduced by the riverbed longitudinal gradient. These results demonstrate that riparian reed zones greatly affected the river water-surface slope and elevated the upstream water level. During flood discharge, water level by riparian reeds could decrease the natural flood carrying capacity of the river and increase the floodwall height on both sides.

Fig. 6 shows the distribution of water levels at Sections B and H. The water surface expressed as a concave shape at the cross section with riparian reed zones [see Fig. 6(a)], while it was nearly horizontal at the cross section without reed zones [see Fig. 6(b)]. This significant difference could be explained as follows: The water level in midstream is lower due to quicker flow velocity, and the water level is higher in the reed zones due to slower flow velocity. This difference in water levels may cause the trans-

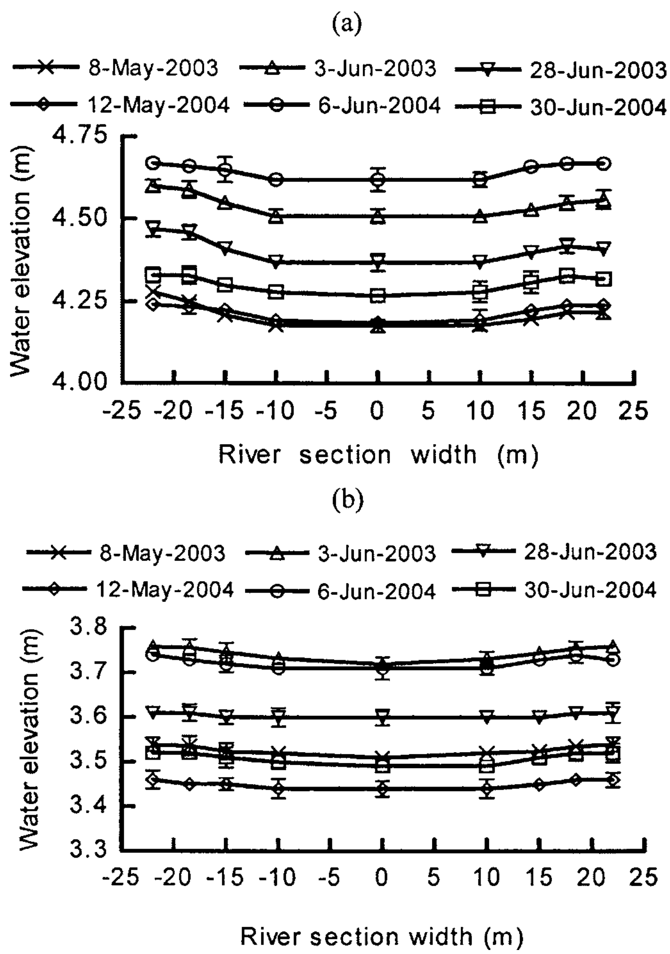

Fig. 6. Distributions of water level at (a) Section B and (b) Section H of the Chaodongweigang River reaches

verse flow at cross sections. Additionally, the results in Table 1 showed that the higher the reed densities, the larger the water level difference was found between the reed zone and the center of the river. However, the lateral water level in the sections without reeds was almost equivalent to the level in midstream. These relationships demonstrated that water level was influenced by reed density, and reed zones played an important role in the water-surface shape at the cross sections.

Conclusions

By comparing a river reach with riparian reed zones to one without reed zones, it showed that riparian reed zones had an important influence on flow regime, water velocity, and water level. The hydraulic resistance induced by riparian reed zones was very strong. At the section of the river with riparian reed zones, the water-surface slope exhibited an obvious concave shape. Reed density demonstrated obvious effects on flow regime. Hydraulic resistance becomes stronger with higher reed density, resulting in a lower water velocity and higher water level. The average water velocity measured in areas with a reed density of 33.0 $stems/m^2$ was 0.151 m/s, and the water level was of 6.8 cm higher than that in the center of the same cross section. When the reed density decreased to 20 $stems/m^2$, the average water velocity and the water level difference were 0.197 m/s and 4.5 cm, respectively. On the other hand, when the reed density increased to 52 $stems/m^2$, the average water velocity decreased to 0.025 m/s, and the water level difference increased to 10.2 cm. Thus, higher reed density causes higher hydraulic resistance, coinciding with smaller water velocity and higher water level in riparian reed zones. Thick reed zones may block river flows and decrease a river's flood carrying capacity and flood discharge velocity. Reed diameter and flexibility also influenced river flow: the larger the diameter and more rigid the reed, the stronger the hydraulic resistance. However, when reed density was very high, the influences of reed diameter and flexibility on water velocity were almost invariable. Meanwhile, higher reed density caused a higher longitudinal water-surface slope and a greater difference in water level between the upstream and the downstream.

Although riparian reed buffers had negative effects on water flow, they play an important role in bank soil erosion, bank slope balance, sand sedimentation, water pollutants purification, and habitat restoration. Therefore, more attention should be paid to the synthesized influences of riparian reed zones on flow velocity and water level during river ecological restorations. River ecological restoration and flood safety should be promoted together.

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