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# Velocity Variations in Salt Marsh Creeks, Jiangsu, China

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**ABSTRACT**

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Velocity variations in a tidal cycle were measured in four salt marsh creeks on the Jiangsu coast, eastern China. Results of regressional analysis show that a marked linear relationship is present between the tidal current velocity and the rate of water level changes. Further, two or three significant velocity surges exist in a tidal cycle. A theoretical analysis indicates that one of the regressional coefficients of the linear equations represents the effect of a component of progressive tidal waves (the tidal waves over the study area are not purely standing waves) and the other coefficient is affected by the geomorphology (i.e. bed slope) of the creeks and the marsh surface. The observed tidal current velocity surges can be related to a rapid water level change (as observed during the initial stage of the flood within a creek) or the combined effects of water level changes and bed morphology (as observed at the end of the flood or during the ebb). Towards the end of the ebb, the surges may be influenced also by the ground water which flows from the marsh surface into the creeks. The established linear relationships may be utilised to develop new techniques to calculate current velocities in the creeks using remote sensing images.

**ADDITIONAL INDEX WORDS:** *Velocity surges, water level, salt marshes, tidal flat, China coast.*

## INTRODUCTION

Previous studies on tidal dynamics in salt marsh creeks have shown that velocity exhibits well-marked pulses throughout the tidal cycle and flood-ebb asymmetry patterns (MYRICK and LEOPOLD, 1963; PETHICK, 1972, 1980; BOON, 1975; BAYLISS-SMITH *et al.,* 1979; HEALEY *et al.,* 1981). PETHICK (1980) has proposed a simulation model to explain velocity variations in association with different water levels and found a close agreement between simulated velocities and velocities measured by BAYLISS-SMITH *et al.* (1979). Furthermore, he suggests that the velocity is a function of the rate of water level change, which is considered to be an independent variable. However, HEALEY *et al.* (1981) has suggested that a number of features of observed velocity-stage curves cannot be explained using PETHICK'S model; they state that bed slopes may have a more important influence on the generation of velocity pulses.

Measurements from the salt marsh creeks near Jianggang in Jiangsu Province, China (Figure 1), as will be reported in the present paper, indicate that current velocities exhibit 2 or 3 well-marked surges which appear at some special periods of time within a tidal cycle; moreover, both the rate of water level changes and the bed slope may be more important to the formation of such surges than have been generally recognized. The flood surge may have some impact on the geomorphological evolution of the salt marsh system, by accelerating the deposition over the upper marsh and creek headwater areas because large velocities can enhance sediment transport directed toward the land (SHI *et al.,* 1995; XU *et al.,* 1994). Previous studies on hydrodynamics and sediment dynamics for the Jiangsu mud tidal flats were concerned mainly with the lower flats (ZHANG, 1992; DING and ZHU 1983), but little is known for salt marshes, especially the hydrodynamics and sediment transport in creeks. In the present contribution, we intend to: (i) analyse relationships between current velocities and the rate of water level changes and other factors such as bed slope, using the data collected from four Jianggang creeks; (ii) provide an explaination for the velocity surges observed in the creeks; and (iii) propose a simple model to relate the velocity to the rate of water level changes and salt marsh geomorphology (i.e. bed slopes).

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## THE STUDY AREA

The Jianggang salt marshes are located on the middle part of the Jiangsu coast (Figure 1), where a muddy substrate supports a variety of densely distributed halophytic plants (*i.e. Suaeda martiima* Dumort, *Suaeda glauca* Bunge and *Imperata cylindrica* Var. Major.) (REN *et al.,* 1984). This area represents the center of a large radial sandbank (or tidal current ridge) system of the southwestern Yellow Sea, where the banks converge (LIU *et al.,* 1989). The sandbank field is approximately 200 km in length from the north to the south and 90 km in width from the east to the west. The study area is macro-tidal, with an average tidal range of 3.9–5.5 m, and the tides are irregularly semidiurnal in character (ZHANG, 1992; ZHANG and CHEN 1992). The East China Sea progressive tidal waves and the southern Yellow Sea rotary tidal waves converge near Tiaozini (for location, see Figure 1). Under such hydrodynamic conditions, the flood flow dominates over the ebb flow on the tidal flat and has a significant influence on the net sediment transport; consequently, fine-grained sediments are transported towards the upper mud

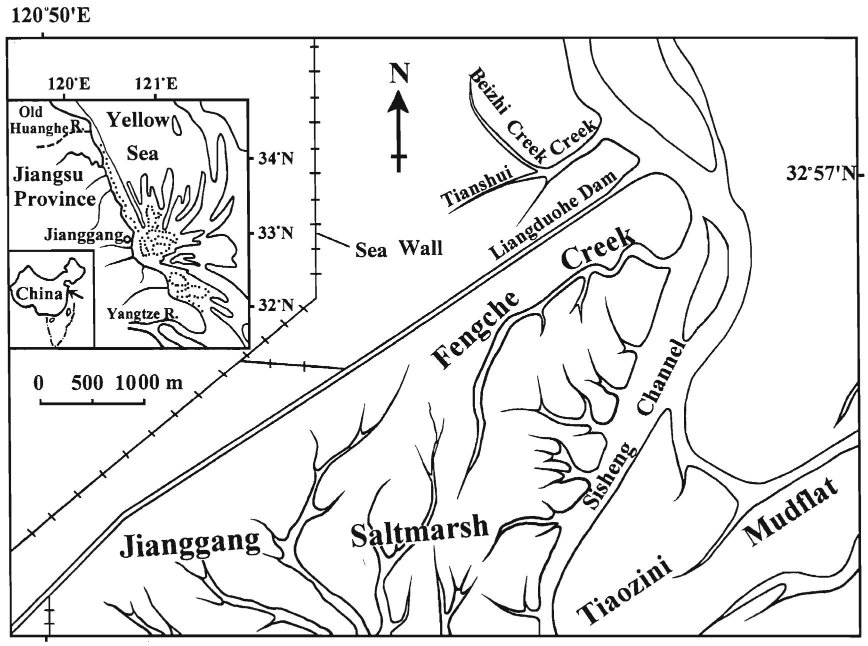


Figure 1. Map of salt marshes at Jianggang, Jiangsu, China (on the basis of 1982 aerial photography).

flat and accumulate there. ZHANG (1995) and ZHANG and CHEN (1992) have observed that the deposition rate on the flat surface is 4–8 cm yr$^{-1}$, most of the sediment being supplied from the offshore sandbanks. The mean grain size ranges between 4.5 and 6.6 $\Phi$. The width of the Jianggang salt marshes generally exceeds 4.5 km, with an average gradient of 0.1%-0.01%. ZHANG's (1992,1995) studies show that the central section of the Jiangsu tidal flat can be divided into a series of longshore cells representing individual hydrodynamic and sedimentary units. The Jianggang salt marshes, which consist of several cells (such as the Fengche cell), prograded towards the east with an average rate of 20–30 m yr$^{-1}$, from 1954 to 1988.

Most tidal creeks are well developed on the Jianggang salt marshes, and are generally obliquely orientated with regard to the coastline (ZHANG and WANG, 1991). The data in this paper were mainly collected from four of these creeks, *i.e.* Fengche Creek, Beizhi Creek, Tianshui Creek and Sisheng Channel (Figure 1). The length of the first three creeks is 3–5 km, extending toward the east. Sisheng Channel is approximately 15 km in length, extending from the north to the south; it is located at the edge of the Jianggang salt marshes, with Fengche and Tianshui Creeks being its branches. In addition, Beizhi is a tributary of Tianshui Creek. In the creek system the tributary channels of Fengche, Tianshui and Beizhi Creeks are much smaller than the main channel.

## METHODS

### Field Observations

In 1979, tidal cycle measurements of currents velocities and water levels were undertaken with an Ekman current meter and a survey rod (accuracy $\pm$2 cm) in half-hour intervals at three stations located at the mouth of Fengche Creek (10th and 11th September), Beizhi Creek (23rd September) and Tianshui Creek (20th September) (Figure 1). From 21st to 22nd September, 1987, tidal currents were measured at the mouth of Sisheng Channel using the same method. Recently, another field observation was undertaken using two direct-reading current meters and survey rods at the mouth and middle reach stations of Fengche Creek on 3rd May, 1996; the velocity was recorded in 5–10 minute intervals. During the measurements, there were northeasterly winds with a speed of about 10 m s$^{-1}$ and heavy-moderate rain; as a result, the high water level was around 0.3 m higher than predicted.

In salt marsh creeks, the water depth always changes in a tidal cycle. In dealing with such a condition, the current meter was suspended by a tripod and could be moved vertically. The flows were measured at the center of the creek and near the 0.6 water depth; the data are assumed to represent the depth mean velocity. At the same time, the water level was read from the survey rod. In addition, the creeks and salt marsh geomorphology (*i.e.* the bed slope and location of creek branches) were surveyed by levelling. Since the location of the creeks had changed rapidly (ZHANG, 1995), the measurement stations cannot be shown on Figure 1. Nevertheless, this will not affect the analysis in the present study.

### Data Processing

The rate of water level changes is:

$$R = \frac{dh}{dt} \quad (1)$$

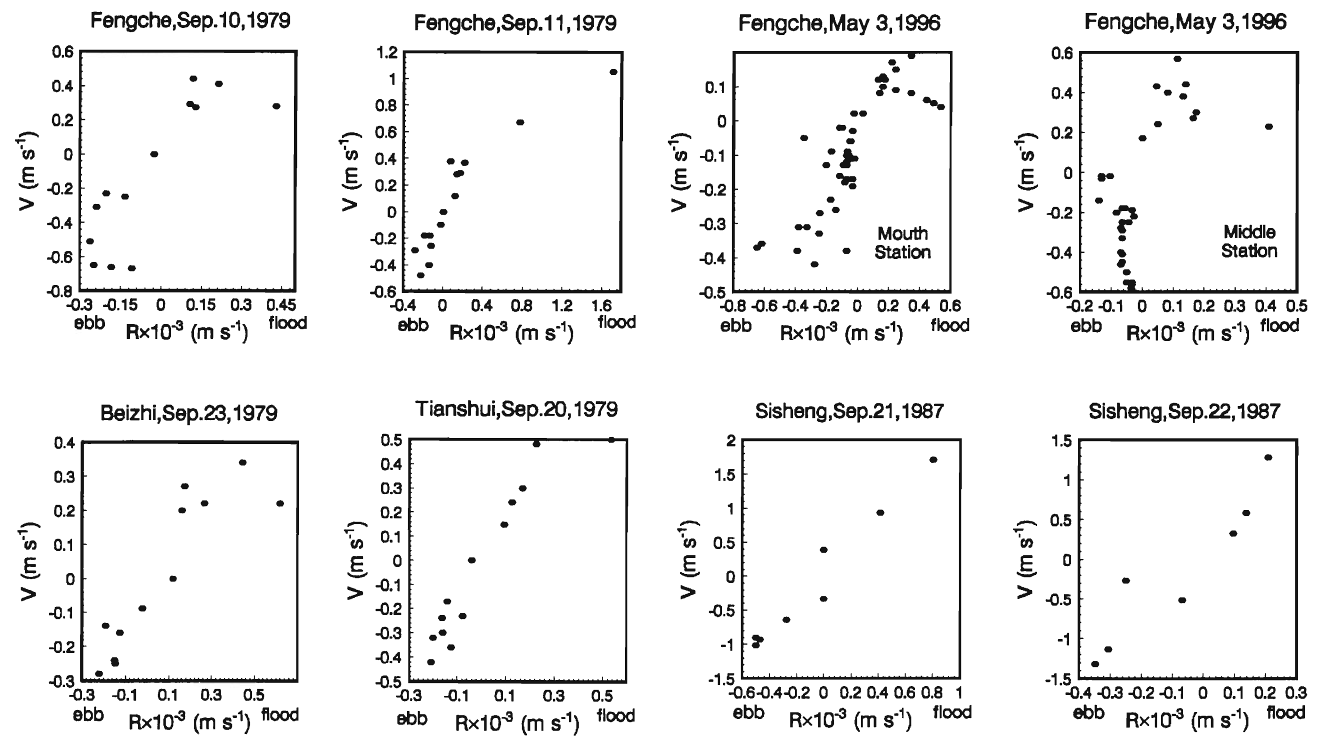


Figure 2. Velocities and rates of water level change obtained from Jianggang salt marsh creeks.

where h is the water level. Hence, the time-series of R can be calculated by:

$$R_i = \frac{h_{i+1} - h_{i-1}}{t_{i+1} - t_{i-1}}, \qquad i = 2, 3, 4, \ldots, n - 1 \qquad (2)$$

In Equation 2, $R_i$ is an average value over the period from $t_{i-1}$ to $t_{i+1}$, rather than an instantaneous value. Base upon Equation 2, time-series of $R_i$ were obtained. Thus, linear regression analysis of the relationship between $R_i$ and the observed tidal current velocity, $V_i$, can be undertaken. In this paper, $V_i$ and $R_i$ are taken as positive values during the flood and negative during the ebb, respectively.

## RESULTS

### Current Velocities and the Rate of Water Level Changes

The current velocity measured in the four creeks and the associated R values calculated using Equation 2 are shown on Figure 2. The data points have a linear pattern for each of the tidal cycles, although some scattering is present. Hence, the current velocity can be related linearly to the rate of water level changes.

### Factors Affecting Velocity Variations

The regression equations obtained are listed in Table 1. The results show that $r > r_\alpha$ for all of the V-R relationships,

Table 1. *Results of linear regression analysis for V-R relationships, for the Jianggang salt marsh creeks (r = correlation coefficient; N = number of V and R data pairs; $r_\alpha$ = critical correlation coefficient at the significant level $\alpha$, which is taken as 0.01 here).*

| No. | Creek | Location | Date | Regression Equation | r | $r_\alpha$ | N |
|---|---|---|---|---|---|---|---|
| 1 | Fengche | mouth | 10/09/1979 | V = −0.069 + 1,672.0R | 0.84 | 0.68 | 13 |
| 2 | Fengche | mouth | 11/09/1979 | V = −0.023 + 753.3R | 0.89 | 0.64 | 15 |
| 3 | Fengche | mouth | 03/05/1996 | V = −0.076 + 533.7R | 0.81 | 0.35 | 50 |
| 4 | Fengche | middle | 03/05/1996 | V = −0.095 + 1,938.9R | 0.64 | 0.44 | 33 |
| 5 | Beizhi | mouth | 23/09/1979 | V = −0.051 + 756.9R | 0.89 | 0.71 | 12 |
| 6 | Tianshui | mouth | 20/09/1979 | V = −0.032 + 1,405.9R | 0.93 | 0.68 | 13 |
| 7 | Sisheng | mouth | 21/09/1987 | V = 0.038 + 2,071.9R | 0.98 | 0.83 | 8 |
| 8 | Sisheng | mouth | 22/09/1987 | V = 0.140 + 3,850.0R | 0.94 | 0.87 | 7 |

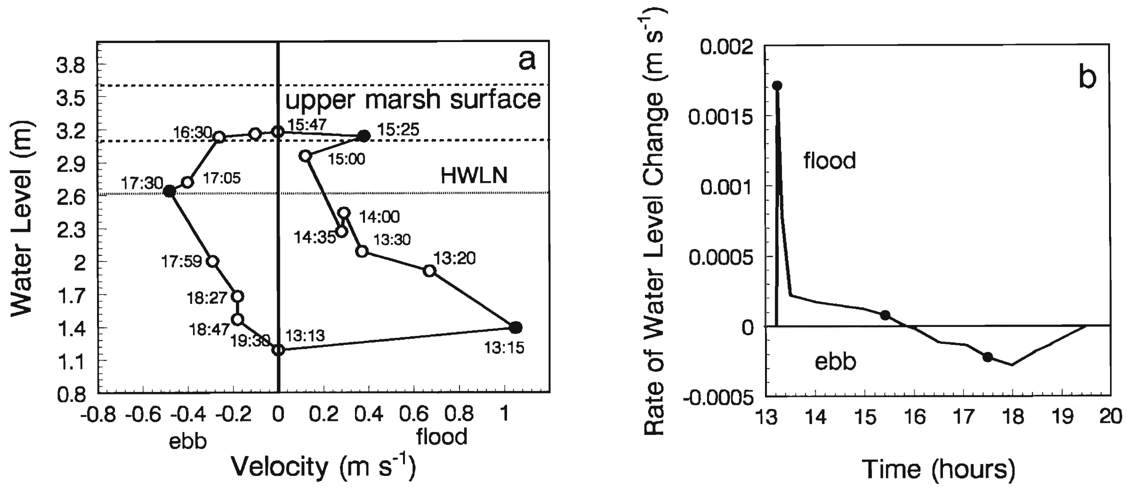


Figure 3. The velocity-water level relationship (a) and the rate of water level changes (b), measured in Fengche Creek, 11th September, 1979 (in the figure, HWLN denotes high water level on neaps).

indicating a significant linear relationship. In the general regressional relationship

$$V = A + BR \tag{3}$$

the magnitudes of the regressional constants A and B are $10^{-1}-10^{-2}$ m $s^{-1}$ and $10^{2}$-$10^{3}$, respectively, although they vary in different equations.

Based upon Equation 3, V is equal to the value of A ($A \neq 0$) when $R=0$. Under such a condition, the velocity is not zero during the high-water period. For instance, weak currents (*i.e.* $-6.9$ cm $s^{-1}$) were present in Fengche Creek on 10th September, 1979, when $R=0$. The velocity in Sisheng Channel was directed to westward *i.e.* towards the land (positive V values in Table 1), but eastward *i.e.* towards the sea in other three creeks (negative V values in Table 1). Equation 3 shows also that when the current velocity is zero, R is $-A/B$. These observations indicate that the tidal waves over the study area are not purely standing waves; they contain a component of progressive waves.

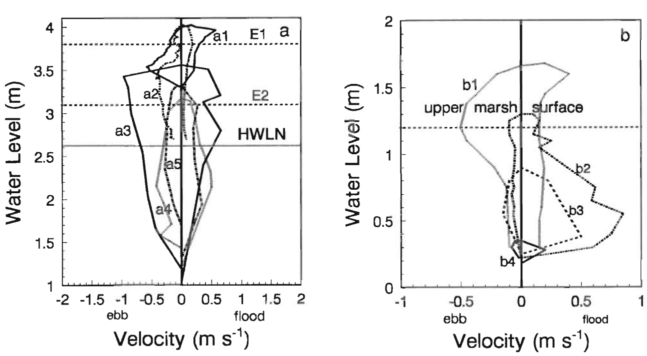


Figure 4. Occurrences of velocity surges in creeks in a tidal cycle on: (a) Jianggang salt marshes, Jiangsu, China (a1 and a2 (middle and mouth stations, respectively): Fengche, 3rd May, 1996; a3: Fengche, 10th September, 1979; a4: Tianshui, 20th September, 1979; a5: Beizhi, 23rd September, 1979) (in the figure, E1 and E2 are the elevation of the upper marsh surface in 1996 and 1979, respectively; HWLN denotes high water level on neaps); and (b) the northern Norfolk marshes, England (Bayliss-Smith, 1979) (b1: headwater station, 8th March, 1977; b2, b3 and b4: Lady Creek, 7th July, 22nd June and 26th June, 1975, respectively).

## Velocity Surges

The current velocity measured in the creeks exhibits 2–3 well-marked surges in one tidal cycle (Figures 3 and 4; and Table 2). The surge strength (represented by the current speed during the surge) is associated with the elevation (in terms of the Local Datum, which is equivalent to the mean low water level on springs in the study area) of the creek bed surface; a relatively small elevation is related to a strong surge (Table 2).

The velocity surge at the early stages of the flood, which was the largest in all surges, was found in every tidal cycle, although in some places the surges were relatively weak. The water level-velocity curve (Figure 3a) shows that the tidal water reached Fengche at 13:13 (Beijing Time), and a large velocity was observed two minuets later. At the same time, the rate of water level change reached its peak value (Figure 3b), which was primarily responsible for the surge. When the flood currents arrived at the salt marsh edge, the water surface slope was enhanced due to the shoaling effect: the influence of the bed friction on the flow increases in response to a sudden decrease in the water depth. On the other hand, since the bed elevation of Fengche Creek was above the mean water level but was still far from the high water level, the rate of water level changes was the largest when the first tidal currents reached this location, at the beginning of the flood phase. In the same manner, the surges occurring at the initial stage of the flood in other creeks, *e.g.* Beizhi and Tianshui Creeks, can be explained. Measurements at the mouth of Fengche Creek on 3rd May, 1996, do not show the occurrence of the initial flood surge; this is, once again, controlled

Table 2. *Surge strength in the creeks over the study area (V = velocity, H = tidal height, P = tidal phase).*

| | | | Bed Elevation | First Surge | | | Second Surge | | | Third Surge | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Creek | Location | Time | (local datum) (m) | V ($m\ s^{-1}$) | H (m) | P | V ($m\ s^{-1}$) | H (m) | P | V ($m\ s^{-1}$) | H (m) | P |
| Fengche | mouth | 79.9.10 | 1.19 | Not Recorded | | | 0.44 | 3.21 | FF | 0.67 | 3.43 | IE |
| Fengche | mouth | 79.9.11 | 1.19 | 1.05 | 1.39 | IF | 0.38 | 3.14 | FF | 0.48 | 2.64 | ME |
| Fengche | mouth | 96.5.3 | 2.50 | 0.19 | 3.06 | MF | 0.42 | 2.64 | FE | None | | |
| Fengche | middle | 96.5.3 | 3.40 | 0.57 | 3.96 | FF | 0.48 | 3.54 | FE | None | | |
| Beizhi | mouth | 79.9.23 | 1.31 | 0.34 | 1.94 | IF | 0.27 | 3.08 | FF | 0.28 | 2.36 | FE |
| Tianshui | mouth | 79.9.20 | 1.21 | 0.50 | 2.14 | IF | 0.42 | 2.15 | ME | 0.36 | 1.58 | FE |
| Sisheng | mouth | 87.9.21 | <0.5 | 1.71 | 2.50* | IF | 1.02 | 3.30* | ME | None | | |
| Sisheng | mouth | 87.9.22 | <0.5 | 1.87 | 2.50* | IF | 1.32 | 3.50* | ME | None | | |

Note: IF denotes early flood time for the location, MF middle flood, FF late flood, IE early ebb, ME middle ebb, and FE late ebb. For Sisheng Channel, water level data are not available; hence, water depth data are used instead.

by the bed elevation. From 1979 to 1996, the bed elevation here was enhanced by 1.31 m, due to siltation. As a result, the bed elevation became close to the high water level and the rate of water level changes could not be large enough to generate the surges. Similarly, the bed of the middle reach of Fengche Creek was much higher in elevation than at the mouth. It could not have an effective response to initial R peak at such a high elevation (see Lines a1 and a2, on Figure 4a). Hence, an initial flood velocity surge does not exist in the tidal creeks with a bed elevation above the high water level on neaps (*i.e.* 2.62 m at Jianggang).

Figure 3 shows that, at the Fengche Creek mouth, maxima of the absolute R values (at the early stage of the flood phase and during the ebb) are associated with tidal velocity surges. However, the surge occurring towards the end of the flood cannot be explained fully by an R maximum; other factors relating to the geomorphology of the tidal creeks and the branching network should be taken into account for such a surge (PETHICK, 1980; HEALEY *et al.,* 1981). In other creeks at Jianggang and the northern Norfolk salt marsh reported elsewhere, two or three marked velocity surges have been observed (Figure 4). The velocity surge occurring during the final period of the flood have been thought to result from the currents overflowing the marsh surface (BAYLISS-SMITH *et al.,* 1979; SHI *et al.,* 1995). Thus, the velocity surge when the water overflows salt marsh surface from the creek is primarily attributed to a sudden change in the local creek-to-marsh slope.

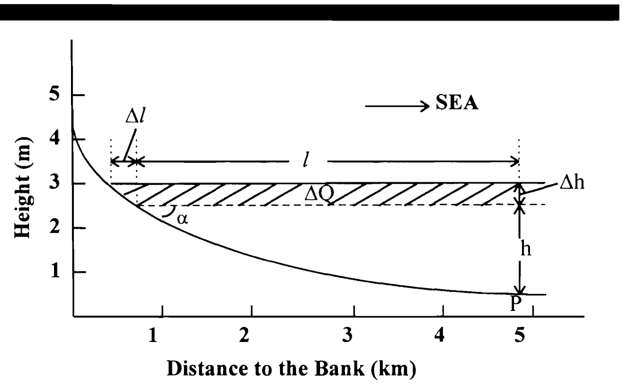


Figure 5. Diagram for the derivation of the interrelationship between V, R and tgα.

It appears that some surges during the ebb may be related not only to the R maxima, but they are also influenced by the bed geomorphology. During the ebb, the direction of the flow is controlled by the bed slope; this causes the tidal water to return into the creek from the marsh surface since levees are not well developed here and the maximum slope is associated with a marsh-to-creek slope. Such phenomena are particularly significant during the final ebb phase, when a thin layer of the tidal water of 5 cm in thickness drains into the creeks from the marsh surface (ZHANG and WANG, 1991). This observation implies that a difference in the water movement during the flood and ebb exists: the flood water movement is controlled by the hydraulic slope (hence, a part of the water reaches the upper marsh without passing through the creeks), whilst the ebb water movement is controlled by the gravity (hence, the water tends to return to the sea through the creeks). Further, some ground water also enters the creeks during the ebb. Therefore, the excessive water can result in the velocity surge during the ebb. In Fengche Creek, according to the measurements on 10th September, 1979, the water volume that drained through the mouth station was $3.828 \times 10^6\ m^3$ during the ebb, which exceeded that of the flood by $1.25 \times 10^6\ m^3$.

When the velocity surge reaches certain intensity, tidal bores may occur in the creeks if the bed topography is suitable. For example, tide bores were observed in Sisheng channel on 22nd September, 1987, in response to a maximum velocity for the initial surge of $1.87\ m\ s^{-1}$.

## DISCUSSION

The relationship between the rate of water level changes and the current velocities in the creeks outlined above may be explained theoretically, assuming that the width is constant within a section of the salt marsh creek. For the flood phase, if the water level rises by $\Delta h$ during the time $\Delta t$ and a section of the creek bottom with a length of $\Delta l$ is inundated (Figure 5), then the water volume ($\Delta Q$) entering the creek within $\Delta t$ can be calculated by:

$$\Delta Q = \Delta h l + 0.5\ \Delta h\ \Delta l \tag{4}$$

or

$$\Delta Q = V\,h\,\Delta t \tag{5}$$

where V is the depth-mean velocity at Station P, and h is the water depth. Combining Equations 4 and 5, we have:

$$V = \frac{\Delta h}{\Delta t}\frac{1 + 0.5\Delta l}{h} \tag{6}$$

Because $\Delta l \ll l$, $l + 0.5\Delta l \approx l$. Writing the average slope of the creek bed as tgα, we have

$$V = \frac{l}{h}\frac{dh}{dt} = \frac{R}{tg\alpha} \tag{7}$$

The same equation can be derived for the ebb condition. A similar equation has been derived elsewhere by GAO and ZHU (1988) for the tidal flat surface. Apparently, it can be seen from Equation 7 that a linear relationship between V and R exits. Moreover, the velocity is proportional to the reciprocal of the slope tgα. The parameter A is not present in Equation 7 in comparison with Equation 3, because Equation 7 is derived for standing tidal waves only. In reality, however, there tends to be a component of progressive waves, although such a component is generally small.

A comparison between Equations 3 and 7 shows that B in Equation 3 is approximately the reciprocal of the creek bed slope tgα if A is neglected. The B values vary in different tidal cycles in a creek (*i.e.* Fengche Creek, in 1979), but the reciprocal of the slope ($tg\alpha \approx 0.001$ in Fengche Creek) of the creek bed from the mouth to the headwater has the same magnitude as the B values. Hence, B is mainly associated with the mouth-to-head creek bed slope.

For a comparison, the data measured from a head water station in the Warham creek, North Norfolk, England (PETHICK, 1980) were also analyzed. The regressional equation obtained is $V = -0.017 + 258.9\,R$ ($r=0.97$, $r_\alpha=0.80$, $N=9$). The B value in this equation implies a bed slope of 0.0039; this is close to the average local slope *i.e.* 0.0036. Hence, the linear relationship between V and R and the physical meaning of Parameter B is valid also for other salt marsh creeks.

Equation 7 can be extended to predict the tidal velocity for a creek system consisting of a number of branches. If the width and length of the area covered by water for each of the branches are known, then the water volume (ΔQ) entering the creek system within Δt can be calculated approximately by:

$$\Delta Q = \Delta h w_1 l_1 + \Delta h w_2 l_2 + \ldots + \Delta h w_n l_n = \Delta h \sum_{i=1}^{n} w_i l_i \tag{8}$$

or

$$\Delta Q = V\,h\,w\,\Delta t \tag{9}$$

where the subscript $w_i$ and $l_i$ represent the width and length of the water-covered area, respectively, for the i-th branch; V, h and w are the velocity, water depth and width of the mouth section of the creek system, respectively. Combining the two equations, we have:

$$V = \frac{\sum_{i=1}^{n} w_i l_i}{wh}\frac{dh}{dt} \tag{10}$$

Based upon Equation 10, it is possible to estimate the time-series of V at the mouth of any creek system using a low-tide remotely-sensed image, if the tidal water level curve is known. This may provide a basis for the remote sensing studies of tidal creek currents.

According to Equation 7, for any location within the creek, the velocity associated with the flood initial surges can be expressed by:

$$V_s = \frac{1}{tg\alpha}\frac{dh}{dt}\bigg|_{h=0} \tag{11}$$

Equation 11 implies that such a surge can occur only when dh/dt is sufficiently large. Using this equation, the important role played by flood surges for geomorphological evolution of the marsh-creek system, which has been noticed by several authors (ANDERSON, 1973, 1984; XU *et al.,* 1994), may be evaluated. A strong flood surge, which is characterized by high velocities and suspended sediment concentrations, can enhance sediments transport towards the land. The measurement at Fengche Creek in 1979 shows that the current velocity of the initial flood surge can be three times larger than the velocity averaged over the flood phase. This indicates that the flood surge has an impact on the hydrodynamics and sediment transport in a creek; it can accelerate the accretion on the upper marsh and creek headwater areas.

## CONCLUSIONS

Based upon hydrodynamic measurements undertaken in four creeks in Jiangsu, eastern China, regressional analysis shows that linear relationships between the current velocity and the rate of water level changes exist. Analysis of the regressional coefficients of the equation indicates that they vary with the velocity during the slack tide and creek orders. The field observations suggest that the tidal waves over the study area are not purely standing waves, but contain a component of progressive waves.

Two or three well-marked velocity surges are present in the creeks in one tidal cycle. An initial flood surge corresponds to a large rate of water level changes. The local creek-to-marsh bed slope is responsible for the velocity surges at the final stage of the flood when the water overflows salt marsh surface and during the ebb when the currents return into the creek. The surges may be influenced also by the ground water which flows into the creeks towards the end of the ebb.

On the basis of a theoretical analysis of the relationship between current velocities and the rate of water level changes, the velocity variations in creeks are controlled by many factors, such as the rate of water level changes, the bed slope along the creek bottom from the mouth to the headwater, the creek-to-marsh bed slopes, the bed elevation of the creek and salt marsh surface. Such a relationship can be utilized to develop new techniques to calculate current velocities in the creeks using remote sensing images.

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