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VELOCITY DISTRIBUTION MEASUREMENTS IN TIDAL STREAMS

by

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SUMMARY

Detailed velocity measurements, at two river sections, made throughout a tidal cycle are presented. One section is in a straight reach of channel with a regular cross section, the other is on a bend with a strongly asymmetrical cross section. Continuous analogue outputs obtained simultaneously from each of nine current meters were sampled at least every ten minutes to give detailed velocity-time records. By performing experiments in two stages with different placement of meters information for fifteen positions in each section was obtained.

The flow patterns were found to differ markedly according to the direction of the acceleration vector and not the velocity vector as might have been expected. An index point at which the velocity bore a constant ratio to the mean velocity in the section was found only in the symmetrical section.

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INTRODUCTION

Investigations into the propagation of tidal waves along estuaries and rivers have been made in the field, in hydraulic models and with the aid of numerical models (1, 2, 3, 4). The numerical approach, which is usually one dimensional, has given good agreement with measured values of both discharge and water surface elevation. Perhaps because of this there has been little interest in the details, e.g. local characteristics and velocity distributions, of tidal flow in rivers.

Whichever method of investigation is used it is necessary to relate measurements made in the flow with mean or representative values at the measuring section. Consideration of this problem has led to the present study which investigates the temporal variation of the velocity distributions at a section throughout a tidal cycle. The detailed results are particular to those sections studied but may be considered typical of the rivers concerned. The major features are indicative of what can be expected on other rivers.

PREVIOUS STUDIES

Miller (3) investigated the possibility of finding a correlation between the velocity at a fixed point and the mean velocity in a section of the Delaware River. He was able to show that the reading on an index meter held at a constant proportional depth, scaled by a suitable factor, gave a reasonably accurate measure of the flow. Readings at the index meter were made every five minutes and at other meters in the section only four to fifteen times a day. The shape of the velocity-time curve at the index meter was used to help construct the velocity-time curves at the other meters which in turn were used to determine the discharge. This must explain some of the correlation between the index meter reading and the discharge which could well be much less than that claimed by Miller. In the present study readings at all meters were taken either every ten minutes or every minute and there were significant variations in shape of the velocity-time graphs between meters.

Ploeg and Kamphius (1) made observations, in the St. Lawrence River, of the variation of stage with time. They found that it was not simple harmonic as assumed by Scholer (2) in his mathematical analysis. This is borne out by the present study.

Velocity distributions at a section are affected by stream geometry, many studies showing bends to have a major influence. The inward pressure gradient resulting from the superelevation of the water surface tends to displace the zone of maximum velocity towards the inner wall as described by Henderson (6). The secondary current or helicoidal motion induced by the bend tends to move the high velocity fluid towards the outer wall. The former is dominant at the start of the bend while the latter increases in strength around the bend and can dominate near the exit. Shukry's results (7) for a laboratory flume show these effects clearly with the point of maximum velocity moving from the inside to the outside as the flow proceeds through the bend. The transfer to the outer bank occurs earlier in the bend for those of lower curvature.

Natural channel sections, as a result of secondary currents, are usually asymmetric with a deeper section, the thalweg, near the outside bank and a point bar at the inside bank. This combined with the generally low curvatures causes the maximum velocity to occur near the outer bank throughout most of the bend. Leopold and Wolman (8) have observed this and also described the general flow distribution in a meander. Hooke (9) has noted the occurrence of two velocity peaks, one in the thalweg and one over the point bar. At certain stages of the tide two peaks were strongly evident in this study.

EXPERIMENTAL CONSIDERATIONS

The experimental program was designed to obtain continuous records of velocity through a complete tidal cycle at a number of points in a given section. This necessitated the use of a number of flow meters simultaneously and the development of a device to convert the output of these meters to analogue form.

Flow Meters: All meters were of the standard bucket wheel type and had been recently rated by the Ministry of Works. The meters were fixed in position and remained continuously immersed, often in highly saline water, for five days at heads of up to four metres of water. With the electronic system used to monitor the meters being sensitive to even small leakage currents a problem of complete and permanent insulation was encountered. It was overcome by spraying the contact probe and terminal with a dehydrolyzing compound and completely enclosing the non-earthed terminal in a butyl rubber sealing compound. Some breakdowns did occur due either to defective insulation or to fouling by weed and other debris suspended in the flow. The meters concerned were removed, repaired, and replaced as rapidly as possible.

The meters could have been misaligned for certain periods because they were fixed against movement in a horizontal plane and, at the change in flow direction of the river, were turned around by hand at an arbitrary time. Tests showed that misalignments of up to 80° caused readings no more than 3% too high and that, at velocities up to 1m/sec, a 180° misalignment resulted in readings approximately 10% low. As the latter would apply only when the velocity was low neither of these sources of error was considered significant.

The Convertor: A device was developed to convert the series of pulses produced by rotation of the bucket wheel on the flow meter to a continuous analogue output which could then be rapidly sampled at regular intervals by a digital data logger. The convertor consisted of a tacheometer circuit containing a monostable which produced a square wave each time the flow meter circuit was closed i.e. produced a pulse. Between the output terminals of the monostable is a capacitor the potential difference across which is, in theory, linearly proportional to the pulse rate in the flow meter circuit. This rate is a linear function of flow velocity. Thus the charge on the capacitor is a linear function of flow velocity and can be continuously monitored and sampled. In practice the output was linear below a velocity of approximately 1.2m/sec. Estimates made of the accuracy of the output were 1% at 0.2m/sec and 5% at 0.03m/sec. Since both the meters and the convertor remain steadily and accurately linear at low rates the system could measure very small velocities with a high degree of accuracy.

The convertor used in the tests was a 10-channel device the outputs from which were monitored by ten channels of a data-logger. Either continuous scans of any number of channels or intermittent scans at time intervals determined by a pre-set digital clock could be made. The output was recorded simultaneously by a typewriter and a paper tape punch.

Test Sections: Tests were made on the Avon and the Heathcote rivers in Christchurch. The two rivers are spring fed, slow flowing, meandering and share a common estuary. Tidal effects extend approximately 20km up each river and saline water can be found 8km up the Avon and 11km up the Heathcote.

The Avon test section was 3.2km from the estuary in a straight section 800m downstream of a gentle right hand bend and 400m upstream of a gentle left hand bend. The section has a small but significant degree of asymmetry the deepest section being at 0.4 of the width from the right hand bank. This must be due to persistence of a secondary current generated in the downstream bend during periods of upstream flow. The channel width at the test section is 34m and the maximum depth varies from 2m to 3m during the tidal cycle. The section is shown in Figure 1.

The Heathcote test section was at the midpoint of a sharp (relative curvature 0.34 and arc 115°) left hand bend 4km from the estuary. It was 400m downstream of a right hand bend and immediately upstream of a slight (15° arc) right hand bend. The section is strongly asymmetrical with a deep thalweg and a shallow point bar, Figure 2. The width is 21m and the maximum depth varies from 2.7m to 4.3m.

Test Procedure: Nine flow meters were used, the measurements being made in two stages. First the meters were arranged in two vertical lines, one at the deepest point in the channel and the other approximately midway between that point and the bank furthest from it. One meter in each line was exposed at just below mid-tide level. Observations were made throughout a tidal cycle with this arrangement, and then the meters were rearranged into a single horizontal line across the channel, just below the low tide level, with one or two meters at greater depths to duplicate measurements made in the first stage. The two stages were run on consecutive days so that, with no rain having fallen for some days beforehand, and with three or four points duplicated in the two stages, it was possible to combine the two sets of records to produce reliable velocity distributions. The meter locations are shown in Figures 1 and 2.

The analogue output from the convertor was sampled at ten minute intervals in the Avon test, with a number of extra readings being taken during slack water at high and low tides. The sampling interval was reduced to one minute in the Heathcote test. The duration of each test was one tidal cycle of approximately twelve and a half hours, plus at least an hour of overlap, and was arranged to cover either two high tides or two low tides.

ANALYSIS OF RESULTS

Not all the results can be presented here. Complete results including some from tests at other sections are given in Dellow (5). Herein, time is measured from the maximum stage at the immediately previous high tide and downstream (upstream) implies towards (away from) the estuary.

Stage-Time Relation: The stage-time curves were all very similar in shape to those of Ploeg and Kamphius (1). The ratio, time of fall to total tidal period was 0.61 in the Avon and 0.64 in the Heathcote. These values increased from 0.5 at the sea and were noticeably affected by changes in channel geometry. The points of contraflexure were well above the mean stage. The stage-time relation is thus not simple harmonic as assumed by Scholer (2) and would be better

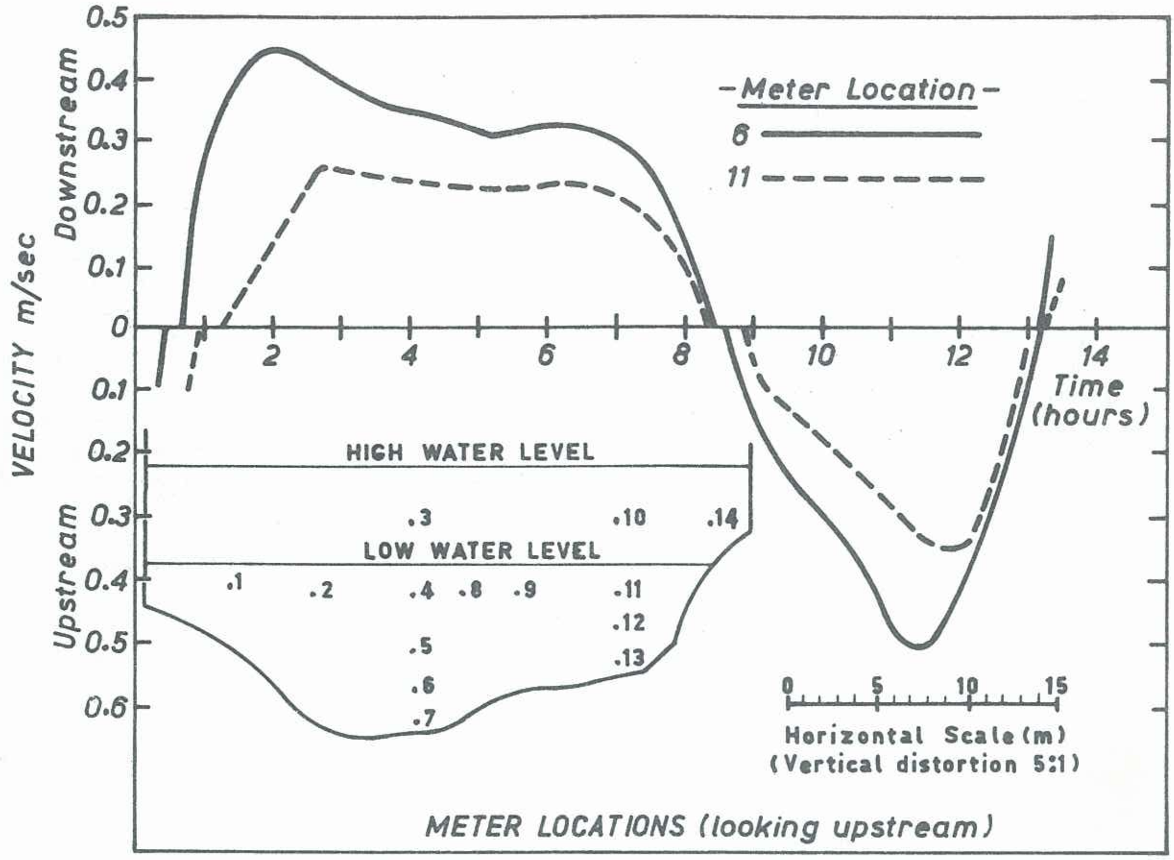

FIGURE 1 Velocity-Time curves and cross section showing meter locations for the Avon River section.

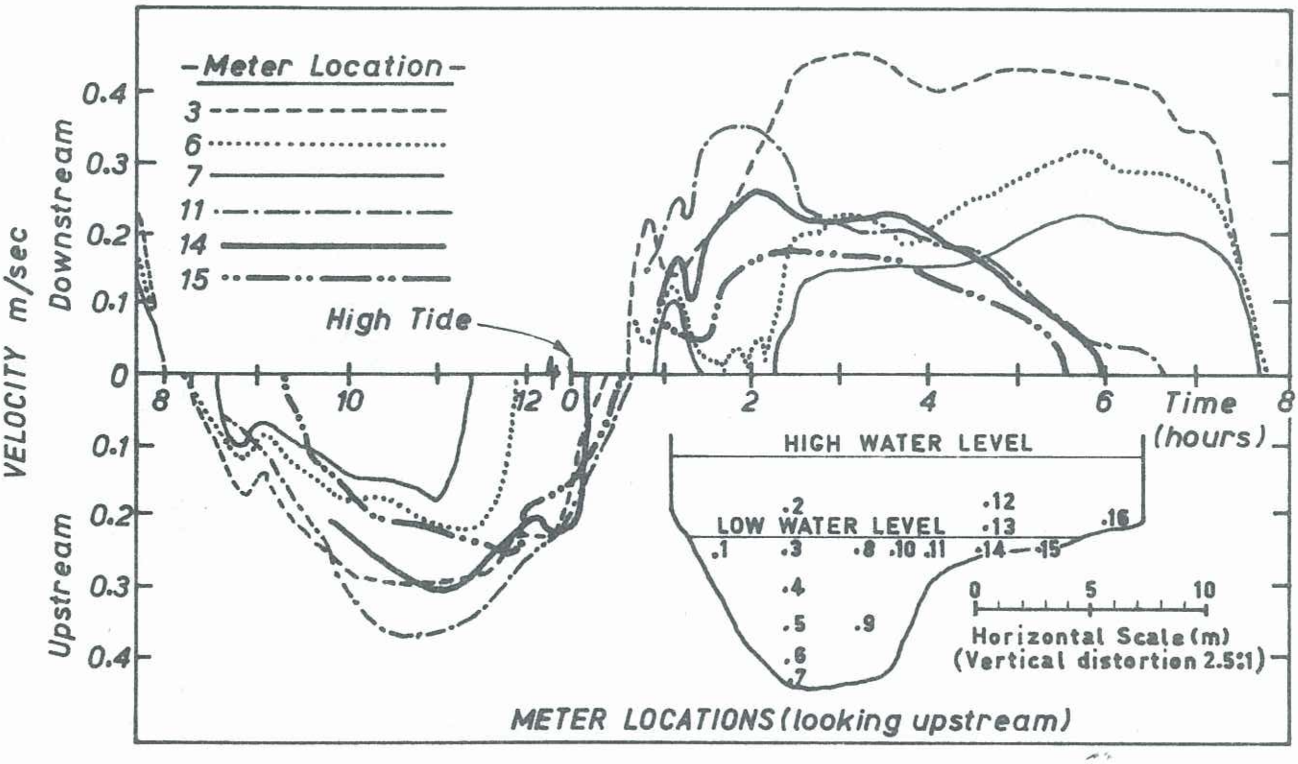

FIGURE 2 Velocity-Time curves and cross section showing meter locations for the Heathcote river section.

approximated by a Fourier series.

Velocity-Time Behaviour: Typical results from the Avon test, Figure 1, show marked differences between periods of upstream and downstream flow. During the latter the maximum velocity is reached in less than two hours. The velocity then falls only slightly over the next five hours until the minimum stage is reached at about 0730 hrs. A rapid deceleration to rest then occurs. During upstream flow the velocity rises steadily for three hours and then falls steadily for one and a half hours.

The maximum velocities at meters near the surface coincided with the points of contraflexure of the stage-time graph. At meters near the bed and towards the bank the velocity maximums were reduced and occurred later in time (up to 45 minutes). Near high tide the flow came to rest first at the surface and later near the bed. With downstream flow beginning at the surface and then at other meters in order of depth, there was a short time at about 0300 hrs when there was, simultaneously, downstream flow at the surface and upstream flow near the bed. At low tide the flow came to rest first at the bed, the stationary zone spreading upwards towards to surface. After slack water upstream flow began at the surface and spread downward over a period of twenty minutes.

In the transverse direction the velocity reached zero near the banks first and, after slack water, flow in the other direction began near the banks and spread towards mid channel. There was also a tendency for flow to both cease and start earlier near the left bank at high tide. This asymmetry suggests that the flow may have been influenced by the left hand bend just downstream and that this behaviour may be characteristic of curving flow.

Typical results from readings made at one minute intervals in the Heathcote test are shown in Figure 2. During upstream flow they are similar to the Avon test results but show a sharp decrease in velocity for a period of approximately 15 minutes at 0900 hours. There is also the sudden premature drop to zero of the velocity at meter No. 7 at 1100 hours, and at meter No. 6 at about 1130 hours, resulting in a growing region of slack water near the bed. This is probably an indication of the existence of a saline wedge with a sharply defined fresh water-salt water boundary, as typically occurs in a well-stratified estuary. With the meters 300 mm apart the interface must have been rising at 0.5 m/sec and have been approximately 170 mm thick. When the remainder of the flow subsequently came to rest it did so first at the surface near the inner bank, quickly spreading to the outer bank, and then spreading steadily downwards as in the Avon. After slack water downstream movement began near the bed on the inside of the bend ten minutes before any movement in the thalweg.

The salt wedge may also have been the cause of the complex and irregular flow pattern during the first two hours of downstream flow. The sudden accelerations at meters 6 (0210 hrs) and 7 (0220 hrs) appear analogous to the decelerations noted above and may signify the emergence of these meters from the saline layer. Over the next $3\frac{1}{2}$ hours there is a decrease in velocity in the upper section of the flow, as in the Avon test, but nearer the bed in the thalweg there is acceleration with maximum velocities occurring near 0600 hrs. There is then a gradual deceleration in the thalweg until low water (0700 hrs) after which the velocities rapidly decrease to zero. Over the point bar (meters 11, 14, 15) the velocity peaks between 0200 and 0300 hrs with the magnitude of the peak increasing from the inside bank. The velocity then falls to zero, first at the inside bank and then successively at meters 14, 11, 10, 8. There is thus a large

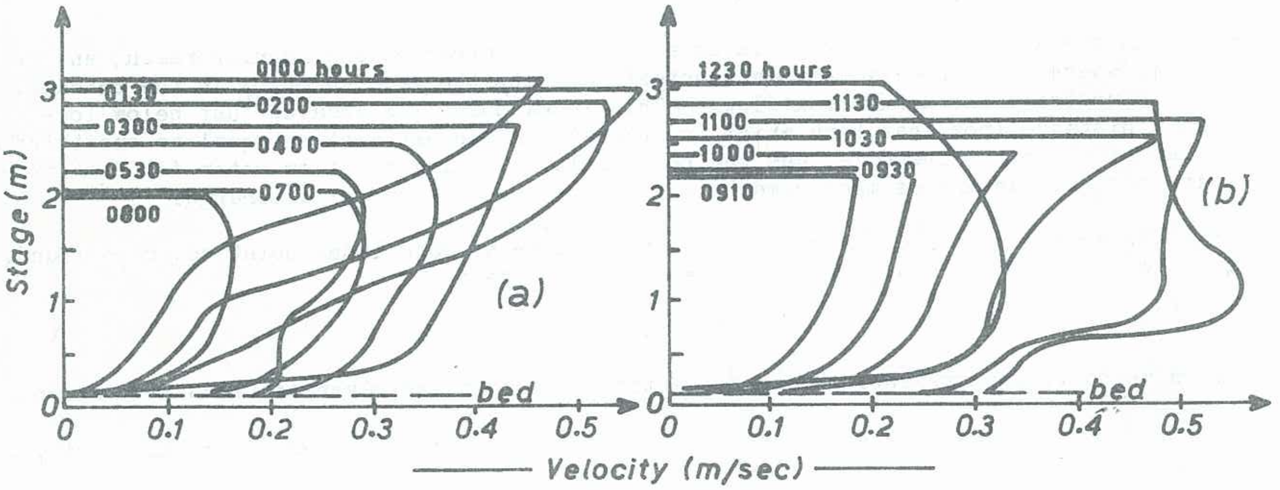

FIGURE 3 Velocity Profiles from meters 3 to 7 Avon River section.
(a) downstream flow (b) upstream flow

body of stationary water over the point bar for some hours before low tide. After slack water, movement begins near the bed on the inside of the bend.

Velocity Distributions: Figure 3 shows velocity profiles, constructed from readings taken on meters 3 to 7, in the Avon River. They show a rapid acceleration near the surface immediately after slack water at high tide. Thereafter velocities near the surface decrease while those at greater depth increase until approximately 0300 hours. The flow then decelerates throughout the whole section with the point of maximum velocity depressed below the surface. During upstream flow the initial surface acceleration is less and the maximum velocity is not reached until two-thirds of the period has elapsed. The maximum velocity occurs at the surface while the flow is accelerating and is depressed when the flow is decelerating.

Plots of the velocity distributions (see Figure 4 for typical examples) show that in the Avon test section there are two velocity maxima during periods of acceleration in the downstream direction, and also during deceleration in the upstream direction. There is only a single maximum during periods of acceleration in the upstream direction and during deceleration in the downstream direction. Furthermore, these maxima occur at the surface while the flow is accelerating in either direction, but are depressed well below the surface while the flow is decelerating, reaching a proportional depth of 0.65 during upstream flow.

Typical velocity distributions for the Heathcote section are shown in Figure 5. Until 0230 hours they show the region of slack water in the base of the thalweg and the maximum velocity to be over the point bar (inside of bend). There is a second, but smaller, velocity maximum in the thalweg. After 0230 hours, when the flow starts decelerating downstream, the outer or thalweg maximum becomes dominant as the inner maximum disappears to give a single peak distribution by 0400 hours approximately. See Figure 5a. The flow over the point bar comes to rest at approximately 0600 hours. After slack water at low tide and until the maximum upstream velocity is reached the maximum velocity remains at the outside. A second velocity peak starts to develop over the point bar at approximately 0930 hours and is well developed by 1030 hours. See Figure 5b. From this time on velocities over the point bar are considerably greater than those in the thalweg. The two peaked distribution is maintained throughout this period.

Hence during period of upstream acceleration (or deceleration in the downstream direction), 0300 hours until 1030 hours approximately, the velocity distribution is biased towards the outside of the bend (thalweg). For the downstream acceleration (upstream deceleration) period the flow is biased towards the inside of the bend. These two periods are separated by the two points of contraflexure of the stage-time graph. An explanation as to why the flow behaviour should divide into two periods according to the acceleration direction, rather than the velocity direction is not apparent.

The Heathcote test section was located at about 0.4 of the total arc of the bend, measured from the upstream end. Thus the results of Shukry (7) would suggest that the maximum velocity should occur near the inside of the bend, particularly during downstream flow, while Leopold and Wolman (8) suggest the maximum should be near the outside. The results of this study favour the latter as there was always at least a local velocity maximum near the outer bank and only during downstream acceleration or upstream deceleration (36% of the time) was there a maximum over the point bar. Leopold and Wolman's statement that the velocity maximum is depressed below the surface is also borne out except during periods of rapid acceleration. Hooke's (9) observation of two velocity peaks is supported during upstream deceleration.

Index Point: In the Avon section, which is in a relatively straight and regular reach, an index point was found where the velocity bears a constant ratio to the mean velocity in the channel, throughout both upstream and downstream flow. This index point was located just below low-water level and at a distance from that bank which is nearest the deepest section equal to one-third of the total channel width. There is thus the possibility of using one flow meter fixed at this point to give both instantaneous measurements and a continuous record of discharge.

For the strongly asymmetrical section in the Heathcote no such index point could be found, even taking the downstream and upstream flow periods separately.

CONCLUSIONS

Detailed velocity measurements throughout a tidal cycle in two river sections have shown:

1. The velocity-time relation during downstream flow is markedly different from that during upstream flow.

2. Maximum velocities occur near the surface while the flow is accelerating and are depressed during deceleration.

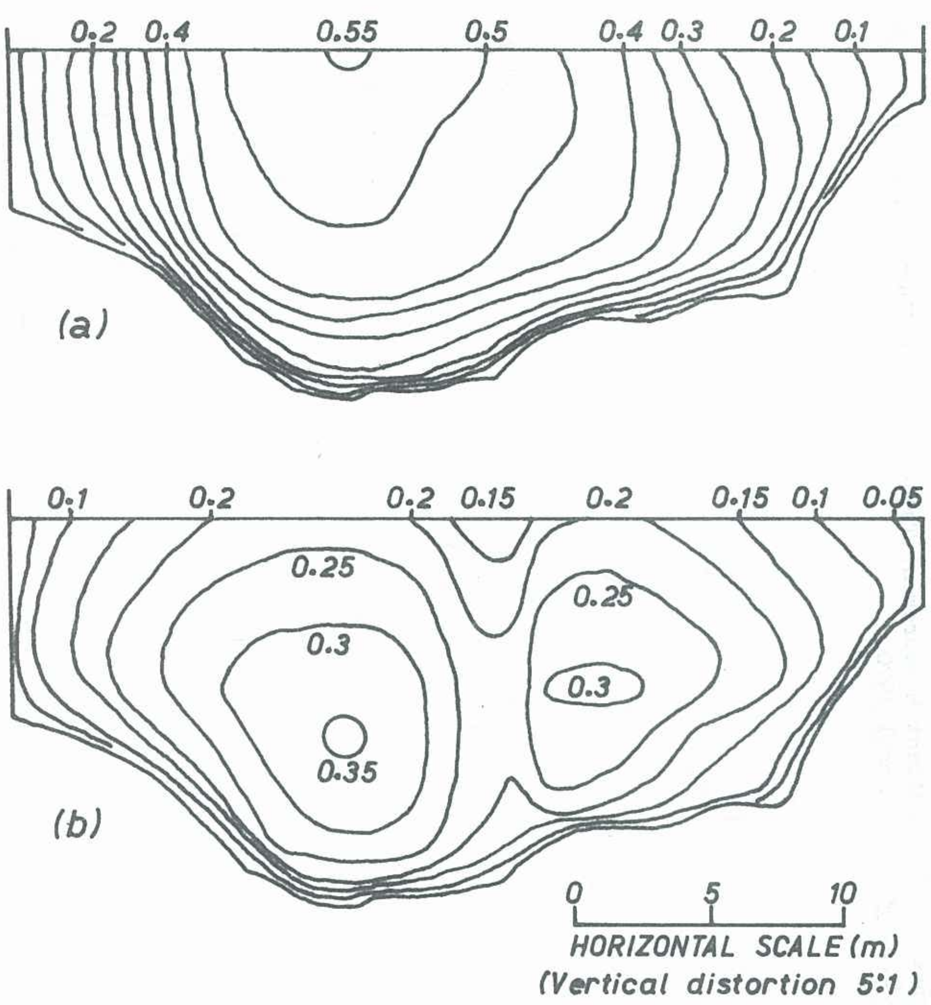

FIGURE 4. Velocity distributions (in m/sec) for the Avon section looking upstream. (a) Time 1100 hours, flow accelerating upstream. (b) Time 1220 hours, flow decelerating upstream.

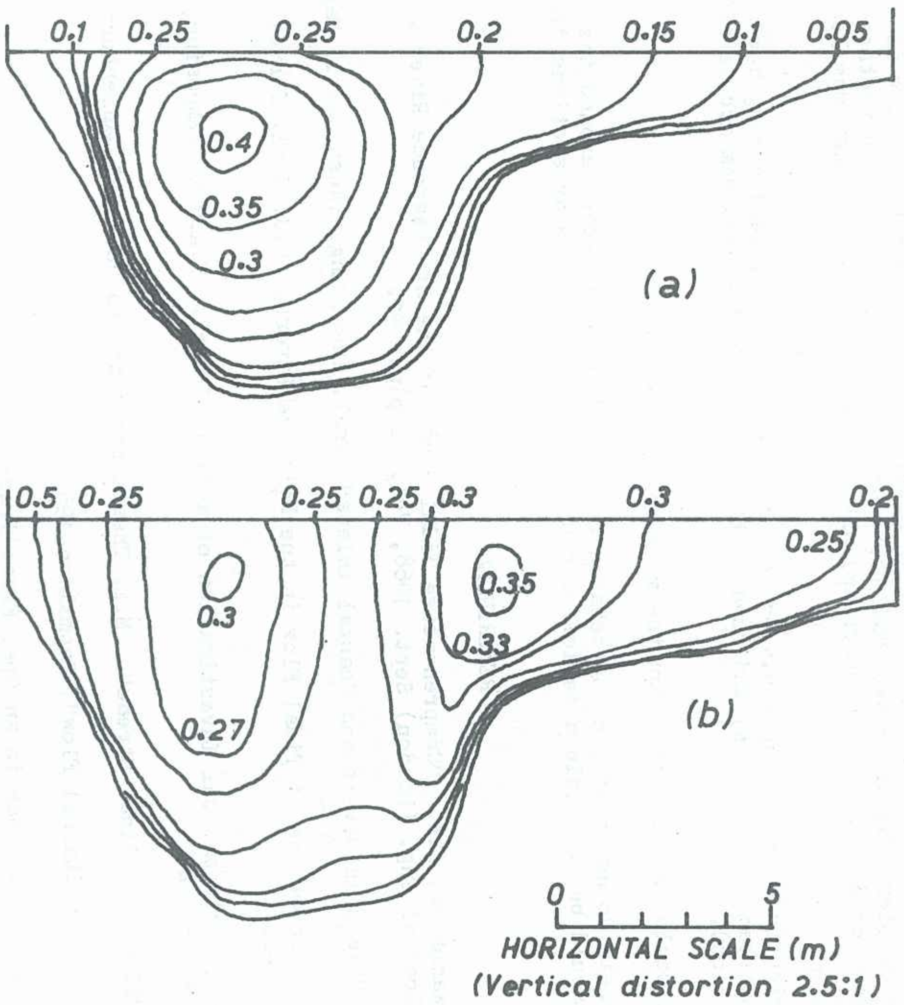

FIGURE 5. Velocity distributions (in m/sec) for the Heathcote section looking upstream. (a) Time 0430 hours, flow decelerating downstream. (b) Time 1030 hours, flow near maximum upstream velocity.

3. Velocity distributions have two distinct forms according as to whether the flow is accelerating downstream (or decelerating upstream) when there are two velocity maxima or whether it is accelerating upstream (or decelerating downstream) when there is one velocity maximum located near the outer bank.

4. Velocity distributions are strongly biased towards the inside of a bend during downstream acceleration (or upstream deceleration) and towards the outside during upstream acceleration (or downstream deceleration).

5. An index point could be found only for the more regular section.

The results herein do not describe the behaviour of the flow as it moves around the bend. A useful extension would be to obtain a series of continuous gauging tests at sections distributed around the bend.

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