Field Measurements of Reynolds Stress near a Riverbank

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ABSTRACT

The Reynolds stress field was measured near the bank of the Powder River in southeastern Montana. The measurements were made from the bank using an aluminum I-beam cantilevered over the water to support a carriage system for positioning an acoustic doppler velocimeter in a vertical plane perpendicular to 1) the bank and 2) the streamwise velocity field. During quasi-steady flow at the peak (71 m^3s^{-1}) of the spring snowmelt runoff in May 1996, turbulent velocities were measured at 25 Hertz along six vertical locations spaced 0.5 m apart and within about 3.5 m of the riverbank.

When the turbulent velocities are transformed to the ray-isovel coordinate system appropriate for this two-dimension problem, the turbulent characteristics near the bed are consistent with similar field measurements made by others for the one-dimensional problem of uniform flow over a horizontal bed far from lateral boundaries. The three turbulent intensities, $(\overline{u'^2})^{1/2}$, $(\overline{v'^2})^{1/2}$ and $(\overline{w'^2})^{1/2}$, normalized by the local shear velocity, u_* were essentially constant with distance above the bed along a ray and the average values were 2.1, 1.4, and 1.2. Future turbulence measurements could be improved by measuring the streamwise flow first, then determining the approximate location of the rays and isovels so that the turbulence measurements could be made along the approximated rays rather than along verticals. In addition, to improve the possibility making turbulence measurements during steady, uniform flow, the site should be carefully selected to minimize local flow accelerations caused by spatial variability of the riverbank. Also, the measurements should be made at times when the stage is constant, no local erosion or deposition of sediment occurs, and when wind velocities are small. [1]

INTRODUCTION

Few measurements have been made of Reynolds stresses in rivers and no complete Reynolds stress fields have been measured near riverbanks. Accurate knowledge of the boundary shear stress is required for calculating both flow and sediment transport in the vicinity of riverbanks. For suspended-load transport, accurate knowledge of the effective turbulent diffusion coefficient fields for both mass and momentum also is essential. For many geomorphic processes, this information is required in the neighborhood of riverbanks. Near a planar boundary, far away from channel walls, the mean velocity obeys a logarithmic relation with distance along a normal or straight line perpendicular to the bottom boundary. Well away from the riverbanks over a flat bed, the direction of the normal is approximately vertical, but this is not the case near riverbanks, even for the simple channel geometries used in laboratory studies (Knight, et al., 1994). Near riverbanks, the direction of the normal deviates from the vertical as

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the boundary changes from nearly horizontal to a sloping or nearly vertical bank. The normal is no longer straight but is a curve or *ray* orthogonal to the isovels and to the boundary. In this ray-isovel coordinate system, the flow equations should predict the same turbulent behavior along a curved ray near a riverbank, as they predict along a straight vertical for the one-dimensional flow problem over a wide, horizontal bed (Lundgren and Jonsson, 1964; Houjou et al., 1990).

Few studies of turbulence in rivers have measured all three components of the instantaneous velocity field, which in channels with irregular beds and lateral boundaries, is required to calculate the Reynolds stresses and boundary shear stresses. Many studies have measured just the streamwise component (Yokosi, 1967; McQuivey, 1973; Sidorchuk, 1996; Nikora and Smart, 1997). Several studies have measured the streamwise and vertical components (Kawanisi and Yokosi, 1993; Roy et al., 1996) and some have measured the streamwise and cross-stream components (Griffith and Grimwood, 1981; Mazumder et al., 1991; Bhowmik et al., 1995). Only a few, however, have measured all three components of the instantaneous velocity. McLean and Smith (1979) used impeller current meters which sampled at 10 Hz, Heslop et al. (1994) used paired electromagnetic current meters sampling at 10 Hz, and Sukhodolov et al. (1998) and Nikora and Goring (2000) used an ADV (accoustic doppler velocimeter) which sampled at 25 Hz. Sukhodolov et al. (1998) found vertical profiles of Reynolds stress measured near the middle of a channel agreed with a semitheoretical expression for one-dimensional flow over a flat bed (Nezu and Nakagawa, 1993). In contrast, a vertical profile at the foot of a bank, measured by Sukhodolov et al. (1998), displayed large differences from the values predicted by Nezu and Nakagawa's theory, perhaps because the data for this site were not presented in the ray-isovel coordinate system. This vertical profile was close to a sloping bank, but unlike the laboratory studies, it did not resolve the Reynolds stresses field across the bank. To date, no published field studies have characterized the Reynolds stress field near or over a sloping riverbank. The goal of this study was to make such measurements.

FIELD CONDITIONS

Acoustic doppler velocimeter (ADV) measurements were made from the bank of Powder River in southeastern Montana. The Powder River is one of the few remaining rivers of its size in the western United States that is not controlled by a dam or other large engineering structure. Its headwaters are mostly in the Bighorn Mountains in north-central Wyoming from which it flows generally northward through Wyoming and southeastern Montana (fig. 1). At Moorhead, Montana, the gaging station near the Wyoming-Montana state line and 9 km upstream from where the measurements were made, the

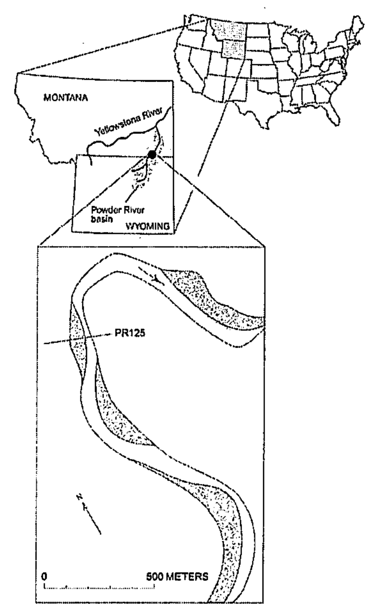

Figure 1. Location of the measurement site on Powder River in southeastern Montana. Cross-hatched areas are new flood plains. Reynolds stress measurements were made from the left bank of the new flood plain; 42 m upstream from cross section PR125.

annual mean discharge is 12.7 m^3/s (U.S. Geological Survey, 1996). The river has a sand and gravel bed, an average slope of 0.0015, and suspended-sediment concentrations, which range from 5,000 to 50,000 mg/L during floods. A major flood (800 m^3/s at Moorhead) occurred in 1978, which widened the channel. After the 1978 flood, new flood plains were deposited in the widened channel and grew to a height of about 1 m in about 18 years (Moody et al., 1999; Moody and Troutman, 2000). ADV measurements were made from the bank of one of these flood plains just upstream from a channel cross section (PR125, Moody and Meade, 1990), which had been resurveyed each year since 1978 (fig. 1). The measurement site was on the left bank of a very slight bend opposite a cutbank located between two large bends in the Powder River. The measurements were made on 28 May 1996 during the spring snowmelt runoff from the Bighorn Mountains. Water discharge was less than bankfull. It peaked at 71 m^{3}s^{-1} on the 28th of May, then remained steady through the 29th (fig. 2). The stage corresponded to a water-level elevation of 1006.03 m, a channel width of 55 m, a mean depth equal to 1.5 m, and a mean cross-sectional velocity equal to 0.87 ms^{-1}. The mean flow was subcritical (Froude number = 0.23) with a width to depth ratio of 37 and a flow Reynolds number equal to 1.1 x 10^6. Suspended-sediment concentration was 18,000 mgL^{-1}, water temperature was 9.8 °C, the specific conductivity for the water was 155000 μSm^{-1}, and the speed of sound in the river was about 1447 ms^{-1}. Initially on 27 May 1996, water depths near the bank (station 25.5 to 29.0 m measured from an arbitrary baseline on the left bank) ranged from 0 to 1m. However, as the water level rose about 0.2 m, fine to very fine sand (65 to 250 μm) was deposited on a flat area between stations 27.4 and 29.0 m. By the morning of 28th of May, water depths had decreased and ranged from 0 to 0.6 m over a very unconsolidated bottom that had a slope of 9° to 13°.

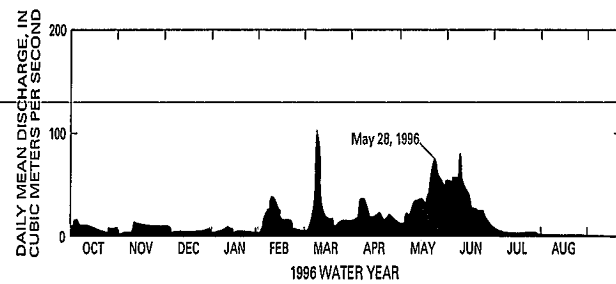

Figure 2. Hydrograph for the 1996 water year at the gaging station at Moorhead, Montana, on the Powder River. Turbulent measurements were collected on three days during the rising and peak stages of a snowmelt runoff flood. Reynolds stress was computed for 28 May 1996

MEASUREMENT METHOD

The ADV was cantilevered over the left bank of Powder River using a 25-ft aluminum I-beam. The I-beam was supported on the bank by a steel platform (a 0.25-inch thick U-shaped, channel beam 6-inch wide x 9-feet long with sides1.75-inch tall) mounted on two vertical pipe supports (fig. 3A). The supports were 1.5-inch diameter pipes, which screwed into a 1.5-inch couplings embedded in concrete footings set flush with the flood plain. Various lengths of supports were available to insure that the steel platform and hence the bottom of the I-beam were bove the water level. A pipe flange was screwed onto the top of each support and leveled. A steel platform was bolted to the pipe flanges. The I-beam was held in place on either side by steel flatbar clamps (1.5-inch x 9-foot long) bolted to the steel platform. With the clamps loose, the I-beam could be moved out over the bank, to a desired distance, with the aid of a roller mounted on the end of the steel platform. Once positioned, the bolts for the clamps were tightened. Two steel stays (previously attached to the end of the I-beam out over the water) were attached to deadmen located onshore and about 5.5 m upstream and downstream from the I-beam.

Tightening the turnbuckles on these stays eliminated any vibration of the I-beam caused by wind or the current flowing passed the ADV.

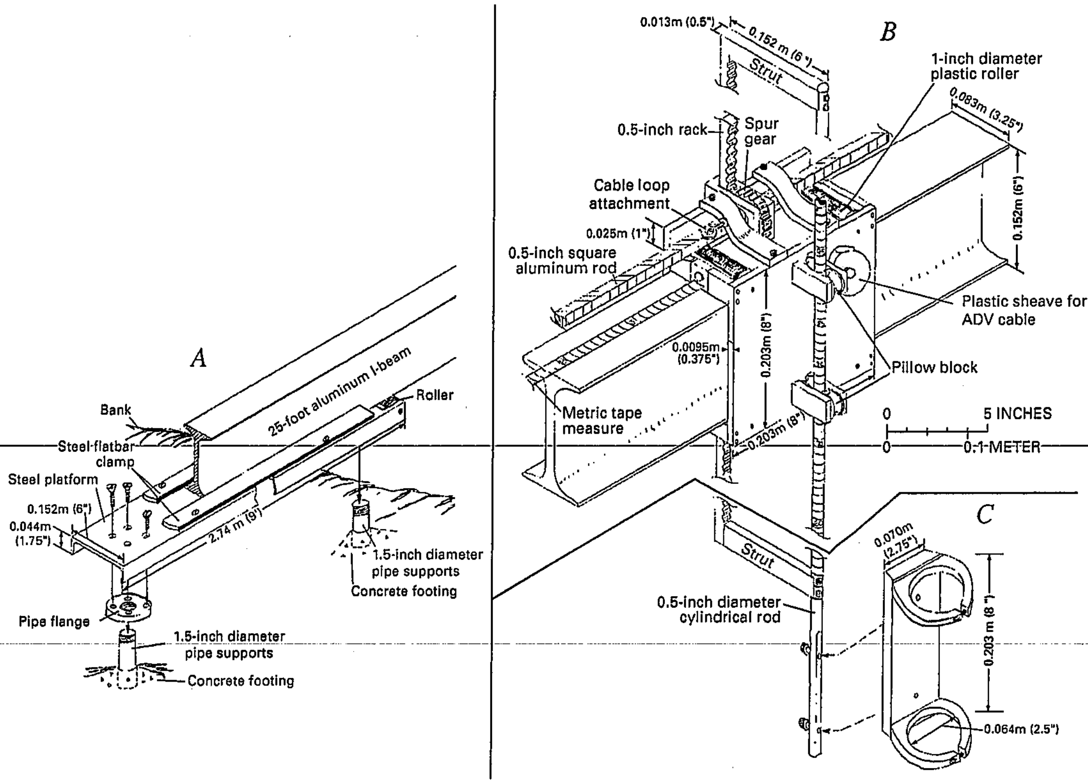

Figure 3. Equipment for collecting turbulent measurements near a river bank using an acoustic doppler velocimeter (ADV). A. Steel platform for mounting the I-beam. B. Details of the carriage assembly. C. Mounting bracket for the ADV.

The ADV was mounted on a carriage system that rode on the I-beam. This carriage allowed the ADV to be moved out away from the bank and to be moved vertically. The carriage had two 1-inch diameter, hard plastic rollers which rolled on the I-beam. It was moved horizontally by pulling a cable loop that was attached to the front and rear ends of the carriage and passed around 2-inch diameter, plastic sheaves mounted at either end of the I-beam (fig. 3B). To measure horizontal distances, the zero end of an automatically-retracting, metric tape measure was attached to the carriage and the tape housing was mounted on the landward end of the I-beam. On 28th of May, the left edge of water was at station 26.2 m and the end of the I-beam was at 29.4 m so that measurements could be made over a distance of 3.2 m away from the bank. A rack and spur gear system mounted in the carriage controlled the vertical motion of the ADV over a vertical range of 2.2 m (fig. 3B). This system consisted of two vertical members, one on either side of the carriage, held together by a horizontal struts at the top and bottom of the members. One member was the rack gear (0.50-inch square stock with 24 pitch teeth on one face) passing through two bearing blocks to maintain the vertical orientation. The other member was a cylindrical rod (0.50-inch stainless steel) passing through two pillow blocks mounted on the opposite side of the carriage to maintain the vertical orientation. The rod was painted white and had markings every 0.01m to determine the vertical position of the ADV. The ADV was mounted at the bottom of this member using a bracket (fig. 3C). The vertical motion was controlled by rotating the landward end of a horizontal rod (0.50-inch square aluminum) passing through two pillow blocks and then through the spur gear and ending in a pillow block at the riverward end of the I-beam. The square rod was not attached to the spur gear so that the carriage could slide along the I-beam.

A right-handed measurement coordinate system was defined based on the system used to measured cross sections of Powder River in the past (Moody and Meade, 1990). Cross-stream or y-direction was measured from the left bank (defined facing downstream) to the right bank and station zero was located on a terrace on the left bank above the elevation of the flood plain. The landward edge of the I-beam was at station 22.15 m. The streamwise or x-direction was parallel to the channel, the positive x-direction was upstream (thus, the streamwise velocity component was negative), and $x = 0$ was located 0.141 m upstream from the center of the I-beam. The z-direction or vertical direction was positive upward with $z = 0$ at the top of the I-beam.

Turbulence measurements were made using an ADV with a 5-cm probe (S/N 1345) on three days during the rising and peak stages of a snowmelt flood. In the field the distance from the probe tip to the sample volume was checked each day and averaged 0.056 m. On 28 May 1996, turbulent velocities were measured first at the vertical farthest from the bank. Measurements were started closest to the bed and the ADV was raised in increments of either 0.05 or 0.10 m to about 0.07 m below the surface. The proximity to the surface was limited by the need to keep the probe and sample volume in the water during the entire sampling interval. Thus, the measurements closest to the surface were at the same depth while the other measurements were essentially the same distance above the bed. After measurements were finished at one vertical, the carriage and ADV were moved toward the bank 0.5 m and measurements were collected at the next vertical. Data files were collected with varying lengths at 25 Hz. Data was collected for 1000 seconds at the locations closest to the bed in order to improve resolution of the near-boundary turbulent structure. Files were 500 seconds long for location in the middle of the water column and 200 seconds for locations closest to the surface. The water depth was about 0.5 m and the mean flow was about 0.50 ms^{-1}, so that an estimate of the peak turbulence frequency (based on Taylor's frozen turbulence hypothesis) was about 1 second. Therefore, the shortest time interval provided about 200 measurements of the low frequency turbulence. Data was recorded in the velocity range 0-1.00 ms^{-1} with an accuracy of 1 percent or 0.01 $m\,s^{-1}$.

RESULTS

Mean velocity

A gusty wind came up during the measurement period and seriously affected the flow at several verticals near the bank. Mean velocity for each component (in the measurement coordinate system) increased with distance from the bed at four of the six verticals. At the vertical 1(station 26.75 m) closest to the bank there was only one measurement 0.074 m below the surface in about 0.10 m of water (fig. 4). The streamwise mean velocity was –0.02 ms^{-1} (negative is downstream), but the mean cross-stream (<-0.01 ms^{-1}) and mean vertical velocities (< -0.01 ms^{-1}) were essentially zero and directed into the bank and into the bed. At vertical 2 (station 27.25 m) in 0.20 m of water both the streamwise and vertical velocities increased from mid depth toward the bed. Two of the three measurements, about 0.02 and 0.07 m above the bed, had skewed data for all three velocity components, so that data from this vertical was not used in the Reynolds stress calculations. While collecting the measurements at vertical 3 (station 27.75 m), the wind produced pulses of upstream flow. Although wind appears to have influenced the flow at this vertical, the mean streamwise component was downstream and decreased from –0.13 ms^{-1} at the surface to <0.01 ms^{-1} at about 0.01 to 0.03 m above the bed. Also at vertical 3, the mean streamwise surface velocity appeared to be anomalous because it was greater than the mean streamwise surface velocity at vertical 4 (farther away from the bank) and did not fit the pattern of streamwise surface velocities decreasing toward the bank. Therefore, measurements from vertical 3 were not used in the Reynolds stress calculations. The wind had a slight effect (producing only one 25 second, 0.05 ms^{-1} upstream pulse) on one measurement of the streamwise velocity at mid-depth at vertical 4 (station 28.25 m). Recall that the measurements were made at different times at different locations and the wind was gusty so that its effect on the various velocity measurements varied. At verticals 5 and 6, the measurements were made before the wind produced noticeable effects on the velocity components. At all three verticals (4, 5, and 6), the mean streamwise velocities decreased toward the bed. The cross-stream velocities (<-0.01 to –0.05 ms^{-1}) were all directed toward the bank except at vertical 5 (station 28.75 m) where the velocity about 0.03 m above the bed was 0.04 ms^{-1}. The vertical velocities were very small, quite uniform with depth, and always directed downward indicating a slight misalignment of the measurement frame of reference. The lack of flow reversal by the mean cross-stream velocity, their similarity in magnitude, and the uniform vertical velocities indicated that no definite secondary flow existed near the bank. Based on the lack of a coherent secondary flow, it was assumed that the small finite cross-stream velocities also were a result of misalignment of the measurement coordinate system.

The data was, therefore, rotated to eliminate the mean cross-stream and mean vertical velocities. Each measurement along the three verticals (4, 5, and 6) was first rotated separately about the y-axis and z-axis to eliminate the cross-stream and vertical velocities, and then the average rotation angles were computed for each vertical. The rotation angles about the y-axis were 7.2°, 5.8°, and 7.8° for vertical 4, 5, and 6 respectively and transformed the data into the x'-, y-, and z'- coordinate system. The rotation angles about the z'- axis were 15.6°, 7.7°, and 4.7°, indicating some convergence of the streamlines among the three verticals. These rotations transformed the data into the x''- y'- and z'- coordinate system. The x''-axis defined the streamwise coordinate of the curvilinear coordinate system. All corrections for misalignment of the measurement coordinate system were small; therefore, the rotated mean streamwise velocity was essentially the same as the measured mean streamwise velocity.

Isovels and Rays

Isovels were determined by four constraints. Two constraints were the coordinates of the velocity at two locations, which were estimated by piecewise logarithmic interpolation between measurement locations on each vertical. And because there was no secondary circulation, the other two constraints were the slope of the isovel at two locations defined by the average rotation angle, θ, about the x''-axis required to eliminate the cross-stream shear stress, τ_{zy} (stress in the y-direction on the plane perpendicular to the z-axis). The same mean streamwise velocity did not occur on all three measured verticals. Only in a limited range of depths did it occur on two verticals (see cross-hatched area in figure 4), and usually it only occurred at one depth on some verticals. Therefore, to provide the second coordinate for some isovels, the surface velocity was linearly interpolated between verticals after logarithmically extrapolating the velocities to the surface. The corresponding rotation angle, θ, at the surface was computed by linearly interpolating between the average rotation angle at each vertical. Using these four constraints, isovels were then computed every 0.01 ms^{-1} as cubic splines. Rays were computed numerically as a series of straight line segments between each isovel. Where the isovels were spaced farther apart than about 0.01 m, additional isovels were added such that the

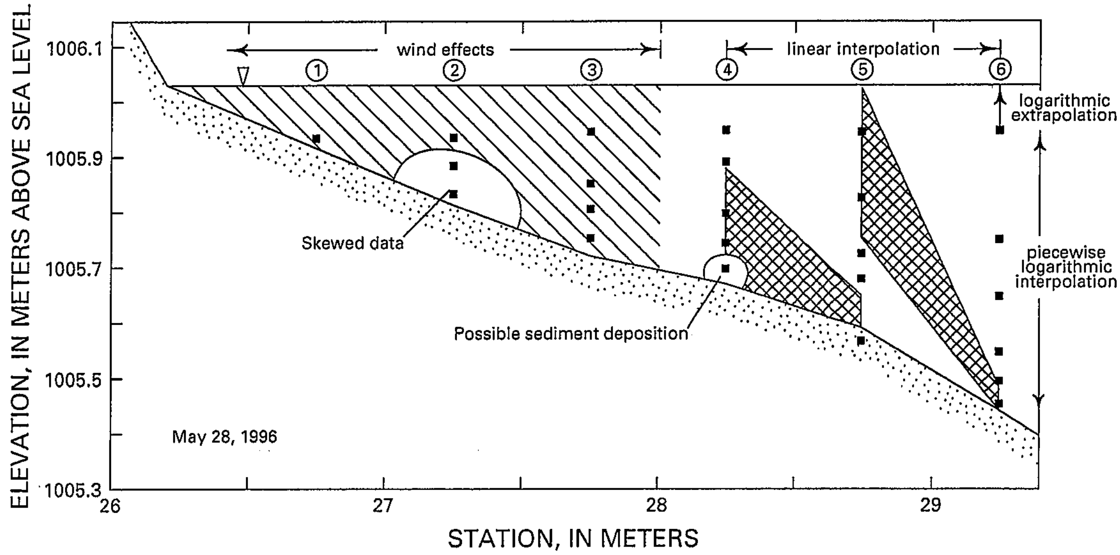

Figure 4. ADV turbulent measurement locations at six verticals (vertical 1 is closest to the bank) near the bank on 28 May 1996. The areas of skewed data, wind influence, interpolation and extrapolation are labeled. The cross-hatched area indicates the region where the same velocities occurred on two verticals.

product of the slopes (equal to -1) of two lines perpendicular to each other (the isovels and rays) was within about 0.05. Three rays (fig. 5) were computed between the three verticals. Ray B passes through the measurement location closest to the bed on vertical 5 and is deemed to provide the most accurate information.

Reynolds Stresses

Reynolds stresses in the fluid coordinate system consist of the three normal stresses, τ_{xx}, τ_{yy}, and τ_{zz}, and the two shear stresses, τ_{zx} and τ_{yx} (table 1). The sixth Reynolds stress, the cross-stream shear stress τ_{zy}, was minimized by rotation through angle, θ, which defined the slope of the isovels. This stress component was not identically zero because θ represents the average value along each vertical. However, only one rotated value of τ_{zy} near the surface at vertical 6 was greater than the measurement accuracy (± 0.2 N m^{-2}). Magnitudes for τ_{yx} were less than 0.9 N m^{-2} and all but one were directed in the downstream direction. These also decreased toward the bank.

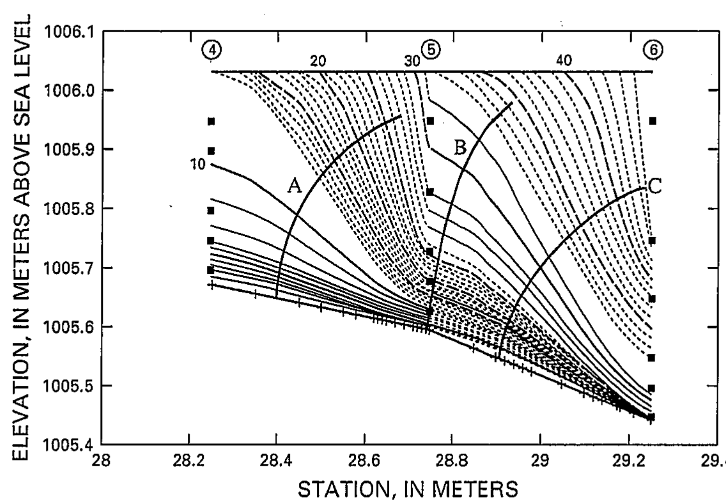

Figure 5. Isovels are shown as solid lines where two slopes and two coordinates were measured. Where slopes and coordinates were interpolated the isovels are dashed lines. The three rays were computed numerically. The bottom is shown as a stippled line with + symbols

Table 1. Rotated Reynolds stresses (N m^{-2})

τ_{xx}			τ_{yy}			τ_{zz}		
Vertical 4	Vertical 5	Vertical 6	Vertical 4	Vertical 5	Vertical 6	Vertical 4	Vertical 5	Vertical 6
-2.3	-3.2	-4.1	-1.3	-1.2	-4.1	-0.6	-0.8	-1.8
-2.1	-3.4	-5.6	-1.3	-1.6	-2.5	-0.6	-1.0	-2.6
-3.1	-4.6	-5.7	-1.1	-2.0	-2.9	-0.5	-1.3	-2.7
-1.6	-4.1	-6.5	-0.9	-1.9	-2.9	-0.4	-1.3	-2.5
	-4.7	-5.7		-1.7	-3.1		-1.3	-2.4
		-5.2			-2.8			-1.9
τ_{zx}			τ_{yx}			τ_{zy}		
Vertical 4	Vertical 5	Vertical 6	Vertical 4	Vertical 5	Vertical 6	Vertical 4	Vertical 5	Vertical 6
-0.5	-0.7	-1.0	-0.3	-0.3	-0.4	0.0	<0.1	-0.3
-0.5	-0.5	-1.4	-0.2	-0.7	-0.7	0.0	<0.1	0.0
-0.6	-1.1	-1.4	-0.4	-0.4	-0.8	0.0	0.1	<0.1
-0.4	-1.7	-1.4	0.0	0.0	-0.7	0.0	0.0	0.1
	-1.1	-1.3		0.8	-0.9		0.0	0.0
		-1.1			-0.3			<0.1

All three normal stresses decreased toward the bank. They ranged from –6.5 to –0.4 N m^{-2}, and the average ratios of these normal stresses τ_{xx}/τ_{zz}, τ_{yy}/τ_{zz}, along the three rays are listed in table 2. The turbulent kinetic energy, k, is ½ the sum of the absolute values of each of the normal stresses

$$k = \tfrac{1}{2\rho}\left(|\tau_{xx}| + |\tau_{yy}| + |\tau_{zz}|\right),$$

and was nearly constant with distance above the bed along each of the three rays (fig. 6A).

The streamwise shear stresses, τ_{zx}, were also nearly constant with distance along the rays away from the boundary. Magnitudes decreased toward the bank and where all directed downstream (fig. 6B). The boundary shear stress can be computed by extrapolating τ_{zx} to the bed. Because turbulence from other than local sources may have been advected through the measurement section near the surface, the boundary shear stress was estimated by linear extrapolation of those values less than 0.22 m above the bed. This gave boundary shear stresses of 0.61, 1.1, and 1.2 N m^{-2} for rays A, B, and C, and corresponding values of u_* equal to 0.025, 0.033, and 0.034 ms^{-1}.

DISCUSSION

Measurement Method

Detecting the bottom was a severe problem in water with a high suspended-sediment concentration (18,000 mg/L). Tests were made in a bucket in the field 1) using local well water, 2) a mixture of 50 percent well water and 50 percent river water, and 3) 100 percent river water. With well water the error was 1.5 percent less than the true depth. However, with the 50-50 mixture the error was 9.9 percent greater than the true depth, and for the river water it was 16.5 percent greater. The suspended sediment increased the signal strength of the sample volume peak from about 59 dB to about 74 dB, but it may also have produced an asymmetrical peak. Suspended sediment definitely decreased the signal strength of the bottom echo peak from about 50 dB to about 36 dB, and raised the signal strength of the minimum between the sample volume and bottom echo peaks. Thus, the bottom echo peak frequently appeared as a shoulder on the main sample volume peak. This phenomena could be seen using the program ADFCHECK (Son Tek, 1995), but was not detected during data collection phase. The sample volume peak and the bottom echo peak were frequently double peaks, which also may have been a result of the high suspended sediment concentration. The acoustic effects of the suspended sediment were not the only problem; the actual deposition of sediment also was a problem. In trying to make measurements as close as possible to the bed, the ADV sample volume was probably buried near the end of one turbulent measurement lasting 1000 seconds, because the average signal correlation parameter decreased from 92-98 to values near 86.

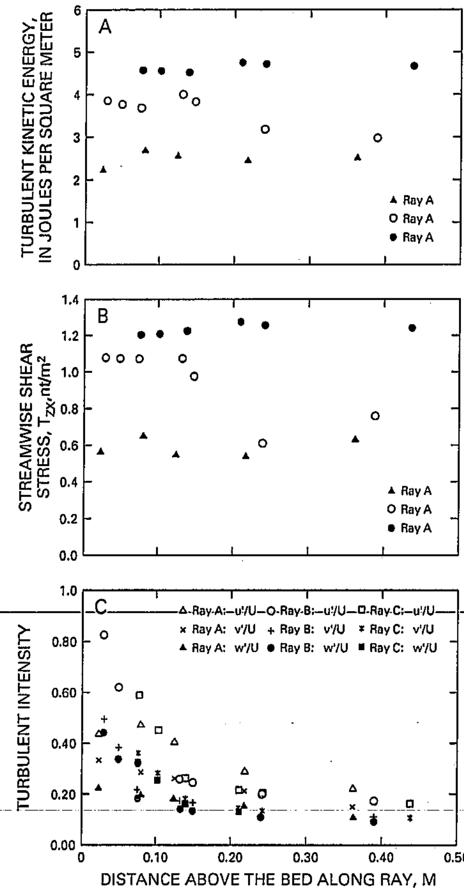

Figure 6. A. Variation of the turbulent kinetic energy, *k*, along three rays. B. Variation in the streamwise shear stress along three rays. C. Variation in the turbulent intensity (normalized by the mean streamwise velocity) along a ray

Mean streamwise velocity gradients in the cross-stream direction were large near the bank. They were about 0.34 ms^{-1} per m at the surface between verticals 4 and 6 and 0.25 ms^{-1} per m near the bottom. The vertical spacing of 0.5 m used in these measurements was too large because the same mean velocities did not occur on all three verticals and only occurred at a limited range of depths at two verticals. Thus, the location of the isovels was uncertain between each vertical and only defined by four constraints. Future measurements of Reynolds stress could be improved by making a few initial measurements to determine the streamwise velocity gradients in the cross-stream direction and general slope of the isovels. With this information, the proper spacing of the measurement locations could be determined and measurements could be approximately aligned along rays, which would decrease the error in having to interpolate between verticals onto a ray.

The 22 turbulence measurements collected on 28 May 1996 took 3.53 hours. This length of time is a disadvantage in the field when the stage and flow conditions could be changing. Data files were collected with varying lengths. Data files alone for the first vertical represented 53 minutes without counting time to reposition the ADV instrument. If each file were reduced to 200 seconds the total sample collection time would have been decreased by 62 percent to 1.33 hours. The turbulence measurements would then have been made during a shorter time interval, which would be more likely to approximate steady-state conditions. In retrospect, it appears that some accuracy should be sacrificed to obtain a more densely sampled velocity field.

Turbulence Characteristics

Reynolds stresses and mean flow properties can be combined in several different ways to characterize the turbulence. The three relative turbulence intensities, $\sqrt{\overline{u'^2}}/\overline{U}$, $\sqrt{\overline{v'^2}}/\overline{U}$, and $\sqrt{\overline{w'^2}}/\overline{U}$, decreased with distance above the bed (fig. 6C). Depth-averaged magnitudes for all three verticals were about three times greater than those reported near the center of a channel by Heslop et al. (1994) for the River Severn and by Sukhodolov et al. (1998) for the Spree River. Normalization of the turbulent intensities by the velocity is not a stable prameterization. The turbulent intensities depend primarily on the shear velocity, whereas the fluid velocity depends on both the shear velocity and the bed roughness. Moreover, in density stratified flows the density stratification reduces the turbulent intensities while it increases the velocity. Use of the shear velocity rather than the local flow velocity provides a more stable relation, particularly for flows that are homogeneous with respect to fluid density. It is likely that the flow velocity is a factor of 2 or 3 higher for a given shear velocity in the Svern and Spray Rivers than in the much smaller Powder River, which has a much coarser bed. When the three turbulent intensities, $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$ and $\sqrt{\overline{w'^2}}$ are normalized by u_*, they are more stable (table 2). The average values along the three rays (2.1,1.4, and 1.2) near the bed are essentially the same as those measured by Soulsby (1981) over a marine sandbank (2.3, 1.8, and 1.2 for an infinitely wide bed), by Sukhodolov et al. (1998) near the bed at the center of a river channel (2.0, 1.5, and 1.0), and those predicted by Nezu and Nakagawa (1993) for laboratory measurements over a flat bed (2.3, 1.3, and 1.6).

Table 2. Depth-averaged values of turbulent characteristics

[Values after the ± symbol are standard errors]

	Ray A	Ray B	Ray C
u'/u_*	2.2 ±0.06	2.0 ±0.02	2.1 ±0.01
v'/u_*	1.4 ±0.01	1.3 ±0.02	1.4 ±0.01
w'/u_*	1.1 ±0.02	1.1 ±0.00	1.3 ±0.02
τ_{xx}/τ_{zz}	4.3 ±0.29	3.4 ±0.06	2.7 ±0.10
τ_{yy}/τ_{zz}	1.9 ±0.07	1.4 ±0.04	1.2 ±0.09
k/u_*^2	4.0 ±0.11	3.3 ±0.04	4.0 ±0.04
$0.5u'^2/k$	0.59 ±0.01	0.58 ±0.01	0.54 ±0.01
$0.5v'^2/k$	0.27 ±0.01	0.24 ±0.01	0.24 ±0.00
$0.5w'^2/k$	0.14 ±0.00	0.17 ±0.01	0.21 ±0.01
τ_{xx}/k	0.24 ±0.01	0.26 ±0.01	0.27 ±0.01

CONCLUSIONS

The cantilevered I-beam system provided a good platform for positioning the ADV near a river bank to with about 0.01m in the horizontal and vertical. The turbulence measurements could be improved by: 1) measuring the mean flow first and determining the approximate location of the isovels and rays before making turbulence measurements, 2) increasing the density of samples in regions where the lateral shear is large, 3) reducing the sampling time to 200 seconds to increase the number turbulence measurements that can be made, 4) locating the bottom each time and positioning the ADV relative to the bottom, and 5) making the measurements in the early morning or at times when wind velocities are near zero. Also the choice of a site where the near-bank flow is unaccelerated is essential for procuring a data set that is accurate enough to use to field-test turbulence closures. Selection of an appropriate field site is perhaps the most important factor in the design of a successful field experiment.

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