CHAPTER 6.
SUMMARY AND CONCLUSIONS

6.1. Summary

A field study of flows over bedforms was conducted in two river systems, the Kankakee River (KANK-1 data set) and the Missouri River (MO-1 and MO-2 data sets). The MO-2 data set was determined to have bedforms that approximated equilibrium dunes, whereas the KANK-1 and MO-1 data sets did not. Detailed vertical velocity profiles were collected with both ADCP and ADV instrumentation at numerous locations along the bedforms. The ADV data has a positive bias of approximately 5% attributable to the data collection platform. Reynolds stress data were determined from some of the data, with good spatial resolution for the Missouri River data set MO-2. Also, limited sediment concentration data were collected for the KANK-1 and MO-1 data sets. Field data sets from Smith and McLean (1977) and Kostaschuk and Villard (1996) were also used in this research. The Smith and McLean data sets, and the June 27 and June 29 data sets of Kostaschuk and Villard (1996) were determined to have bedforms that can be classified as near-equilibrium dunes. The June 21 data set of Kostaschuk and Villard (1996) had bedforms that did not fit into the equilibrium dune category. The existing methods for predicting bedform type were found to be lacking in their ability to accurately predict the type of bedform present in the field experiments considered in this research.

The spatially averaged and at a vertical velocity distribution was logarithmic in nature for all data sets. Flow separation was noted in the measurements over the Missouri River bedforms, with the smaller superimposed bedforms appearing to be the controlling feature on the MO-2 data. There is good collapse of the spatially averaged field-scale velocity data in both inner and outer scales (log-linear and velocity defect form).

Laboratory flume data produce similar flow behavior to field-scale flows over equilibrium dunes, although there appears to be more sensitivity to boundary conditions in the laboratory-scale velocity data. Multi-layered, spatially averaged logarithmic velocity profiles occur for flows over equilibrium dunes. The wavelike response of the flow in the outer region, with velocity decreasing throughout the flow depth over bedform troughs, and vice-versa over bedform crests, is present in both field and laboratory-scale flows. Turbulence production may be more appreciable in the outer region of a large river flow than for flume flows. Measured laboratory- and field-scale Reynolds stress distributions appear to support this conjecture. In general, there is similarity between the Reynolds stress distributions at laboratory- and field-scales, with the field flows having the highest shear stresses in the zones of flow separation and along the shear layer, as also was noted in the laboratory data of Bennett and Best (1995). MO-2 data have a quasi-equilibrium shear-stress distribution in the outer region, which is not apparent in the laboratory data. This disparity in the outer region of the spatially averaged Reynolds stress distribution is postulated to be due in large part to the differences in turbulence generation contributions of the two flow scales. It is obvious that field-scale flows sometimes present bedform geometries that cannot be classified as equilibrium dunes and, thus, are different from many of the bedforms present in laboratory studies.

Available velocity models were evaluated with the field data. The Smith and McLean (1977) and Nelson and Smith (1989A) models performed adequately when each was applied according to bedform type, with the Smith and McLean (1977) model working well for equilibrium dunes and the Nelson and Smith (1989A) model working well for flows where form resistance is minimal (elongated bedforms, gradual lee slopes, etc.). The Fedele and Garcia (2001) model of spatially averaged velocities did not perform as well as the other models. The Fedele and Garcia conceptualization of the spatially averaged shear-stress distribution, with the form stress corresponding to the maximum stress, appears to match the MO-2 data well. Their conceptual-velocity model inadequacies appear to stem from the incorrect assumption of the vertically averaged mean velocity corresponding to the velocity at the equilibrium level, which stemmed from observations in laboratory flume experiments.

The velocity-defect model, accounting for the wake effect through knowledge of the gross Richardson number, estimated the vertically averaged mean velocity within 2%, and estimated point velocities to within +/-10% for $z/H>0.1$. If sediment concentration cannot be estimated, the model performance decreases slightly, with vertically-averaged mean velocity still accurate to within 2% for all but one data set (+3.7%), but point velocity accuracies decreasing to +/- 10% for $z/H>0.3$.

Shear partition models of Einstein (1950) and Nelson-Smith (comes collectively from Smith and McLean, 1977; Wiberg and Nelson, 1992; and Nelson and others, 1993) were evaluated with the field data collected in this research. Einstein's model had an absolute average percent error of 11.3%, whereas the Nelson-Smith model had an absolute average percent error of 22.2 % when the smaller bedforms were used as the geometry in the Nelson-Smith method. The Nelson-Smith model requires the estimation of bedform geometry. The Einstein (1950) model is recommended over that of the Nelson-Smith model based on both the better relative error estimates being better for Einstein and the need for bedform geometry in the Nelson-Smith method.

6.2. Conclusions

6.2.1. Similarity of Laboratory and Field Investigations

In general, laboratory- and field-scale flow fields over dunes are similar. MO-2 and MO-1 data sets both had detectable flow separations downstream of the bedform crest, with negative velocities being recorded for MO-2. This type of flow was readily apparent in laboratory flume data. Bedform height to flow depth ratios of observed flows in the field data (not only of this research but other research in the literature) range from 1/4.4 to 1/10.8, whereas most of the laboratory flume data tends to stay in the range of 1/5 with the flume study of Bennett and Best (1995) using a ratio of 1/2.9. Bedform wavelength to flow-depth ratios for the field data had a much greater range (1.17 to 63) than the laboratory flume data (2.46 to 5.43). The bedforms present in the laboratory experiments fit in the category of equilibrium dunes, whereas the field data discussed in this research was divided into two categories of bedforms: 1) bedforms that approach equilibrium dunes and 2) bedforms that do not approach equilibrium dunes (washed out dunes, developing dunes, etc.). The MO-2 data, Smith and McLean (1977) data sets, and two of the Kostaschuk and Villard (1996) data sets have bedforms that approach equilibrium conditions. The KANK-1 data, MO-1 data, and Kostaschuk and Villard (1996) June 21 data set have bedforms that cannot be characterized as equilibrium dunes.

The local velocity profiles of the laboratory results collapse well on the field data near dune crests, with the profiles being logarithmic in nature. The laboratory results for Lyn (1993) collapse well with the field data near bedform troughs; however, the results of Bennett and Best (1995) do not collapse well in this region. This result likely is attributable to the larger ratio of dune height to flow depth for the Bennett and Best (1995) data. The good collapse of the Lyn (1993) laboratory data at both the crest and the trough indicates that the flume does a reasonably good job of simulating field velocity profiles over dunes with similarity of geometry and flow. There is a lack of universal flow structure close to the bed in the local velocity profiles, for both the field- and laboratory-scale data when flow separation was noted.

The spatially averaged laboratory velocity data appear to have similarity parameters equivalent to those for field data; however, the ability of the laboratory data to collapse is not as good (figure 4.34). The inability to collapse is thought to be the result of higher sensitivity of the laboratory data to boundary conditions such as bedform geometry ratio, bedform to flow depth ratio, etc. The laboratory data (which have equilibrium dunes for bedforms) have two-segment, log-linear velocity profiles similar to the field data collected over equilibrium dunes (figure 4.37). The portion of momentum extracted by the bedform is similar for both the laboratory and field scales.

Few laboratory flume studies have been done that examine the effects of superimposed bedforms on the flow field. The superimposed dunes of MO-2 were thought to be the controlling feature for much of the flow process near the bed, as well as affecting the similarity parameters of the outer region. The traditional model of flow separation, flow reattachment, diffusion of momentum defect, and boundary-layer development is confirmed.

Laboratory- and field-scale spatially averaged shear stresses are similar in the bottom half of the flow. The upper half of the flow reveals differences, with field-scale flows approaching a quasi-equilibrium stress profile (which is not present in laboratory flows). This difference indicates that there is a dynamic balance between the inertial and pressure forces that was not present in the laboratory flume data.

Pressure gradient (topographically induced) effects felt for the entire depth of flow for field-scale flows. This “wavelike” response of the flow to the bedforms also was apparent in the flume experiments. However, contribution to overall turbulence production is greater in the outer region of the large river flow as compared to the laboratory flumes.

Coles wake parameter for the local velocity profiles was found to vary from as much as +0.252 at the crest of a dune to –0.286 in the trough, which is a larger range than resulted in the laboratory work of Lyn (1993). Lyn (1993) found an equivalent range of –0.05 to +0.1. In most cases, the wake coefficient was positive in locations where the bed elevation was increasing (adverse pressure gradient) and negative in locations where the bed elevation was decreasing (favorable pressure gradient). There appears to be a lag present in the wake coefficient data, as the inflection points between positive and negative wake coefficients do not align with the dune crest.

6.2.2. Spatially-Averaged Velocity Profiles

The spatially averaged velocity profiles for those experiments with bedforms that do not approximate equilibrium bedforms can be well characterized with a single logarithmic function. The spatially averaged velocity profiles for those experiments with bedforms that approximate equilibrium dunes have a two-segment logarithmic relation. All the field data collected in this research collapse sufficiently well when plotted in inner scales (bulk shear velocity and the composite roughness length); however, the collapse is better when the data are plotted in velocity-defect form. There appears to be universal flow structure close to the bed in the spatially averaged data.

When evaluating the present spatially averaged velocity-profile models, the models of Smith and McLean (1977) and Nelson and Smith (1989A) perform adequately when properly applied to flow with appropriate types of bedforms. These models are highly sensitive to the bottommost roughness parameter estimation. As such, the Smith and McLean (1997) model works best when the bedforms approximate equilibrium dunes, where form roughness is an important part of the overall roughness. The Nelson and Smith (1989A) model works best when the bedforms are not equilibrium bedforms, where form roughness is important, and where the grain roughness predominates.

The standard velocity-defect-wake model was tested for the spatially averaged velocity profiles of field data, with bedforms present. Coles wake parameter was presented as a function of the gross flow Richardson number, which requires some knowledge of the vertical-density distribution (sediment concentration being the predominate factor in the density). The model estimates the vertically averaged mean velocity to within 2% and estimates the point velocities to within +/- 10% for z/H>0.1. If sediment concentration cannot be estimated, the model was tested with the assumption that the wake effect was negligible. The vertically averaged mean velocity was found to be within 2% for all but the Smith and McLean (1977) 69-W1 data set (+3.7%), but the point velocities accuracies decrease to +/- 10% for z/H>0.3. The velocity-defect-wake model was found to consistently describe the velocities of the observed field data better than either the Smith and McLean (1977) or the Nelson and Smith (1989A) models.

6.2.3. Shear Stress Partitions

The local shear-stress distribution present in the MO-2 data set has the stress increasing away from the bed in the near-bed wake regions behind bedforms, reaching a maximum near the center of these wake regions and then decreasing to near zero at the water surface. The conceptualized spatially averaged shear-stress distribution of Fedele and Garcia (2001) fits the measured MO-2 data. The Reynolds stress at the "equilibrium" level corresponds to the estimated form stress magnitude; however, the point velocity at that level does not correspond to the vertically averaged mean velocity. Thus, the turbulence production above this level is not negligible as postulated by Fedele and Garcia (2001). As the Fedele and Garcia (2001) conceptualization is based on laboratory data (where the assumption of negligible turbulence in the outer region is apparently reasonable), it is likely that turbulence scale effects induce large differences in the contribution of the outer region to turbulence generation for laboratory flume flows and large river flows.

Two methods of shear partitioning: 1) Einstein (1950) and 2)Nelson-Smith (Smith and McLean, 1977; Wiberg and Nelson, 1992; and Nelson and others, 1993) were evaluated against form and grain shear stresses for the Missouri River data sets (MO-1 and MO-2) estimated using a methodology used by Nelson and others (1993). Both of these methods require knowledge of the total shear stress. Einstein's method requires knowledge of the mean velocity, whereas the Nelson-Smith method requires knowledge of the bedform geometry. Einstein's method had an absolute average percent error of 11.3%, whereas the Nelson-Smith method had an absolute average percent error of 22.2% when the smaller bedforms were used as the geometry in the Nelson-Smith method. Through application of the Nelson-Smith model, it is apparent that the smaller superimposed dunes are the controlling feature in regards to flow and stress distributions over bedforms. The Einstein (1950) method is recommended over that of the Nelson-Smith method based on both the better relative error estimates being better for Einstein and the need for bedform geometry in the Nelson-Smith method.

Drag coefficients were computed for each of the Missouri River data sets (MO-1 and MO-2). The drag coefficients for MO-1 and MO-2 data were 0.14 and 0.21, respectively. These values are comparable to those determined in other studies by Smith and McLean (1977) and Nelson and others (1993).

6.2.4. Recommendations for Future Research

Recommendations for future research are listed as follows:

1. Collect additional detailed velocity data sets of a similar nature on rivers at this scale (in the presence of bedforms). This would allow broader and more definitive conclusions on scale differences.
2. Collect more detailed sediment concentration data along with the detailed velocity data over bedforms. This will allow investigation into stratification issues.
3. Refine the data collection process to allow better confidence in the turbulence data. This requires redesigning the modified P-61 platform and suspension equipment to increase the stability (steadiness) of the ADV.

4. Collect additional concurrent ADCP/ADV to investigate the ability of the ADCP to compute Reynold's stress data. Investigate the feasibility of providing "operating" rules for filtering of near-bed ADCP velocity data dependent on the geometry of the bedforms present.
5. Collect surface velocity data (using radar or similar technology) and using the velocity-defect model, analyze the errors in estimating the water discharge in comparison to conventional methods at an existing USGS gaging station.