CONVECTIVE ACCELERATION EFFECTS FROM TRANSVERSE IN-STREAM STRUCTURE INSTALLATIONS

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Abstract: Transverse instream structures are rapidly gaining popularity in stream restoration and bank stability applications, yet are implemented with an incomplete knowledge of induced structure hydraulics. Transverse structures extend laterally from the channel bank into the flow field, serving to redirect conveyance away from the outer bank of the channel for navigation and erosion objectives. Three types of instream structures, the spur dike, vane, and bendway weir, were constructed and evaluated within a physical model representation of a natural channel. High-resolution mean-flow and turbulent velocity data were collected from similar planimetric structure configurations with a focus upon convective acceleration and turbulence at the structure tips. The zone of influence at the structure tip is critical for design considerations due to implications for sediment mobility and structural integrity. This research presents specifics of flow effects at the tips of the three structure classifications, provides comparisons between structure types, and gives implications for design procedures and sediment mobility.

INTRODUCTION

An emphasis on alternative methods for bank stabilization and river restoration in meandering systems has gained momentum in recent years. Transverse in-stream structures have been utilized in channel bend stabilization projects as a means of diverting erosive forces away from the outer bank of a migrating river. Bendway weirs, spur dikes, and bank-attached vanes are specific types of in-stream structures, identical planimetrically, yet different in their cross-sectional geometries and intended hydraulic effects. Planimetric and cross-section schematics of in-stream structures are provided in Figure 1, detailing differences between structure classifications in the cross-sectional view. In a general hydraulic sense, bendway weirs redirect flows over the top of the crests, spur dikes shift flows around the structure tip, and bank-attached vanes combine both crest overtopping and redirection around the tip to the channel center. Typical geometric parameters of interest for instream-structure design are the structure width, W, length, L, spacing, S, elevation difference between the water-surface elevation and structure crest elevation, Δz, planform angle, θ, and crest-slope angle, φ. Guidelines for the construction and installation of instream structures in channel bends as functions of the geometric parameters exist, yet are largely anecdotal.

Bendway weirs were initially developed by the U.S. Army Corps of Engineers to improve navigation in bends of the Mississippi River (Derrick et al., 1994). Structures are typically placed in series along the outside of a channel bend, are angled upstream, and have a submerged crest elevation at design flow. Flows encountering the crest are redirected to the channel center over the structure axis. Three primary sources for documentation and interpretation of bendway-

weir design and construction guidance were identified as McCullah and Gray (2005), Lagasse et al. (2009), and Julien and Duncan (2003). Currently, design guidelines for bendway-weir configurations are anecdotal, and have largely been developed on the basis of expert judgment (Rhoads, 2003).

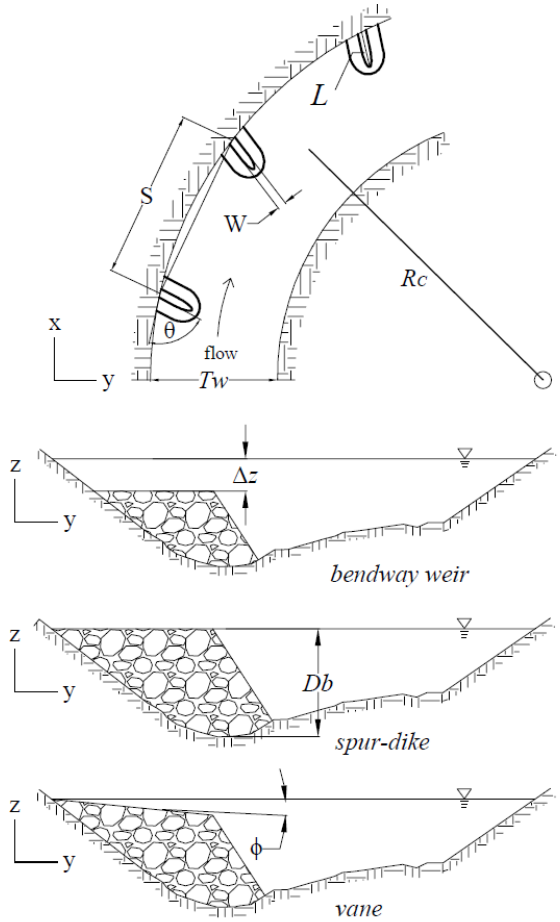

Figure 1 Instream structure geometric parameter definitions

Spur dikes, also referred to as groynes or jetties, extend from the outer bank to the channel center. They are placed in series throughout a channel bend, and are set either perpendicular or angled to the stream flow direction. In contrast to bendway weirs, spur-dike crest elevations are constructed at the design water-surface elevation and no conveyance is meant to overtop the structure crest. Spur-dike hydraulics encourage sedimentation within the structure grouping, or field, and provide outer-bank erosion protection (Radspinner et al., 2010). Current design guidelines for spur dikes are summarized by the Federal Highway Admninistration publications of Brown (1985) and Lagasse et al. (2009).

Bank-attached vanes, also known as barbs, represent a hybrid between the bendway weir and spur dike. Sturctures are constructed with a crest elevation at the design discharge water-surface elevation at the outer bank and extend into the channel at a downward angle. Vanes allow an increasing level of flow to pass over the structure crest moving into the channel center. Similar to the other transverse in-stream structure types, vanes are constructed in series and set either

perpendicular or angled upstream to the flow direction. Unique publications of geometric design criteria, including summarizations from Rosgen (2001), McCullah and Gray (2005), Brown and Johnson (1999), and others, are found in NRCS (2005), Johnson et al. (2001), and Maryland (2000).

Transverse instream structures are designed to deflect outer-bank conveyance to the channel-center, increase flow resistance near the base of the outer bank, and inhibit helical motion and redistribution of momentum near the outer bank (Derrick, 1997). Field data from studies such as Scott et al. (2011), Rhoads (2003), Smith and Wittler (1998), and Wardman and Papanicolaou (2006) for bendway weirs, and Dahle (2009) for vanes, have confirmed that transverse instream-structure configurations are typically effective at redirecting bulk channel conveyance to the central channel. Investigations into specific flow patterns associated with single structures and configuration fields have been conducted utilizing physical and numerical modeling. Hydraulics associated with transverse instream structures have been reported as three-dimensional and complex, yet the literature indicates specific and recurring trends of flow behavior across independent sources.

Abad et al. (2008) coupled surveyed field data with a three-dimensional numerical model to emulate flow characteristics at various flow depths around a bendway-weir configuration installed in an Illinois meander bend. Key insights from the study included areas of convective acceleration and high boundary shear-stress at the tips of the structures, increased velocity and shear stress over the crest of the structure at the bankline, and locally increased bed shear downstream of the crest due to plunging flows. At the lowest flow evaluated in the study, the modeled bendway weirs did not experience overtopping flows, therefore behaving as spur dikes. Acceleration and increased boundary shear stress at the structure tips, over the structure crest at the bankline, and at the overtopping jet and bed interface were noted.

Jia et al. (2002, 2005, 2011) investigated the efficacy of bendway weirs to disrupt the helical secondary current in channel bends and documented flow patterns using numerical and physical modeling on a single structure angled 70º upstream. Acceleration of the flow velocity over the weir crest and around the structure tip, and a recirculation zone directly behind the structure were reported.

McCoy et al. (2007) detailed numerical modeling results of flow encountering submerged, bendway-weir like structures angled perpendicular to the approaching flow. Evaluated structures had abrupt, blunt noses instead of being gradually angled into the channel center. Authors noted significant convective acceleration over the structure crest and around the blunt structure tip. Flow encountering the structure separated at a stagnation velocity zone at the structure face, and was redirected over and around the obstruction. Recirculation zones, or eddys, were observed to form behind the structures and between adjacent structures. Streamlines were not shown to exhibit substantial planimetric circulation in the upper water column and the effects of the structure field diminished within two structure lengths of the downstream crest. Conveyance was observed to shift to the inner channel, away from the increased roughness of the modeled structure series.

Duan (2009) performed laboratory physical modeling on a spur dike installed in a straight, mobile-bed channel under clear-water conditions. Results of the study included documentation of flow separation downstream of the structure, strong planimetric recirculation in the upper water-column which decayed moving deeper into the flow, induced cross-sectional rotation, and high tip velocities. Flow interaction with the spur dike shifted the conveyance and bulk mean kinetic energy to the outside of the tip of the structure and incited circulation and increased turbulent kinetic energy downstream and behind the structure crest.

Jamieson et al. (2013) installed vanes constructed from scaled riprap in a mobile-bed, trapezoidal laboratory channel bend and collected bathymetry and velocity data. Vanes were imbricated in series and constructed according to NRCS (2005) guidelines. Planimetric velocity measurements illustrated an effective conveyance shift from the outer bank at baseline conditions to the channel center with the installed structure configurations. Authors noted scouring downstream of the vane crests which was attributed to the combination of plunging crest flow and local acceleration around the vane tip. When vanes were constructed with the bank key-in point below the water surface, increased outer-bank erosion was noted, similar to bankline flow acceleration noted for bendway weirs (McCoy et al., 2007, Abad et al., 2008). Varying degrees of disruption of the secondary current was noted for the vane configurations and was attributed to the strength of plunging flow over the vane crest.

Studies from the literature indicated a recurring set of hydraulic trends associated with the installation of transverse in-stream structures. The bulk flow conveyance is shifted towards the channel-center, acceleration occurs around the structure tip, and acceleration is observed along the outer bank at the bankline key in for submerged crests. This proceeding focuses upon the quantification of the convective tip acceleration that occurs for bendway weirs, spur dikes, and bank-attached vanes. Comparable physical models of the three structure types were constructed and resulting hydraulics were quantified. Tip velocities were isolated and information pertaining to maximum tip velocities for structure design was obtained.

PHYSICAL MODELING

The Middle Rio Grande River between Cochiti Dam and Elephant Butte Reservoir in New Mexico has been the focus of extensive river restoration work since the upstream Cochiti Dam construction in 1975. The dam effectively disconnected the sediment continuity to the downstream reach, resulting in a geomorphic shift from a historically braided channel to a slightly sinuous, incising system. The United States Bureau of Reclamation, as the responsible agency for management of the river, jointly launched an investigative study on the performance of transverse in-stream structures with Colorado State University. A physical model was constructed at a 1:12 Froude scale representing two surveyed bends from the Middle Rio Grande. A model schematic and topographic representation of the flume is presented in Figure 2 and an image of the completed downstream bend of the model is presented in Figure 3. The downstream bend of this physical model was selected to investigate tip velocity effects between the three structure types, and comparable physical model structure configurations were designed.

Physical models of bendway-weirs, spur dikes, and bank-attached vanes were designed according to slightly different methodologies. However, each configuration was constructed to

have the largest amount of direct comparability between structure types. Spacing, structure width, and orientation angle were identical. Quantified design parameters are summarized in Table 1. The process of bendway-weir design included available guidelines to ensure applicability to the current state of knowledge. Thornton et al. (2011) evaluated four spur-dike configurations in the same physical model as the current study. Methodologies reported by Thornton et al. (2011) describe spur-dike geometric parameter determination by a variation of projected length to match a desired cross-sectional area blocked percentage (A*). Following these methods, the spur-dike configuration was designed to match a desired A* value of 19.4. The lower crest height of the bendway weirs made alterating A* to match that of the spur dikes impractical. The vane configuration kept the same length of the spur dikes and incorporated a 10% sloped crest.

Hydraulic parameters such as the channel top width and design flow depth are integral parts of instream-structure design; however, parameters vary with longitudinal distance along naturally-formed channel bends due to pool and riffle sequencing and erosional processes. It was assumed for the purposes of the instream-structure design that such parameters are bend-averaged at a bankfull, or approximately two-year return interval, scaled prototype discharge of 6,000 ft^3/s (12 ft^3/s model scale). Top-width for the model was found by bend-averaging surveyed waterlines at the bankfull flow condition across the representative channel-bend cross sections. The hydraulic flow depth (D) was determined as the most representative parameter for instream-structure design criteria and was calculated from each cross-sectional T_W and flow area (A) using $D = A/T_W$ and were averaged across the downstream bend. Cross-sectional flow area was calculated from numerical integration of surveyed bathymetric data.

Bendway-weir crest length was specified as the distance from the intersection of the weir crest and the channel bankline to the weir tip, not including the transition slope from the crest to the channel bottom (Lagasse et al., 2009). Also, the weir should be long enough to cross the stream thalweg (Lagasse et al., 2009). Setting the crest length at $T_W/3$ for the downstream bend resulted in structures which adhered to ranges of L from the literature and generally crossed the stream thalweg. For each spur-dike structure, a projected cross-sectional bathymetry and area blocked was determined. Starting with a crest height at the bank waterline and specifying a tie-in slope of 1V:1H, the projected crest length was adjusted such that the total cumulative weir blockage was 19.4% of the baseline cross-sectional flow area. Vanes were designed such that the $L_{W\text{-}PROJ}$ at each structure was the same as the spur-dike configuration. Crest lengths for the spur dike and vane configurations ranged from $T_W/4$ to $T_W/3$. The calculated range of $L_{W\text{-}PROJ}$ for impermeable spur dikes exceeded the maximum design from Lagasse et al. (2009); however, vane crest lengths fell within specified ranges found in the literature.

Crest elevations were determined based upon the intended hydraulic effects of the structures. Spur dikes and vanes have crest elevations which are set at the design flow water-surface elevation at the bankline tie in. Bendway-weir crest height was set at one-third of the bend-averaged bankfull hydraulic flow depth, or two-thirds of the hydraulic flow depth below the water surface.

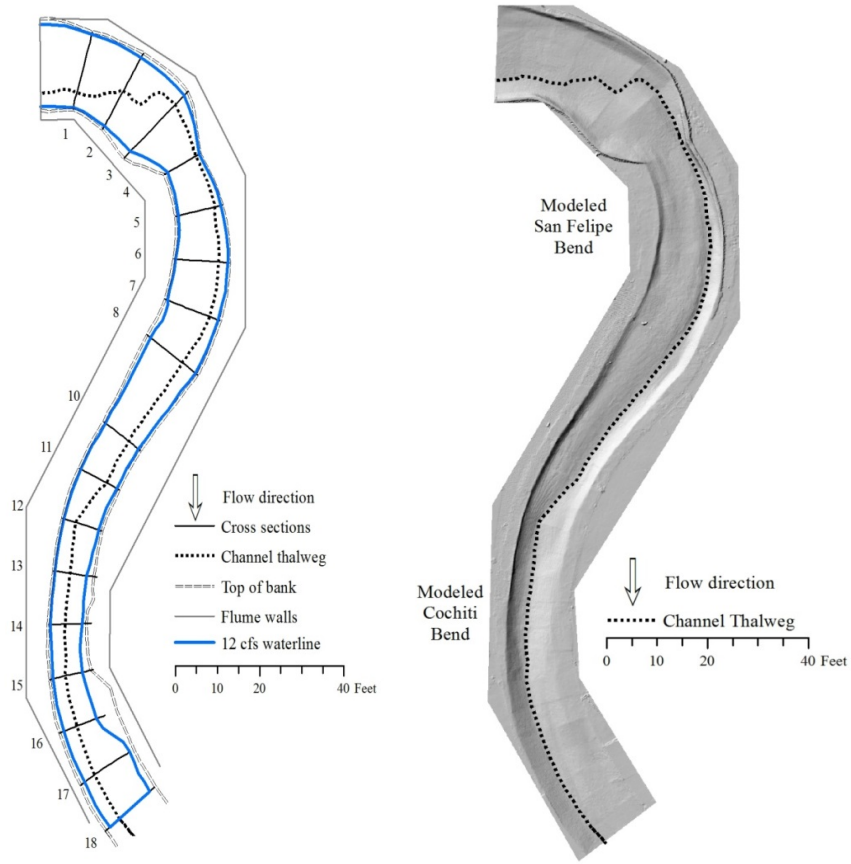

Figure 2 Native topography plan view schematic and constructed surface

Crest orientation angle was established at 60º, measured clockwise from the bankline tangent. The orientation angle coincides with design recommendations for bendway weirs, yet violates spur dike and vane recommendations (Lagasse et al., 2009; NRCS, 2005). Crest widths were constructed from approximately 0.3 ft to 0.5 ft angular rock, corroborating with design guidelines specifying instream structure crest widths of $d_{100} - 3d_{100}$, where d_{100} is the diameter of the largest grain size implemented in construction. Additionally, crest widths were set at a prototype 12 ft, allowing construction equipment to traverse the structure during installation. Each transverse instream structure was constructed from a plywood for centered in the crest and angular rocks were placed to form the required dimensions. The completed structures were impermeable to interstitial flows due to the plywood template. Topographic representations of the structures from LiDAR data, flume schematics, surveyed waterlines, and velocity data-collection locations are presented in Figure 4.

Mean-flow and turbulent velocity characteristics were obtained using two acoustic Doppler velocimeters (ADV). A SonTek® ADV of ±1% measured accuracy, and a Nortek Vectrino® ADV of ±0.5% accuracy were both utilized. ADV data have been collected in laboratory and field applications, and further details may be found in Voulgaris and Trowbridge (1998), Wahl (2000), McLelland and Nicholas (2000), Strom and Papanicolau (2007), and many others. ADV instruments operate at a high frequency (≥ 25 Hz) and allow for the determination of mean and fluctuating velocity components over the course of a sampled time period. A minimum of 1500

velocity data were obtained at each data-collection location. Data were processed using WinADV as detailed by Wahl (2000), and data used for instream-structure analyses typically had percentage-good scores greater than 70%, correlation values greater than 70, and signal-to-noise values greater than 15.

Figure 3 Completed native-topography downstream bed surface

Table 1 Instream structure configuration parameter design and values

Design parameters

Configuration	*Length*	*Height*	*Top width*	*Spacing*	θ
BW05	$T_W/4$	0.333 D	$2d_{100}$ - $3d_{100}$	2.69L	-
V05, SD05	$T_W/3$ - $T_W/4$	D *	$2d_{100}$ - $3d_{100}$	2.69L - 4.79L	-

* V05 has sloping crest at 7%

Design values

Configuration	*Length (ft)*	*Height (ft)*	*Top width (ft)*	*Spacing (ft)*	θ *(°)*
BW05	3.554	0.247	1.0	9.30	60
V05, SD05	variable	variable	1.0	9.30	60

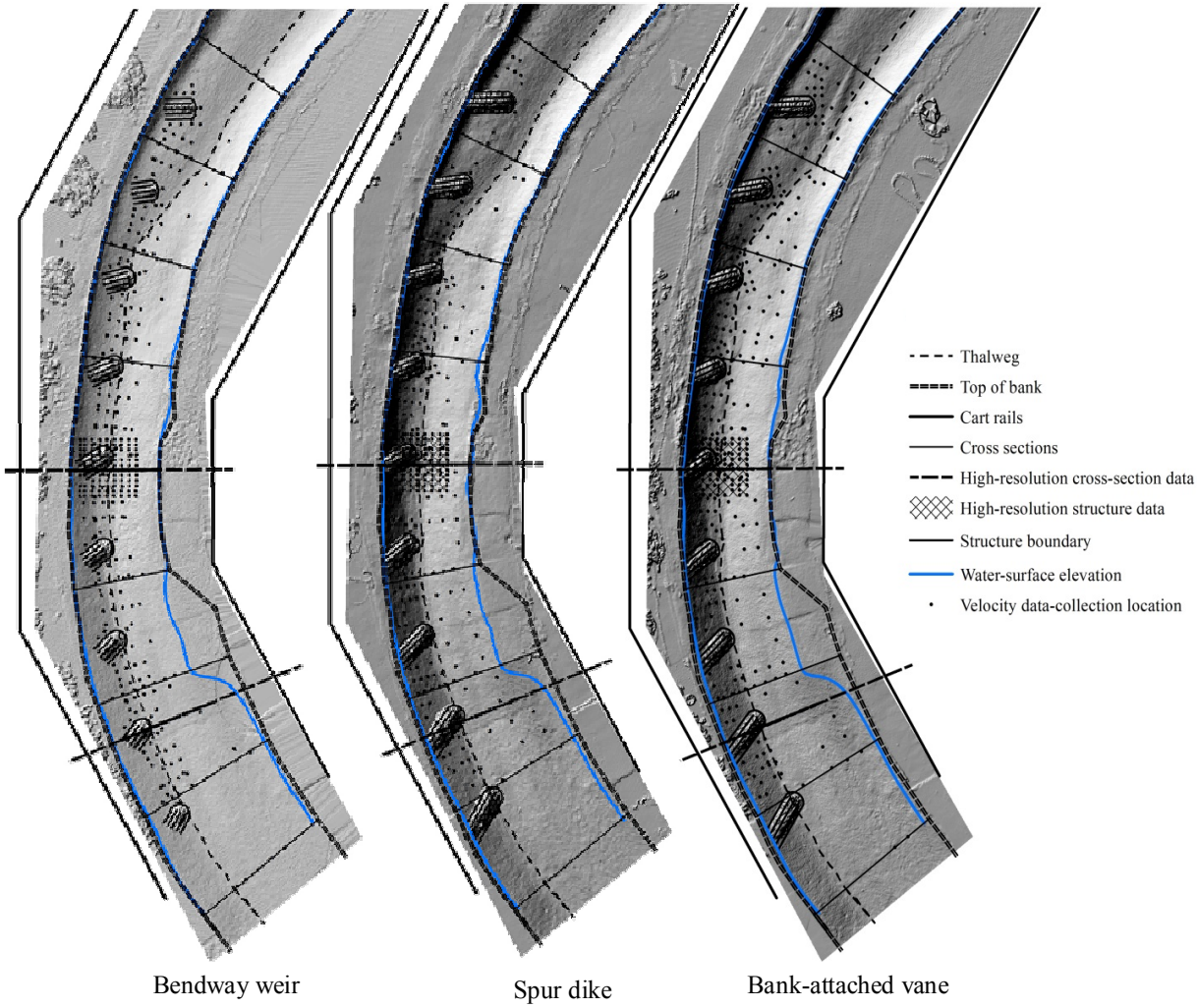

Figure 4 Constructed in-stream structure configurations and data-collection points

IN-STREAM STRUCTURE DATA RESULTS

Velocity data collected at each of the data-collection locations were processed and tabulated. Data at 60% flow depth measured below the water surface elevation were extracted as a surrogate for the depth-averaged flow. Velocities were normalized by the bend-averaged baseline cross-sectional velocity, computed through flow area and volumetric flow rate. The normalization value was found to be 1.702 ft/s at bankfull, normal-depth flow conditions. In general, all evaluated structure configurations exhibited velocities lower than the baseline velocity at the outer bank of the channel, and shifted the conveyance to the channel-center and inner-bank where all configurations showed velocities higher than baseline conditions. Normalized velocity values range from approximately zero to two for all configurations, corresponding to full velocity reduction or velocity doubling from baseline conditions, respectively.

Figure 5 depicts interpolated normalized velocity distributions for the evaluated in-stream structure configurations. Blue shades indicate velocities slower than the normalization condition, or less than unity, and red shades indicate velocities faster than normalization conditions, or greater than unity. For all structures, a strong gradient occurred between reduced and accelerated velocities, illustrated by the rapid transitions in the velocity distributions. The location of the shear gradient was found in the vicinity to the outer bank of the structure tips. Highest velocities were noted at the inner-bank vicinity of the structure tips.

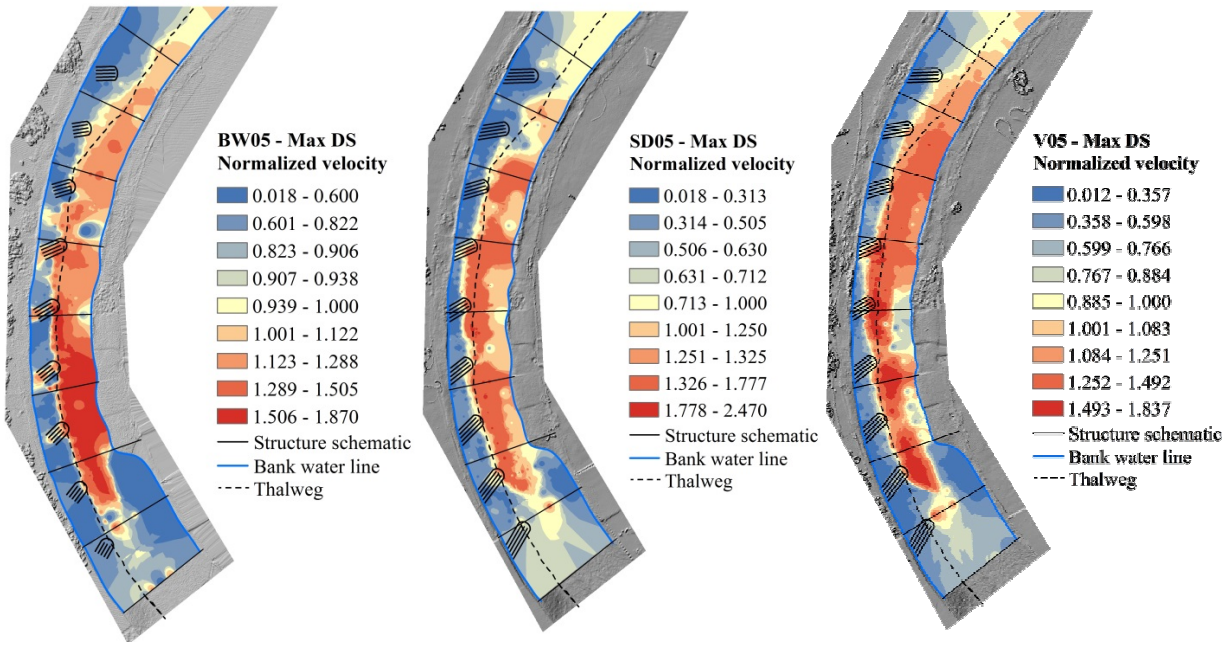

Figure 5 Normalized velocity fields (BW, SD, V = bendway weir, spur dike, vane, respectively)

Flow encountering the in-stream structures was observed to have specific features depending on the structure type. The bendway weir redirected flow over the top of the structure crest to the channel center, yet also split the conveyance to the outer bank. A localized region of higher velocity was noted at the outer-most bank region for the bendway weirs, coinciding with results reported by Lyn and Cunningham (2010) and McCoy et al. (2007). A strong degree of turbulence was noted for the bendway weirs as a function of the vertical induced currents. Velocity vectors recorded around a bendway weir are displayed in Figure 6 where flow redirection, vertical acceleration, and plunging flow are visualized. Spur dikes with no crest overflow exhibited strong planimetric recirculation zones between structures similar to those reported by Yossef and de Vriend (2011). This flow pattern was not observed for bendway weirs and to a much lesser degree in the bank-attached vane configuration. Strong recirculation zones may lead to scalloping of the bank and eventual flanking. The vanes did not exhibit outer-bank split conveyance or strong planimetric recirculation zones. A common hydraulic trait for all structures was the convective acceleration around the tip of the structure crest. Visualized in Figure 6, flow is redirected around a stagnation velocity point at the structure interface, spatially accelerating around the tip of the structure. As noted in Koken and Constantinescu (2014) and Minor et al. (2007), the tip of transverse in-stream structures is the focal point for initiation of sediment mobility. Laboratory results indicated that the tip of the structures experience the

highest velocities in the channel. Crest-tip velocities were isolated from the full dataset and analyzed for each structure type.

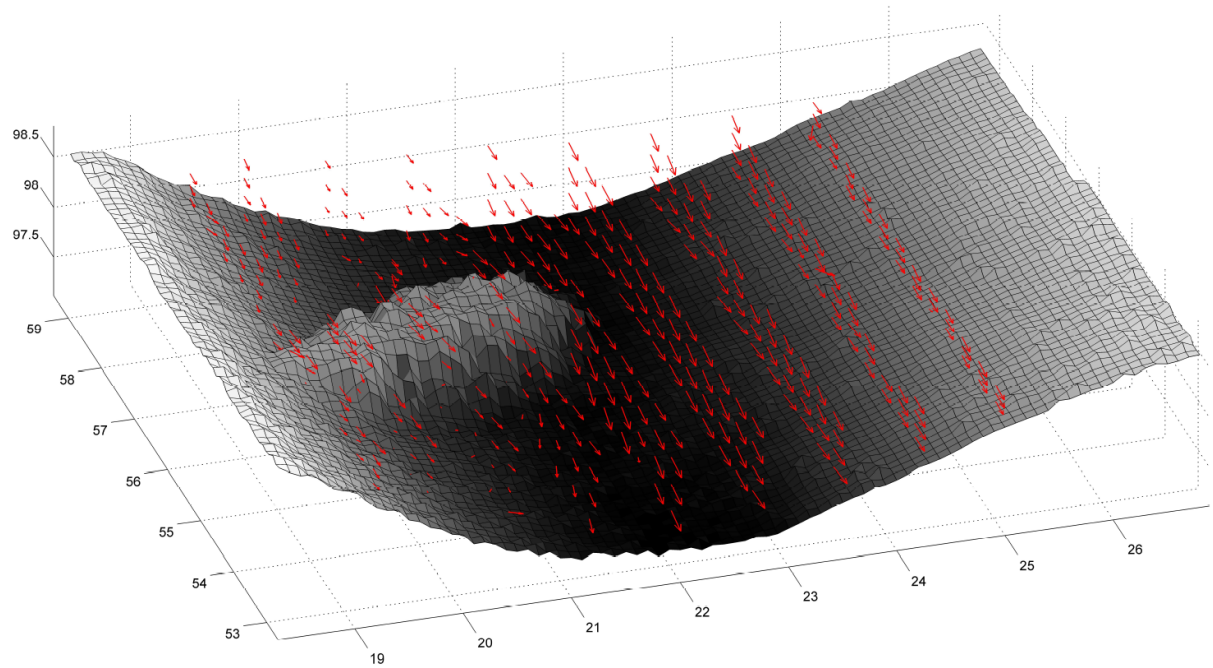

Figure 6 Velocity vectors (red) recorded around a bendway-weir structure (looking upstream)

STRUCTURE CREST TIP VELOCITY ANALYSIS

Increased velocity at the structure tip is directly related to the convective acceleration imposed by the structure boundary. Quantification of the velocity increase is important for structure stability through correct rock sizing and construction methods. Data located at the tip of the structures and in the near vicinity were isolated from the full data-collection location set illustrated in Figure 4. Values were normalized by the bend-averaged baseline flow condition and the maximum value and mean value were extracted from the dataset. Table 2 summarizes the maximum and average velocity and normalized values for each configuration. Maximum normalized velocity (*MVR*) values ranged from approximately 1.6 to 1.7 with the bank-attached vanes producing the smallest values and the spur dikes the largest. On average, normalized velocity values (*AVR*) range from approximately 1.3 to 1.6, with the bendway-weir configuration producing the smallest values and the spur dike the largest.

Table 2 Structure tip velocity summary

Configuration	Max vel. (ft/s)	*MVR*	Avg. vel. (ft/s)	*AVR*
Bendway weir	2.898	1.703	2.238	1.315
Spur dike	2.933	1.724	2.721	1.599
Bank-attached vane	2.692	1.582	2.437	1.432

Results adhere to physical intuition of the flow field. A larger channel obstruction decreases the cross-sectional flow area and increases flow acceleration. Spur dikes were the largest structure, followed by vanes, then bendway weirs which corresponds to the normalized average tip velocity magnitudes. The maximum observed velocity for the spur dike was also the largest recorded during testing. Bendway weirs produced a higher maximum velocity than the bank-attached vanes. The flow field for the bendway-weir configuration was more erratic and turbulent than the other structures. Observed hydraulics and high maximum velocities indicate that the bendway-weir structure type in particular should be evaluated further to fully understand hydraulic mechanisms.

SUMMARY AND CONCLUSIONS

Transverse in-stream structures are being installed to mitigate outer-bank erosion and stabilize migrating river channels. A physical model study of bendway weirs, spur dikes, and bank-attached vanes was undertaken in order to facilitate investigation of specific hydraulics associated with the structures and the differences between them. One configuration of each structure classification was installed according to recommended design guidelines from the literature and the desire for structure comparability. Models were evaluated under bankfull, design flow conditions and comprehensive velocity data were collected throughout the flow field.

Velocity distributions indicated that the tips of the structures were highly susceptible to the strongest hydraulics in the channel. Structure stability requires that rock sizing be appropriately scaled to expected velocities. Tip velocities for the structures were isolated and normalized by the baseline velocity averaged throughout the bend. It was found that on average, spur dikes had the highest tip velocities, followed by bank-attached vanes and bendway weirs. Maximum tip velocity analysis indicated that structure installations increased velocities up to 1.72 times the baseline average velocity. From the results of this study, it is recommended that rock sizing methods based upon flow velocity include a factor of safety of two times the baseline bend-average velocity.

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