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Role of macroturbulence to sustain turbulent energy in decelerating flows over a gravel bed

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Running Title:

Macroturbulence in Decelerating Flow Over Gravel

21

22 **Abstract**

23 New experimental data and turbulence analyses are used to elucidate the role of
24 macroturbulence to sustain energy in streamwise decelerating and vertically expanding open
25 channel flows over a gravel bed such as those found in river pools. Quality assurance of the
26 turbulence measurements was verified by the close comparison between results of time-averaged
27 quantities calculated with the measurements and published semiempirical equations for
28 decelerating flow over gravel beds. The presence of macroturbulence within the flow is verified
29 using turbulence decomposition, spectral analysis, and the distribution of time-averaged
30 quantities. The vertical expansion velocity provided 40% of the turbulent energy production in
31 the vertical suggesting that the expansion velocity interacts with macroturbulence in the outer
32 region to generate and redistribute energy. Spectral analyses show that net turbulent energy is
33 primarily lost through the decelerating flow at 1 to 10 Hz frequencies associated with the
34 bursting process and dissipative scales while the primary streamwise energy reduction is less
35 pronounced in the macroturbulence range. Vertical and transverse turbulent energy within the
36 macroturbulence range actually becomes more energetic as the flow decelerates.
37 Macroturbulence makes up ~ 50% of the total streamwise turbulent kinetic energy, and the loss
38 of macroturbulence energy through the decelerating flow lags well behind that of the decreasing
39 intensity of bursting as identified with quadrant analysis. Taken together, the results of this
40 study suggest that macroturbulence is a defining feature of the fully rough expanding flow that
41 sustains itself from bed-derived bursting as well as flow nonuniformities.

42 *Keywords:*

43 Macroturbulence; gravel bed river; turbulence; roughness; decelerating

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46 **List Of Symbols**

47 $D_{u,v,w}$ = empirical coefficients for streamwise, vertical, and transverse turbulent intensities

48 D_{50} = particle diameter for which 50% of particles are finer

49 D_{84} = particle diameter for which 84% of particles are finer

50 D = uniform flow depth

51 F = production of turbulent energy by the vertical velocity gradient

52 Fr = $U_m(gH)^{-1/2}$ is the Froude number

53 G = primary production of turbulent energy

54 H = flow depth

55 H' = hole size used to separate strong motions from velocity fluctuations

56 K^+ = $k_s U_* v^{-1}$ is the shear Reynolds number

57 Re = $U_m H v^{-1}$ is the Reynolds number

58 $S_{u,v,w}$ = streamwise, wall normal, and transverse velocity spectrum

59 T_B = $3 H V^{-1}$ bursting period defined by outer variables

60 TKE = turbulent kinetic energy

61 T_s = moving average time-step used to isolate macroturbulence

62 U = time-averaged streamwise velocity component

63 U_{avg} = cross-sectional mean velocity

64 U_{max} = maximum streamwise velocity

65 U' = root mean square of streamwise velocity fluctuations

66 U_* = shear velocity

67 V = time-averaged wall normal velocity component

68	V_{mag}	=	magnitude of the time-averaged velocity vector
69	V_{exp}	=	expansion velocity induced by the deceleration
70	V'	=	root mean square of wall normal velocity fluctuations
71	W	=	time-averaged transverse velocity component
72	W'	=	root mean square of transverse velocity fluctuations
73	b	=	log-law constant of integration for hydraulically rough flows
74	k_s	=	equivalent roughness height
75	m	=	empirical coefficient used to fit power law to velocity distribution
76	u	=	instantaneous streamwise velocity component
77	u'	=	instantaneous fluctuating component of streamwise velocity
78	$\overline{u'v'}$	=	primary Reynolds shear stress component
79	v	=	instantaneous wall normal velocity component
80	v'	=	instantaneous fluctuating component of wall normal velocity
81	w	=	instantaneous transverse velocity component
82	w'	=	instantaneous fluctuating component of transverse velocity
83	x,y,z	=	stream wise, wall normal, and transverse directions
84	β	=	Clauser pressure gradient parameter $\beta = \frac{H}{U_*^2} g \left(-S_0 + \frac{\partial H}{\partial x} \right)$
85	Π	=	Coles wake strength
86	κ	=	von Karman constant
87	ω	=	frequency
88			

90 **1. Introduction**

91 The behavior of turbulent eddies in streamwise deceleration and vertical expansion
 92 regions of open channel flow is recognized to help control fluvial processes in river pools as well
 93 as backwater zones (Thompson et al., 1998; MacVicar and Roy, 2007). However, the vast
 94 majority of turbulence studies of flow over gravel beds have focused on uniform flow conditions,
 95 and we recognize that assumptions of uniform-like eddy structures will yield unsatisfactory
 96 approximations when applied to nonuniform reality (Nezu, 2005; Church et al., 2012). Our
 97 motivation in this study was to elucidate the role of depth-scaled turbulent structures, termed
 98 macroturbulence, within gradual vertical expanding flows over gravel beds. The overall goal was
 99 to investigate macroturbulence for streamwise decelerating and vertically expanding open
 100 channel flow and thereafter elucidate the role macroturbulence plays to sustain turbulent energy
 101 in the outer region of the flow field.

102

103 The velocity distributions and turbulent eddy processes in hydraulically rough uniform
 104 flows over gravel beds have been well documented in the literature (Hurther et al., 2007;
 105 Rodriguez and Garcia, 2008; Belcher, 2009). These studies indicate that shedding from
 106 individual roughness elements induces a roughness region that extends $\sim 2.5D_{84}$ (Belcher and
 107 Fox, 2009). The amalgamation of multiple shed eddies produces hairpin packets that eject away
 108 from the bed, and in many instances, reach the free surface and affect the entire flow structure
 109 (Shvidchenko and Pender, 2001; Hurther et al., 2007; Belcher, 2009). The outer flow region is
 110 populated with quasi-streamwise roll cells and remnants of the near-bed bursting process. We
 111 recognize that outer region turbulence exists as a continuum from the viscous scale to at least the

channel depth. However, consistent with the literature, we discretize instantaneous turbulent motions into two broad classes (Nezu and Nakagawa, 1993; Adrian et al., 2000; Belcher, 2009) including: (i) the bursting process consisting of eddies shed from individual roughness elements with low momentum fluid packets moving away from the bed (ejections) and high momentum fluid moving toward the bed (sweeps); and (ii) macroscale structures or ‘macroturbulence’ comprising the entire flow depth with a rolling motion and advecting in the streamwise direction (Shvidchenco and Pender, 2001; Fox and Patrick, 2008). These two prominent instantaneous processes are defined by a separation of scales but are believed to be intimately linked as bursting motions enhance large-scale flow structures and large-scale motions are thought to initiate bursting by pumping high momentum fluid toward the bed (Roy et al., 2004; Belcher, 2009; Adrian and Marusic, 2012).

Bursting motions have historically received more attention in uniform rough flows than macroturbulence until quite recently. For the latter, in-depth macroturbulence investigations for uniform open channel flow over gravel with moderate Froude number ranges (0.5 to 1) and relative submergence similar to gravel bed rivers (H / D_{84} from 3 to 15) have shown the pronounced presence of macroturbulence through the use of decomposed acoustic Doppler velocimeter data, decomposed digital particle image velocimetry data, and decomposed large-scale particle image velocimetry data (Fox et al., 2005; Fox and Patrick, 2008; Belcher, 2009; Fox and Belcher, 2011). In addition to the existence of macroturbulence, visualization, and measurements of macroturbulence for the uniform flow case have shown the functional role macroturbulence plays for rough bed flows including connectivity to the bursting process, responsibility for downrushing of fluid to the bed, and the production of high and low

momentum zones of fluid (Roy et al., 2004; Hurther et al., 2007; Belcher, 2009).

One open channel flow scenario for which macroturbulence has not been studied is the nonuniform flow when the fluid is decelerating in the streamwise direction and expanding in the vertical. Streamwise decelerating and vertically expanding open channel flow over a gravel bed consists of a boundary layer continually developing in the streamwise direction. As flow gradually expands in the vertical direction, streamwise velocity decreases to satisfy continuity. The continuity-induced positive wall normal velocity component is called the expansion velocity. Theoretically derived expressions determine the expansion velocity as a function of local streamwise velocity, bed normal position, and water surface slope (Song and Graf, 1994; Kironoto and Graf, 1995). The wall normal expansion velocity is a nonhelical flow of Prandtl's first kind (Church et al., 2012). The addition of the deceleration in the streamwise direction and vertical advection significantly alters the equations of turbulent momentum and energy from the idealized uniform flow case. The decelerating streamwise velocity represents a decreased energy source to dampen primary production of turbulence, while the expansion velocity potentially represents an increased energy source for the secondary production of turbulence.

A number of studies have shown that the structure of the time-averaged turbulence in vertically expanding flows differ from that of uniform flow by a number of features including: increased wake strength for the streamwise velocity distribution (Song and Graf, 1994; MacVicar and Rennie, 2012), nonlinearity of the primary Reynolds shear stress (Kironoto and Graf, 1995; MacVicar and Rennie, 2012), an amplification of the streamwise and vertical turbulent intensities in the upper half of the flow depth (Song and Chiew, 2001), and turbulence

generation away from the boundary (MacVicar and Roy, 2007; Thompson, 2007). Implicit in the explanations of these past results for decelerating flow has been an emphasis upon the primary bulk momentum changes of the nonuniform flow, including a dampened streamwise velocity and net positive wall normal velocity, and their impacts on turbulent energy production *via* the bursting mechanism in the near bed-region. For example, the ratio of ejections to sweeps in the bursting process determined using quadrant analysis has shown that these processes are not significantly affected by decelerating flows (Afzalimehr et al., 2012). Thus, the bursting process in streamwise decelerating and vertically expanding flows is expected to retain its form but is dampened as energy production from the mean velocity gradient is reduced.

As mentioned, studies have not yet considered the mechanism of three-dimensional macroturbulence in streamwise decelerating and vertically expanding open channel flow, and the role of macroturbulence on sustaining and redistributing turbulent energy in pools and backwater zones is of interest to the community. The vortical nature of the macroturbulence suggests the potential to assist with turbulent energy production from an interaction with mean energy gradients and to redistribute energy in the vertical and transverse directions. Reasons that macroturbulence has not been explicitly considered or studied previously for nonuniform gradually decelerating open channel flow over gravel may be attributed to: (i) the lack of decomposed turbulence visualization results from digital particle image velocity measurements and acoustic Doppler velocimetry profiles until recently for open channel flows with gravels (Hurther et al., 2007; Belcher, 2009); (ii) the loss of the imprint of macroturbulence on Reynolds-averaged turbulence terms and thus the lack of knowledge of its presence in the flow (Church et al., 2012), and (iii) perhaps the lack of investigations where macroturbulence is easily

181 identifiable using decomposition methods (Shvidchenko and Pender, 2001).

182

183 The overall goal was to provide the first study, to our knowledge, that investigates
184 macroturbulence for streamwise decelerating and vertically expanding open channel flow over
185 gravel and thereafter elucidate the role macroturbulence plays to sustain turbulent energy in the
186 outer region of the flow. To meet this goal, our specific objectives of this study were: (i) to
187 calculate turbulence time-averaged parameters for the experimental flow case and compare with
188 the empirical descriptions of others in order to provide quality assurance for our data and
189 potentially extend the macroturbulence results beyond the data set presented here; (ii) to perform
190 turbulence decomposition and spectral analysis of the velocity data in order that the imprint of
191 macroturbulence upon the instantaneous velocity signal could be discerned; and (iii) to estimate
192 the turbulent kinetic energy, turbulent energy production, and quadrant partitioning of bursting
193 events using the turbulence data in order to elucidate the role macroturbulence plays in
194 sustaining outer region energy. We focus on a hydraulically rough, nonuniform, gradually
195 decelerating open channel flow over gravel with a Froude number ranging from 0.5 to 0.8. By
196 providing experimental results of time-averaged quantities and statistical measures for this flow
197 case, we overlap previously reported time-averaged values from flow studies that have Froude
198 number up to 0.6 for nonuniform open channel flow over gravel (Song and Graf, 1994; Ahmed
199 and Rajaratnam, 1998; Afzalimehr and Anctil, 1999; Song and Chiew, 2001; MacVivar and Roy,
200 2007; Afzalimehr, 2012; Afzalimehr and Rennie, 2012; MacVicar and Rennie, 2012), which
201 helps provide quality assurance of our data sets but also extends the nonuniform turbulent open
202 channel flow literature database to the higher Froude numbers approaching transcritical flows.
203 With our specific objectives in mind, we use traditional Reynolds average turbulent quantities as

well as instantaneous and statistical measures of the three-dimensional instantaneous velocity signal in order to discern how the streamwise mean velocity deceleration coupled with the increased vertical expansion wall normal velocity impacts the structure of turbulence, including turbulence production, bursting near the bed and macroturbulence in the outer region.

2. Methods

Methods were designed to meet the specific objectives and in turn work toward a conceptual model for macroturbulence in nonuniform flow. We investigated macroturbulence through the use of flume observations, collection of three-dimensional instantaneous velocity data, computation of time-averaged turbulence parameters, turbulence decomposition, spectral analysis, turbulent energy production, and quadrant analysis; and thereafter, analyses of those results were used to yield specific interpretations about macroturbulence. The flume setup produced backwater conditions in a mildly sloping open channel consisting of fully turbulent flow over a gravel bed that was vertically expanding. The effects of vertical flow expansion on time-averaged turbulence statistics was described first by using traditional time-averaged turbulence parameters to provide quality assurance of the data collected and extend the applicability of empirical equations to transcritical flows. Thereafter, the double layer turbulence structure (i.e., macroturbulence and bursting) was investigated with time series analysis using the Triple Decomposition Theorem, spectral methods, turbulence energy production, and the quadrant splitting technique. The Triple Decomposition Theorem, spectral methods, and turbulence energy production were used to identify the imprint of macroturbulence on the instantaneous velocity signal and to quantify macroturbulent energy. The quadrant splitting

method illustrates the characteristics of the shear-produced bursting process, which likely is highly connected to macroturbulence. In the following subsections, we provide the details of the methodology including the experimental setup, velocimetry, time-averaged analysis, turbulence decomposition, spectral methods, turbulent energy production, and quadrant analysis.

2.1 Experiments

Experiments were conducted in a tilting, recirculating gravel-bed flume that was 12 m long and 0.61 m wide (e.g., see Belcher, 2009). The flume channel's bed was surfaced with gravel embedded on fiberglass-resin panels, and channel sidewalls were acrylic plates. Particle size distributions of the bed material had a standard deviation of 1.4 mm and particle size for which 50% of the particles were finer than 4.4 mm. The flume slope during testing was 0.006 m m⁻¹, and the water flow rate was 43 l s⁻¹. Flow entering the flume at the channel inlet was conditioned using a 127-mm long honeycomb of 6.4-mm diameter plastic tubes. Prior to obstructing the flow and creating backwater decelerating conditions, quasi-uniform flow conditions were established in the test section extending from ~5 m downstream of the inlet. The quasi-uniform flow was established by equipping the flume outlet with semipermeable bars to minimize drawdown effects near the free overfall. The quasi-uniform flow extended for ~5 m through the test section, and development of quasi-uniform flow verified consistency of flume slope throughout the testing section. Thereafter, emergent cylindrical obstructions of three differing diameters were placed downstream of the fixed measuring location to control the vertical expansion at the measuring location. The obstruction and backwater flow conditions produced an adverse pressure gradient, dH/dx , equal to 0.005 m m⁻¹ (± 0.001). These flow conditions resembled those in backwater pools which are commonly found in rivers upstream of

obstructions and in tributaries with large sediment supply relative to mainstem transport capacity.

Prior to data collection, water surface elevations were measured from the bottom of the roughness elements using rulers attached to the channel sidewalls, and the flow was allowed to stabilize. Stabilization of flow properties were ensured by monitoring water temperature, maintaining constant elevation in flume reservoir and head box, and measuring flow rate through the supply. Verification of flow stability was also confirmed by observing stabilization of the first three statistical moments of velocity prior to data collection. This was completed in the test section for each obstructed flow condition and for uniform flow conditions. The experimental conditions are summarized in Table 1, in which $Fr = U_m(gH)^{-1/2}$ is the Froude number, $Re = U_m H \nu^{-1}$ is the Reynolds number, $K^+ = k_s U_* \nu^{-1}$ is the shear Reynolds number. Testing occurred for a range of 13 flow depths, which allowed vertical expansion > 50% of the quasi-uniform flow depth. The Fr and Re ranged from 0.49 to 0.81 and 2.2×10^4 to 5.3×10^4 respectively; and the range of K^+ was 207 to 360, hence the flows studied were all subcritical and fully hydraulically rough.

2.2. Velocimetry

During testing, an acoustic Doppler velocimeter (ADV) was placed stationary and moved vertically using a high precision crank shaft. Care was made to maintain the ADV in a fixed streamwise position ensuring that orientation with the flow direction was consistent between measured profiles. The flow expansion was controlled using three diameters of emergent cylindrical obstructions and varying x / D from 1.5 to 22, where x is the distance upstream of the

obstruction and D is the uniform flow depth. Velocimetry data was collected with the ADV to include 13 velocity profiles each at a different flow depth (see Table 1) in the decelerating flow that was expanding in the vertical. For each velocity profile, 18 to 34 individual ADV time series were collected at each location. For each time series, 4500 instantaneous velocity readings were collected using the ADV, which is the type known as a 50-Hz *SonTek MicroADV*. The ADV measured velocity in a small sampling volume (0.09 cm^3) with resolution of 0.01 cm s^{-1} and accuracy of 1% of measured velocity. Data collected with the ADV was processed with the Bureau of Reclamations software *WinADV32*, which was used to filter data as suggested by the probe manufacturer. To ensure good quality data, filtering was performed to remove points with a signal to noise ratio < 15 or correlation $< 70\%$ as described by Wahl (2000). The ADV was oriented down looking to obtain near-bed velocity measurements. Following the collection of measurements with the probe in the down-looking position, the probe was reoriented side looking to obtain mid-depth to near surface measurements. During testing, extreme care was taken to ensure proper alignment between the ADV's coordinate system and the streamwise, vertical, and transverse planes of the flow. The coordinate systems of the side-looking and down-looking ADV were matched in the vertical by applying a vertical translation to one coordinate system such that discontinuities were removed from the TKE and V_{mag} profiles, where TKE is the turbulent kinetic energy and V_{mag} is the magnitude of the velocity vector. After ensuring that the measuring volumes corresponding to each ADV orientation were matched, the vertical orientation of all measurements were adjusted such that at $y = 0$, $V_{mag} = 0$. The ADV coordinate system was then adjusted to match the stream coordinate system by applying a series of orthogonal matrix rotations to the velocity vector to minimize the depth-averaged transverse flow component.

296

297 2.3. Time-Averaged Turbulence Parameters

298 Turbulence analyses of the velocimetry data included calculation of time-averaged
 299 parameters. The time-averaged streamwise U , vertical V , and transverse W flow velocities were
 300 calculated as

$$301 \quad U = \frac{1}{n} \sum_{i=1}^n u_i, \quad V = \frac{1}{n} \sum_{i=1}^n v_i, \quad W = \frac{1}{n} \sum_{i=1}^n w_i, \quad (1)$$

302 where u_i , v_i , and w_i are instantaneous velocities at a point along the channel centerline and n is
 303 the total number of measurements. The root mean square of velocity fluctuations for the
 304 streamwise u , vertical v , and transverse w components were calculated as

$$305 \quad \begin{aligned} U' &= \left[\frac{1}{n} \sum_{i=1}^n (u_i - U)^2 \right]^{0.5} \\ V' &= \left[\frac{1}{n} \sum_{i=1}^n (v_i - V)^2 \right]^{0.5} \\ W' &= \left[\frac{1}{n} \sum_{i=1}^n (w_i - W)^2 \right]^{0.5} \end{aligned} \quad (2)$$

306 The primary Reynolds shear stress component was calculated as $-\overline{u'v'}$, where $u' = u - U$, $v' = v$
 307 $- V$ and the overbar indicates the time-average. The energy associated with fluctuating
 308 components of velocity is the turbulent kinetic energy (TKE) and was calculated as

$$309 \quad TKE = \frac{1}{2} (U'^2 + V'^2 + W'^2) \quad (3)$$

310 The friction velocity (U_*) was estimated by extrapolating the primary component of Reynolds
 311 shear stress to the bed as

$$312 \quad U_* = \lim_{y \rightarrow 0^+} -\overline{u'v'}(y) \quad (4)$$

313 The friction velocity was also estimated using the Clauser method by fitting the streamwise

velocity distribution in the near-bed region. Deviations in shear velocity estimated using the two methods were noted and extrapolation of shear stress to the bed was used as it is the most direct method for fully rough flow. The pressure gradient parameter (β) defined by Clauser was used to describe the streamwise adverse energy gradient as the flow decelerates and U_* decreases.

2.4. Turbulence Decomposition

Turbulence decomposition was used to visualize and quantify energy-containing eddies associated with different frequency scales. Triple decomposition of the velocity signal was used to enable visual inspection of the fluctuating components for describing the imprint of macroturbulence on the velocity time series. Velocity time series can be decomposed into a mean velocity component and two fluctuating components representing low frequency macroturbulence and fast fluctuating high frequency small-scale eddies *via* the Triple Decomposition Theorem introduced by Hussain and Reynolds (1972) and expressed for the streamwise velocity as

$$u(t) = U + u'(t) + u''(t) \quad (5)$$

where u and U are the instantaneous signal and temporal mean; u' is the low frequency (0.1-1 Hz), large-scale signal used to isolate macroturbulence; u'' is the remaining high frequency (1-10 Hz), small-scale associated with shedding; u' was isolated using the moving-average over a time-step T_s as

$$U + u'(t) = \frac{1}{T_s} \int_{t-\frac{T_s}{2}}^{t+\frac{T_s}{2}} u'(t') dt' \quad (6)$$

Selection of an appropriate value for T_s was performed using visual inspection of smoothed time series for varying values of T_s (Fox et al., 2005; Fox and Patrick, 2008; Lacey and Roy, 2008;

Fox and Belcher, 2011). The time step T_s of 1 second was chosen from the visual inspection and further justified by the fact that estimation of the bursting period using outer variables ($T_s = 3HU_{max}^{-1}$ Nezu and Nakagawa, 1993) was always < 1 second.

2.5. Spectral Analysis

Spectral analysis of the velocity time series signals was performed to verify the prominent macroturbulence identified with turbulence decomposition and to quantify the turbulent kinetic energy across the macroturbulence frequency range. The spectrum was estimated using the discrete Fourier transform of u , v , and w with the fast Fourier transform method as

$$S_z(\omega) = \sum_{j=1}^n Z_j e^{(-2\pi i)(j-1)(\omega n/25-1)/n} \quad (7)$$

where the input variable Z represents the u , v , or w time series. The velocity spectra in variance preserving form was calculated as the product of the spectral energy density and associated frequency, $S_z(\omega)\omega$. When plotted in variance-preserving form, broad spectral peaks correspond to the frequency of an energetic mean or dominant eddy passing the velocity sensor (Boppe and Neu, 1995; Venditti and Bennett, 2000; Venditti and Bauer, 2005), and the area under the variance preserving spectra represents the total variance associated with the frequency range (Venditti and Bennett, 2000). The variance associated with macroturbulence was estimated by calculating the area under the spectra in the frequency range between 0.1 and 1 Hz.

2.6. Turbulent Energy Production

Production of turbulent energy was calculated in our analysis to understand the potential role of the vertical expansion velocity and macroturbulence upon energy generation. Turbulent

energy is produced by Reynolds stress components acting on mean velocity gradients (Nezu and Nakagawa, 1993). In open channel flows, the primary production and dominant turbulent energy source is derived from the vertical gradient of streamwise velocity given as

$$G = -\overline{u'v'} \left(\frac{dU}{dy} \right) \quad (8)$$

For uniform flow, Equ. (8) is the mechanism to produce turbulence; while for vertically expanding flow, a vertical term arises and turbulent energy can be produced from the vertical gradient of the expansion velocity given as

$$F = \overline{v'v'} \left(\frac{dV}{dy} \right) = V'^2 \left(\frac{dV}{dy} \right) \quad (9)$$

The vertical velocity induced by the gradually expanding flow was estimated by integrating the continuity equation and applying boundary conditions to derive the expansion velocity as

$$V_{exp} = U \frac{y}{H} \frac{dH}{dx} \quad (10)$$

Equation (10) shows V_{exp} is zero in uniform flows and positive toward the free surface in decelerating flows as the flow depth (H) increases in the streamwise direction.

2.7. Quadrant Analysis

Quadrant analysis was used to investigate the bursting process within the turbulent flow. The quadrant analysis method is a well-established technique to identify coherent structures in single point velocimetry data (Willmarth and Lu, 1972; Nezu and Nakagawa, 1993; Lee and Bass, 2012). The method consists of representing the instantaneous streamwise and vertical velocity components in a (u' , v') coordinate system. In the first quadrant, both the u' and v' signals are positive, representing outward interactions. The second quadrant represents low

momentum fluid ($-u'$) moving away from the bed ($+v'$), termed ejections. The third quadrant consists of negative u' and v' , termed inward interactions. The fourth quadrant represents high momentum fluid ($+u'$) moving toward the bed ($-v'$), termed sweeps. The second and forth quadrants (i.e., ejections and sweeps) were analyzed specifically in this study with the intent to investigate their joint probability function across the flow depth.

Focus on the bursting ejections and sweeps was carried out because the fact that these motions contribute to the generation of Reynolds shear stress (Robinson, 1991). The bursting process can be described as violent upward ejections of low-speed fluid and intruding sweeps of high-speed fluid at a shallow angle toward the bed. The two-dimensional velocity signature of ejections and sweeps has been found to physically indicate the passing of three-dimensional hairpin vortex structures, including a vortex head indicated by a second quadrant event, high speed fluid below the vortex head, and a shear layer caused by stagnation-point flow from the second and forth quadrant interaction (Adrian et al., 2000). Taken together, the shedding process identified with quadrant analysis depicts generation of Reynolds shear stress, which is paramount to turbulence investigations of turbulent energy production and modelling using Reynolds Averaged Navier-Stokes methods.

When performing the quadrant analysis, conditional averaging of the instantaneous fluctuating velocities was used to identify ejection and sweep events as strong contributors to shear stress generation. Conditional averaging involves selection of a threshold level, H' , referred to as the 'hole size', which is defined as $H' = |u'v'|/U'V'$ (Willmarth and Lu, 1972). The 'hole' concept is used to distinguish between significant turbulent structures and weaker

velocity perturbations (Lee and Bass, 2012). In this study, the hole size $H' = 2$ was selected to be consistent with previous studies in gravel-bed rivers (Buffin- Blanger and Roy, 1998; Lacey and Roy 2008). The ejection and sweep angles were also estimated as $-\tan^{-1}(u' v'^{-1})$ for the events greater than H' in second and fourth quadrant events, respectively.

3. Results

Results of this study are organized to first compare the traditionally reported first- and second- order statistical moments of velocity and the covariance of the streamwise and vertical velocity fluctuations (i.e., time-averaged turbulence parameters) with previously reported semiempirical equations for vertically expanding flow. We provide comparison of the time-averaged results in order to highlight the quality assurance of our data set, extend the empirical formula to transcritical flows, and show the potential to extend our macroturbulence results beyond the specific velocity profiles measured here. We then provide the thrust of our results that works toward understanding the role of macroturbulence in decelerating flows over gravel. To meet this goal, the imprint of macroturbulence upon the time-averaged parameters is summarized; and thereafter turbulence decomposition analysis, spectral analysis, and analysis of energy production are calculated from our data to elucidate macroturbulence. The study is complemented using quadrant analysis to estimate characteristics of the bed-derived bursting process in our study.

3.1. Data Quality Assurance via Time-Averaged Parameters

Streamwise time-averaged velocity, U , scaled with bed shear velocity, U_* , is shown in Fig. 1A and U is shown in dimensional form in Fig. 1B. Streamwise time-averaged velocity decreases as flow depth increases consistent with the decelerating nature of the open channel flow and continuity. Scaling U with U_* reduces the variation in distributions by $\sim 15\%$, however, Fig. 1A shows the wake effect in the outer region of the decelerating flow for $U U_*^{-1}$. The wake effect has been shown to exhibit dependence upon the adverse pressure gradient, and therefore we plot the Log-Wake Law modified for an adverse pressure gradient (Nezu et al., 1994; Song and Graf, 1994; Kironoto and Graf, 1995; Song and Chiew, 2001; Onitsuka et al., 2009). The modified Log-Wake Law was plotted as

$$\frac{U}{U_*} = \frac{1}{\kappa} \ln \left(\frac{y}{k_s} \right) + b + \frac{2\Pi}{\kappa} \sin^2 \left(\frac{\pi y}{2H} \right) \quad (11)$$

where the von Karman constant is $\kappa = 0.41$; the equivalent roughness height is $k_s = 2D_{84} = 1.12\text{cm}$; the constant of integration is $b = 8.5$; and the wake strength (Π) is estimated by the functional dependence on the adverse pressure gradient (β). For the latter, we use the linear fit between Π and β recently presented by Onitsuka et al. (2009) as

$$\Pi = 0.07\beta + 0.27 \quad (12)$$

The relationship by Onitsuka et al. (2009) includes their experimental data along with the data collected by Nezu et al. (1994) and Song and Graf (1994) to extend the applicability to a range of pressure gradients and relative roughness. Figure 1B shows that $U U_*^{-1}$ is well described by the modified Log Wake Law. This finding extends previous research to higher Froude numbers.

Figure 1C shows the streamwise turbulent intensity ($U' U_*^{-1}$), and Fig. 1D shows the standard deviation of streamwise velocity fluctuations (i.e., U' not normalized by U_*). Fig. 1C includes a solid line indicating the expected profile for $U' U_*^{-1}$ in uniform flows as defined by

Nezu and Nakagawa (1993) and given as

$$U'/U_* = D_u \exp(-y/H) \quad (13)$$

where the empirical coefficient $D_u = 2.3$ in uniform flow. As shown in Fig. 1C, the streamwise turbulent intensity for the nonuniform flow over gravel is amplified relative to the uniform flow equation especially as moving farther from the wall, which agrees with previous studies of decelerating flows over a gravel-bed (Song and Graf, 1994; Kironoto and Graf, 1995; Song and Chiew, 2001). In Fig. 1D, we show Equ. (13) with D_u fitted to our data with a mean value equal to 2.7. Our increased D_u fit is in close agreement with the results reported by Song and Chiew (2001), and we found that D_u estimated in the current study falls within the experimental results of Song and Graf (1994), Kironoto and Graf (1995), and Song and Chiew (2001).

The primary Reynolds shear stress ($-\overline{u'v'}$) distribution is shown in Figs. 1E,F. The $-\overline{u'v'}$ increases from the bed to the maximum value attained around $y/H = 0.2$ then decreases as the free surface is approached. Our primary Reynolds shear stress results are consistent with rough bed, open-channel, decelerating flows in that the distribution shows pronounced nonlinearity thus diverging from the uniform case (Song and Graf, 1994; Kironoto and Graf, 1995; Song and Chiew, 2001; Afzalimehr, 2010; Afzalimehr et al., 2012). Song and Chiew (2001) empirically fit the streamwise velocity distribution to derive the nonlinearity of the primary Reynolds shear stress in nonuniform, gradually expanding, open channel flow over gravel; and we test that equation for our data, given by Song and Chiew (2001) as

$$\frac{\overline{u'v'}(y)}{\overline{u'v'}(0)} = 1 + \beta \frac{y}{H} - (\beta + 1) \frac{(1+m)^2}{m(m+2)} \left(\frac{y}{H} \right)^{(m+2)/m} \quad (14)$$

and m is

$$\frac{U}{U_{avg}} = \frac{1+m}{m} \left(\frac{y}{D} \right)^{1/m} \quad (15)$$

where U_{avg} is the cross-sectional mean velocity. The Reynolds stress collapses well when scaled by the shear velocity with the outer region being well described by the nonlinear relationship shown as a solid line in Figs. 1E,F.

Vertical and transverse turbulence intensities (Fig. 2) are presented similarly to the streamwise component and are compared with profiles from uniform flow (Nezu and Nakagawa, 1993) given as

$$V'/U_* = D_v \exp(-y/H) \quad (16)$$

$$W'/U_* = D_w \exp(-y/H) \quad (17)$$

where the empirical coefficients D_v and D_w are equal to 1.27 and 1.51, respectively, for uniform flow. The nonuniform decelerating flow causes an amplification of both the vertical and transverse turbulence intensities far from the wall as compared to uniform flow, which is consistent with previous findings for the vertical component (Song and Graf, 1994; Kironoto and Graf, 1995; Song and Chiew, 2001; Afzalimehr, 2010) and transverse component (Song and Chiew, 2001; Afzalimehr, 2010). Bed shear velocity fails to collapse V' well, and the distribution of V' is not well described by exponential decay toward the free surface. Fig. 2B shows the decelerating flow reduced V' by 20% at the normalized bed distance $y/H = 0.2$, while reduction in the near surface region $y/H = 0.8$ was negligible. The location of maximum V' occurs near $y/H = 0.2$ for the velocity profile when the fluid just starts decelerating ($H = 10$ cm), while the maximum V' moves toward the free surface and occurs at $y/H = 0.5$ for the velocity profiles where the fluid has pronounced vertical expansion ($H = 14.3$ cm). This result is

consistent with Afzalimehr (2010) in which location of maximum V' shifted away from the bed as the flow expansion became more pronounced. W' also increased rapidly from the bed to a maximum around $y / H = 0.2$ then steadily decreases toward the free surface for the remainder of measurements. Turbulence anisotropy, $(W'^2 - V'^2)U_*^{-1}$ (Figs. 2 E,F), increases from the bed to a maximum value at $y / H = 0.2$ then steadily decreases to $y / H > 0.6$ and remains approximately constant toward the free surface. Turbulence anisotropy has not been highlighted in past studies of decelerating flows over gravel; however, measured vertical and transverse turbulent intensities in previous research show these values differ in the outer region and thus indicate some similarity to this study (Song and Chiew, 2001; Afzalimehr, 2010).

3.2. Imprint of Macroturbulence on Time-Averaged Parameters

Time-averaging smears instantaneous streamlines of macroturbulent cells that are known to fluctuate considerably (Hutchins and Marusic, 2007), however, some features of the time-averaged results should be highlighted in order that the imprint of bursting and macroturbulence on time-averaged parameters can be realized. Regarding bursting, the impact of flow deceleration on decreasing near-bed turbulent energy production (Figs. 1D, 2B, 2D) is consistent with the concept that the strength of bed-derived bursting is reduced as shown by the fairly nice collapse of streamwise time-averaged velocity, streamwise normal stresses and the primary Reynolds shear stresses when scaled with the friction velocity (see Figs. 1 A, C, D) (Nezu and Nakagawa, 1993). On the contrary, the enhancement of outer region turbulence relative to the shear velocity in the decelerating flow (Figs. 1A,C,E and Figs. 2A,C,E) suggests that macroturbulence mechanisms, rather than solely near-bed bursting, are responsible for turbulent energy generation in the outer region of the decelerated flows. The outer region streamwise

velocity distribution does not collapse with bed shear stress and was empirically accounted for with additional wake strength in decelerated flows. This indicates disconnect between the bed shear stress and outer region macroturbulence responsible for wake formation. Similarly, the primary component of Reynolds shear stress collapsed reasonably well when scaled by bed shear velocity yet was amplified in the outer region to exhibit nonlinearity, and the streamwise turbulent intensities underwent the greatest reduction in the near-bed region and remained relatively unaffected near the free surface.

Perhaps most pronounced, vertical and transverse turbulent intensities do not scale with the shear velocity, do not decay exponentially, and are enhanced for the decelerated flow conditions in the outer region, which cumulatively suggests outer region macroturbulence is not fully controlled by the near-bed, shear-produced bursting process. The imprint of macroturbulence on the vertical and transverse time-averaged parameters is further realized through plotting of turbulence anisotropy. Anisotropy of turbulence is recognized to be responsible for the production of streamwise vorticity, indicating the presence of three-dimensional rotating turbulence structures (Nezu, 2005). The enhancement of turbulence anisotropy relative to the bed shear velocity throughout the flow expansion indicates increased vorticity generation away from the bed as the fluid expands and thus suggests that anisotropy is not fully controlled by the near-bed, shear-induced bursting process.

3.3. Imprint of Macroturbulence on the Instantaneous Velocity Signal

Application of the Triple Decomposition Theorem (Hussain and Reynolds, 1972) reveals macroturbulence imprinted on the velocity signal as shown by the low frequency, large-scale

539 fluctuations in Fig. 3. Visually, we show that the large-scale fluctuations range in frequency
540 from 0.3 to 1 Hz and are consistent across the vertical and in the streamwise direction across the
541 various flow depths of the vertically expanding flow. These fluctuations for the expanding flow
542 scale well with macroturbulence features measured for uniform and nonuniform flows in gravel-
543 bed flumes and rivers (Shvidchenko and Pender, 2001; Roy et al., 2004; Fox et al., 2005; Hurther
544 et al., 2007; Lacey and Roy, 2007). More specifically, the fluctuations in the decelerating flow
545 are the same approximate frequency and amplitude as those recently measured in uniform flows
546 that vary across Froude number and roughness conditions as those presented here (see Fox and
547 Belcher, 2011; Stewart et al., 2013). For the uniform flow cases of Fox and Belcher (2011) and
548 Stewart et al. (2013), we previously performed in-depth characterization of the frequency,
549 intensity, geometry, and instantaneous fluid trajectories of the macroturbulence features using
550 proper orthogonal, large eddy, and Galilean decompositions of digital particle image velocimetry
551 data (Belcher, 2009; Belcher and Fox, 2009; Fox and Belcher, 2011), decomposition of free
552 surface velocity fields measured with large-scale particle image velocimetry (Fox and Patrick,
553 2008; Fox and Belcher, 2011), and triple decomposition of acoustic Doppler velocimeter and
554 velocity bend sensor measurements (Fox and Belcher, 2011; Stewart et al., 2013). Those tests
555 showed the macroturbulence as quasi-streamwise cells with alternating low-speed/high-speed
556 fluid and with swirling fluid trajectories in the intermediate region that showed occasional
557 reconnection at the bed. A similar form for the macroturbulence is assumed in this study given
558 the high consistency between the decomposed velocity signals in Fig. 3 and the stated papers and
559 the consistency of the hydraulic and roughness conditions performed across the uniform and
560 nonuniform flows. With regard to the function of the macroturbulence in the decelerating flow,
561 turbulence energy analysis will be quantitatively presented next in this paper; however, we point

out that visually we see in Fig. 3 that the amplitude of the decomposed streamwise velocity fluctuations decreases as the flow decelerates in the near-bed region and at 40% of the flow depth (bottom and middle rows of Fig. 3) but shows very little decrease in amplitude closer to the free surface (top row in Fig. 3).

3.4. Analysis of Macroturbulence Energy

Spectral analysis was used to quantify the turbulent energy of the full frequency ranges (0.1-10 Hz) and that associated with macroturbulence (0.1-1 Hz) as the fluid decelerates. Figure 4 shows the streamwise velocity spectra in variance-preserving form. The area under the streamwise velocity spectra decreases as the flow becomes more decelerated (i.e., moving from column one to two to three in Fig. 4) consistent with the distribution of U' (see Fig. 1), which shows a decrease in energy associated with streamwise velocity fluctuations. The streamwise spectral energy is greatest closer to the bed (i.e., bottom row of plots in Fig. 4) and decreases as the free surface is approached (i.e., middle and top rows in Fig. 4). When plotted in variance-preserving form, the broad spectral peaks correspond to the frequency of an energetic mean or dominant eddies passing the velocity sensor (Boppe and Neu, 1995; Venditti and Bennett, 2000; Fox et al., 2005; Venditti and Bauer, 2005), and these broad spectral peaks are observable in our spectral plots and comprise the imprint of macroturbulence on the energy spectra (Fox et al., 2005). In order to quantify the energy associated with the macroturbulence, we integrated across the broad spectral peaks in the velocity spectra. Fig. 5A shows that the streamwise velocity spectra of the macroturbulence frequency range decreases as vertical expansion increases. However, the decrease in macroturbulence energy is much more pronounced near the wall and almost no difference exists at $y/H = 0.8$ when comparing the two flow cases of $H = 10.9$ and

14.3 cm shown in Fig. 5A, which in turn agrees with the visual observations in Fig. 3. Nevertheless, streamwise macroturbulence energy is lost throughout the decelerating flow. To quantify the net energy loss, we integrated the results in Fig. 5A across the vertical to calculate the macroturbulence energy in the outer region of the flow, which is shown in Fig. 5B. As shown, the streamwise macroturbulence energy is reduced by $\sim 30\%$ in the decelerated flow as the flow depth increases from 10 cm to almost 14.3 cm (Fig. 5B). The total reduction in streamwise velocity variance is $\sim 50\%$ across the deceleration (see Fig. 1B). This comparison indicates that more streamwise turbulent energy is lost by high frequency fluctuations associated with bursting and dissipation scales than is lost by lower frequency macroturbulence.

The vertical and transverse velocity spectra also decrease as flow becomes more decelerated (see Figs. 6 and 7); however, the decrease is less obvious than was observed for streamwise spectra. The greatest reduction in vertical spectral energy comes at the normalized bed distance $y/H = 0.2$, while the core of the flow and the near-surface region loses less energy as the flow expands. The decrease in vertical spectral energy as the free surface is approached does not occur, which agrees with the results in Fig. 2B. Near the free surface, vertical turbulent energy is reduced at high frequencies, while energy at low frequencies increases as the flow becomes more decelerated (see top row of Fig. 6). Vertical macroturbulence energy decreases as the flow expands for the lower half of the flow, while in the upper half of the flow macroturbulence contains more energy (Fig. 5C). When integrated across the flow depth, the vertical macroturbulence energy is flat or slightly increases across the decelerated flow (see Fig. 5D). Similarly, the transverse spectra shows increases in turbulent energy in the macroturbulence range with perhaps some slight decreases at higher frequencies across the

decelerated flow (Fig. 7), and macroturbulence transverse energy increases in the outer region as the flow becomes more decelerated (Fig. 5E). When integrated across the flow depth, the transverse macroturbulence energy shows a constant increase across the expanded flow (Fig. 5F).

Results of the spectral analysis reveal net turbulent energy is lost from all velocity components in decelerating flows, but the turbulent energy being lost is primarily at middle to high frequencies (1-10 Hz) associated with the bursting process and dissipative scales. The vertical and transverse velocity fluctuations associated with macroturbulence (0.1-1 Hz) actually become more energetic in the outer region, particularly near the free surface. Comparison of spectra analyzed here with research from flows over gravel beds is limited; however, some casual comparison with turbulent boundary layer flows subject to adverse pressure gradient is possible. For example, Lee and Sung (2008) and Harun et al. (2013) found that large-scale turbulent features become more active in adverse pressure gradient flows over fixed-plate boundary layers.

The pronounced macroturbulence energy throughout the streamwise decelerated and vertically expanded flow prompted us to calculate the vertical turbulent energy production term in the flow throughout the expansion as well as calculate the potential impact of the vertical expansion velocity on the energy generation (see Fig. 8). Figure 8 shows turbulent energy production occurs as a result of the vertical expansion velocity, and this mechanism is not present in two-dimensional uniform flows (see Church et al., 2012, p. 7). The expansion velocity is responsible for 40% ($\pm 2.3\%$) of the vertical production term. The remaining measured turbulence production is likely derived from the bursting process (i.e., ejections and sweeps) and

perhaps other results of the nonuniformity discussed later. Nevertheless, the expansion velocity in nonuniform flows is shown to help generate turbulent energy thus providing a mechanism to increase vertical velocity fluctuations particularly in the outer region.

3.5. Characteristics of the Bursting Process

Quadrant analysis allowed us to gain a better understanding of the bursting process, i.e., ejections and sweeps, in the nonuniform flow. Somewhat surprisingly, the frequency of ejection and sweep events are not effected by flow deceleration and expansion (Figs. 9C,D) despite the fact that the bursting period calculated using outer variables ($T_B = 3 H U_{max}^{-1}$; Nezu and Nakagawa, 1993) doubles from 0.43 to 0.82 s when the flow depth increases from $H = 10$ cm to $H = 14.5$ cm. A similar result was reported by Alfzalimehr (2010) in which the frequency of ejections and sweeps did not show differences in a nonuniform flow over gravel. The consistency of ejections and sweeps across the decelerating region might be related to the structure of macroturbulence, which we discuss later. Angles of ejections and sweeps relative to the bed determined from quadrant analysis of the streamwise and wall normal velocity components are shown in Figs. 9A and 9B, respectively. The ejection and sweep angles are minimum near the bed and increase toward the free surface consistent with research in rough bed uniform open channel flows at high Reynolds number (Adrian et al., 2000; Lelouvetal et al., 2009). The most expanded flow examined here shows an increase in the angles for the entire flow depth except in the very near bed roughness region. These results suggest that the bursting process changes to become more aligned in the wall normal direction in decelerating flows.

4. Discussion

We show for the first time to our knowledge evidence that macroturbulence plays a functional role in turbulent energy transfer within decelerating open channel flow over a gravel bed. Evidence of the existence of macroturbulence within the streamwise decelerating and vertically expanding flow over gravel (Figs. 3, 4, 6, and 7) was not surprising to us given the reported presence of macroturbulent features within uniform flows in gravel bed-rivers and flumes with similar hydraulic characteristics as studied in this work (Roy et al., 2004; Hurther et al., 2007; Fox and Belcher, 2011). Nor was it particularly surprising, albeit interesting, that the streamwise component of the macroturbulent energy decreased in the lower half of the flow depth as the flow decelerated (Figs. 5A,B) given the suggested linkage between macroturbulence and near-bed bursting (Adrian and Marusic, 2012). What did surprise us was that macroturbulent energy in the transverse and vertical actually became stronger in the outer region as the fluid expanded and streamwise macroturbulence remained similar in the outermost region of the flow as the fluid expanded (Fig. 5). These results suggest bursting and flow nonuniformity from the vertical expansion provides the mechanisms to sustain macroturbulence in these flow conditions. Following from these results, we suggest macroturbulence as a defining feature of fully rough flow over gravels that derives energy from bursting as well as flow nonuniformities.

A common suggested hypothesis in the peer-reviewed literature has been the connectivity between the near-bed bursting process and macroturbulence (Roy et al., 2004; Hurther et al., 2007), and the present study tends to corroborate this concept. Previous research has suggested that the bursting process could be organized by macroturbulence sweeping motions such that bursting occurs at the edge of macroturbulence cells for turbulent boundary layer flows (Kline et

al., 1967; Schoppa and Hussain, 2002; Marusic et al., 2010) and recently for wall-bounded flows (Adrian, 2007; Adrian and Marusic, 2012). Our results suggest that the form of macroturbulence varies little throughout the streamwise deceleration and vertical expansion and that at the same time the frequency of ejections and sweeps associated with bursting does not change (Figs. 9C,D). The consistency of macroturbulence and bursting characteristics of this flow suggest that the bursting process dynamically evolves with the macroturbulent structure without changing its spatial organization, which in turn helps trigger ejection and sweep events. On the other hand, turbulent energy produced at the bed from the bursting process is less intense as the fluid decelerates (Figs. 1A,C,D) and in turn less energy is available for transfer *via* the macroturbulence. Cumulatively, the results imply that bursting is less intense as there is less bulk fluid shear at the boundary and thus supplies less energy to macroturbulence but that the spatial distribution is determined by macroturbulence, and hence the spatial distribution of bursting is much slower to change as compared to the intensity of bursting.

Perhaps the most interesting finding of the turbulent structure throughout the streamwise decelerating and vertical expanding flow was the strengthening of macroturbulence in the cross-sectional plane as seen by the increased vertical and transverse components of macroturbulence energy (Figs. 5C,D,E,F) as well as the nearly constant energy of the streamwise component of macroturbulence energy in the outermost region. We attribute the sustained energy of macroturbulence at least partially to the effect of the vertical expansion, which provides an energy source for turbulence. Evidence that energy production from the vertical expansion supplies energy to macroturbulence was shown by calculation of the turbulent production in the vertical (Fig. 8). The vertical turbulent energy production term calculated with the expansion

velocity explains 40% ($\pm 2.3\%$) of the vertical energy production measured in the outer region. The existence of three-dimensional macroturbulence then provides a mechanism for energy redistribution to the transverse and streamwise components *via* generated vorticity (Nezu, 2005; Nikora and Roy, 2012), which is shown by the fluid anisotropy throughout the flow depth in all the decelerating flow profiles (Fig. 2F). The redistribution mechanisms associated with the macroturbulence structure and the suggested interaction of the macroturbulence structure with the vertical expansion are further corroborated with the results of the vertical profiles for the vertical and transverse turbulent intensities (see Figs. 2A,C). The lack of collapse of the turbulent intensities with the friction velocity and the increased magnitudes in the upper half of the flow depth suggests that the dampened bursting process at the near-bed region associated with the decreased streamwise mean velocity does not explain well the vertical energy terms. Rather, the vertical and transverse turbulent intensities in the upper half of the flow depth are suggested to be heavily impacted by energy production from the vertical expansion interacting with the vorticity of the macrotubulence.

As previously mentioned, evidence of connectivity of the bursting process to macroturbulence is suggested by our results; however, our results also point to the idea that macroturbulence lives and dies differently than bursting alone. In general, decelerating flows are recognized to cause the death of turbulent energy, but it is suggested that the dampening of macroturbulence lags behind that of the decreasing intensity of bursting. To this end, we suggest macroturbulence as a defining feature of the flow structure for fully rough flow over gravels that provide a skeleton to the turbulent structure that can sustain itself from nonuniformities as well as bursting. In the case of the decelerating flow over gravel presented here, we show that it is

likely that the nonuniformity associated with the expansion velocity helps feed mean energy directly into macroturbulence (Fig. 8), and macroturbulence redistributes turbulent energy to the transverse velocity component thus strengthening turbulence in the cross-sectional plane. Some experimental results from past studies over gravel beds with flow nonuniformities tend to corroborate the concept of the existence of macroturbulence and strengthening of macroturbulence in the presence of nonuniformities, although these previous papers were not studying this idea explicitly. For example, Papanicolaou and Hilldale (2002) show a common feature reported for a transverse expanding open channel flow in that the primary component of the turbulent kinetic energy is maximized far from the wall rather than near the gravel bed. A potential macroturbulence explanation of the results of Papanicolaou and Hilldale (2002) results is that the transverse velocity of the expansion acts to sustain the energy of macroturbulence that is manifested in the turbulent energy signal. Similarly, little evidence has been found that macroturbulence changes pronouncedly in the presence of large obstructions within the flow. Fox et al. (2005) experimentally studied a barb (i.e., a hydraulic control structure) that extended over halfway across the gravel-bed channel in the transverse and vertical directions, and Lacey and Roy (2007) studied an isolated pebble cluster equal to 30% of the flow depth in a gravel-bed stream; and both studies found that the localized changes from the nonuniformities did not disrupt the imprint of macroturbulence upon the decomposed velocity signals. Again, a potential macroturbulence explanation of the results of Fox et al. (2005) and Lacey and Roy (2007) is that the macroturbulence is at least partially sustained from the vertical velocities associated with fluid expansion and contraction upstream and downstream of the obstacles.

As a final point of significance with regards to future study of macroturbulence, we

highlight that the macroturbulence portion of the streamwise turbulent kinetic energy makes up ~ 50% of the total streamwise turbulent kinetic energy in the tests reported here, which agrees well with previous studies that have shown that the macroscale flow features in high Reynolds number flows contain 50% of the turbulent kinetic energy (Liu et al., 2001; Belcher, 2009). We used our spectral energy results to integrate the total streamwise turbulent energy across the macroturbulent wavenumbers and across the flow depth and found that macroturbulence comprised 44% of the streamwise turbulent kinetic energy for the production and transfer subranges at $H = 10.9$ cm and comprised 54% of the energy at $H = 14.3$ cm. The relative influence of macroturbulence to the net turbulent kinetic energy of the flow as well as the potential mechanics of macroturbulence to transfer energy highlight a need to place future research on elucidating the role of macroturbulence in turbulent flow phenomena in gravel-bed rivers.

5. Conclusions

Results of this study support the hypothesis that macroturbulence plays a functional role within streamwise decelerating and vertically expanding flow over gravel by redistributing turbulent kinetic energy in the vertical and transverse directions. Specific results that support the hypothesized macroturbulence are as follows:

- The enhancement of outer region turbulence relative to the shear velocity in the streamwise decelerating and vertically expanding flow suggests that other turbulence mechanisms, rather than solely near-bed bursting, are responsible for turbulent energy generation.

- Macroturbulence is imprinted on the velocity signal as shown by low frequency, large-scale fluctuations in the decomposed velocity time series suggesting a similar form as shown in uniform flow over gravels including quasi-streamwise cells with alternating low-speed/high-speed fluid with swirling trajectories and connectivity to the bed.
- Results of the spectral analysis reveal net turbulent energy is lost from all velocity components in decelerating flows, but the turbulent energy being lost is primarily at middle to high frequencies associated with the bursting process and dissipative scales. Also, vertical and transverse velocity fluctuations associated with macroturbulence become more energetic in the outer region as the flow decelerates.
- Results estimate that the vertical expansion velocity provides 40% of the turbulent energy production in the vertical suggesting a mechanism that interacts with macroturbulence in the outer region to redistribute energy.
- The frequency of ejection and sweep events are not affected by flow deceleration, while the interactions become more aligned in the wall normal direction suggesting the potential of macroturbulence to spatially organize the bursting process.

Taken together, the results of this study suggest that macroturbulence is a defining feature of fully rough flow over gravels that that can sustain itself from bed-derived bursting as well as flow nonuniformities. Macroturbulence makes up $\sim 50\%$ of the total streamwise turbulent kinetic energy in the tests reported here. While the primary streamwise macroturbulence energy decreases with bed-derived turbulence production, the loss of energy lags behind that of the decreasing intensity of bursting. Further, the vertical and transverse macroturbulence energy increases in the outer region throughout the streamwise deceleration. The sustaining nature of

792 macroturbulence suggests that additional energy production associated with the flow
793 nonuniformity feeds turbulent energy from the vertical and transverse mean components and that
794 the vertical velocity of the expanding flow is highlighted as one such mechanism.

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926 **Table 1**

927 Hydraulic conditions for the experimental tests.

Run	H , cm	U_{avg} , cm s^{-1}	K^+	Re ($\times 10^4$)	Fr	U^* , cm s^{-1}	β
1	9.6	71	436	6.8	0.81	6.15	-0.87
2	10	70	414	7.0	0.78	6	-0.59
3	10.1	69	415	7.0	0.77	5.9	-0.49
4	10.4	71	416	7.4	0.74	5.85	-0.43
5	10.9	67	377	7.3	0.71	5.5	-0.38
6	11.2	67	375	7.5	0.65	5.3	-0.32
7	11.6	66	367	7.6	0.64	5.26	-0.19
8	11.7	64	354	7.5	0.62	5.25	-0.10
9	13.3	60	319	8.0	0.60	4.6	0.11
10	13.7	58	296	8.0	0.59	4.65	0.22
11	13.9	59	306	8.2	0.59	4.5	0.26
12	14.3	57	288	8.2	0.58	4.25	0.44
13	14.5	53	294	7.7	0.58	4.25	0.47

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Fig 1. Statistical measures of velocity that conform to bed shear velocity (A) and (B) streamwise velocity component normalized by bed shear velocity and shown in dimensional form. (C) and (D) Root mean square of streamwise velocity component U' normalized by bed shear velocity and shown in dimensional form. (E) and (F) Primary component of Reynolds shear stress $-\overline{u'v'}$ normalized by squared shear velocity and shown in dimensional form.

Fig 2. Turbulence quantities resilient to APG (A) and (B) root mean square of vertical velocity component V' normalized by bed shear velocity and shown in dimensional form. (C) and (D) Root mean square of transverse velocity component W' normalized by bed shear velocity and shown in dimensional form. (E) and (F) Anisotropy of turbulence in the vertical and transverse directions normalized by bed shear velocity and shown in dimensional form.

Fig 3. The slow fluctuating streamwise velocity component isolated with $T_s = 0.2$ s.

Fig 4. Spectral analysis of selected streamwise velocity in variance-preserving form normalized by variance. Flow depth and normalized measuring location shown in the upper left corner.

Fig 5. Integral of velocity power spectral densities showing energy between 0.1 and 1 Hz. (A) and (B) Energy associated with streamwise macroturbulence normalized by the total energy between 0.1 and 10 Hz (C) and (D) Energy associated with wall normal macroturbulence normalized by the total energy between 0.1 and 10 Hz (E) and (F) Energy associated with wall normal macroturbulence normalized by the total energy between 0.1 and 10 Hz

Fig 6. Spectral analysis of selected wall normal velocity in variance-preserving form. Flow depth and normalized measuring location shown in the upper left corner.

Fig 7. Spectral analysis of selected transverse velocity in variance-preserving form. Flow depth and normalized measuring location shown in the upper left corner.

Fig 8. Turbulent energy production from vertical velocity. Solid symbols are total production estimated using measured data. Open symbols are production associated with the velocity expansion and are calculated using the theoretical expansion velocity.

Fig 9. Quadrant analysis with hole size $H = 2$ for selected velocity profiles. (A) and (B) Angles relative to the bed of ejections and sweeps respectively. (C) and (D) depicts the frequency of ejections and sweeps respectively.