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Turbulence signatures of natural river morphology in four dimensions

Giuditta Trinci[1,2] | Gemma L. Harvey[1] | Alexander James Henshaw[1] | Walter Bertoldi[2,3]

[1]School of Geography, Queen Mary University of London, London, UK

[2]Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy

[3]Center Agriculture Food Environment, University of Trento, Trento, Italy

Correspondence
Giuditta Trinci, School of Geography, Queen Mary University of London, Mile End Road, London E1 4NS, UK.
Email: giuditta.trinci@qmul.ac.uk

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Abstract

Turbulent flow in natural river channels drives geophysical processes and exerts a fundamental influence on aquatic biota. An extensive range of turbulence properties have previously been synthesized into four categories or “dimensions” with ecological relevance: intensity, periodicity, orientation and scale (IPOS). We apply this framework across three rivers with differing morphologies in order to assess the statistical coherence of the four IPOS categories within turbulence field data and their utility in discriminating between fundamental units of river habitat. Intensity, periodicity-scale and orientation were identified as the key gradients in the turbulence data set using multivariate analysis. These gradients all revealed statistically significant differences between rivers and/or geomorphic units. The intensity gradient accounted for the highest variance and most pronounced inter-reach differences, but the periodicity-scale and orientation gradients were also useful in distinguishing between certain combinations of rivers and/or geomorphic units. Different turbulence gradients, or combinations of gradients, were important in characterizing differences between rivers and geomorphic units (riffes, pools, steps). The gradients provided improved prediction of geomorphic units compared to standard hydraulic variables (mean velocity, depth), although the extent of improvement in prediction varied between river morphologies. The analysis reveals the statistical coherence of the four categories or “dimensions” of turbulence in multivariate space, connects the ecologically defined IPOS categories of turbulence properties with river types and fundamental units of river habitat (geomorphic units). Turbulence signatures of natural channel morphology are expressed across all four dimensions of turbulence, providing clear evidence that these four dimensions should be routinely considered in ecohydraulics and hydromorphology research to facilitate a full understanding hydraulic habitat.

KEYWORDS
ecohydraulics, field conditions, geomorphic units, turbulence signature

1 | INTRODUCTION

The turbulent properties of river flow exert a fundamental influence on flow resistance, sediment transport and river morphology, and on the growth and survival of aquatic biota (Nepf, 2012; Nikora, 2010). Despite this, turbulence is largely overlooked in traditional physical river habitat assessments and river restoration design in favour of aggregate measures such as mean velocity or Froude number that are often used to characterize the hydraulics of geomorphic units (Trinci et al., 2017). This reflects the practical challenges associated with the direct field measurement of turbulence, and the somewhat bewildering array of options available for representing turbulence (Lacey et al., 2012). Turbulence is quantified by direct measurement of flow velocity at high frequency, flow visualization or computational fluid dynamics, and a wide range of descriptors can be employed to represent various turbulence characteristics (Franca & Brocchini, 2015; Lacey et al., 2012; Wilkes et al., 2013). A small number of studies have explored the turbulent properties of visually identifiable channel geomorphic units such as riffles and pools (MacVicar & Roy, 2007a; Harvey & Clifford, 2009; Roy et al., 2010) although these have tended to focus on an individual site, a small range of geomorphic units and/or a limited range of turbulence properties. Similarly, the laboratory experimentation on which much of our understanding of turbulence-biota relationships is based is known to generate different ranges of turbulent properties to those expected in natural channels and has tended to focus on a relatively restricted and unstandardized range of turbulence descriptors (Lacey et al., 2012). There remains a lack of studies that integrate a wide range of turbulent properties to explore variation across river types and at smaller spatial scales (within a river reach; $\sim 10^0$–10^1 m^2) such as geomorphic units. Geomorphic units are river landforms with characteristic morphology and sediment properties (e.g., steps, riffles, runs, pools) at spatial scales that are directly relevant to the habitat use of aquatic organisms such as invertebrates and fish (Vezza et al., 2014; Wilkes et al., 2013). They have been described as the "building blocks" of river systems (Fryirs & Brierley, 2022).

A framework proposed by Lacey et al. (2012) provides a helpful synthesis of ecologically relevant turbulence descriptors into four main categories or "dimensions" of turbulence: intensity, periodicity (predictability), orientation and scale of turbulence (the "IPOS" framework). The IPOS framework represents a novel, practical and ecologically based approach to organizing and interpreting a wide range of turbulence data but has not yet been widely applied in ecohydraulics research. IPOS has been applied in laboratory experiments to characterize turbulence in relation to fishway design (Roth et al., 2020) and in the field to explore fish habitat use (Trinci et al., 2020) but further analysis across river types and geomorphic features is required to validate the utility of the framework. The objectives of the study were (i) objectively identify gradients in turbulence properties across rivers and geomorphic units using field data and assess their alignment with the ecologically based IPOS framework; (ii) evaluate the utility of the derived gradients for distinguishing river reaches and geomorphic units.

2 | MATERIALS AND METHODS

2.1 | Field sites

Field data were collected under low flow conditions (discharges below Q_{50}, the flow equalled or exceeded 50% of the time) between May and September 2015 from three semi-natural European rivers across an energy gradient (Figure 1): a high-gradient step-pool reach (Vermigliana); an intermediate gradient riffle-pool reach (Tagliamento); and a low gradient chalk stream with characteristic aquatic macrophyte stands (Frome). Sites were chosen to minimize levels of management of the instream environment and riparian zone and capture sequences of bedforms in rivers across a bedform roughness gradient that is representative of temperate environments (Henshaw et al., 2020). Discharge (Q) values were measured for each site for the survey period and compared to hydrological data from historical records from the nearest gauging station. Q at the time of survey were as follows: Frome 0.58 m^3 s^{-1} (low flow, Q_{95}: 95% exceedance), Tagliamento side channel used for the study reach 3.52 m^3 s^{-1} and Tagliamento main channel at Venzone gauging station 42 m^3 s^{-1} (median flow, Q_{50}, 50% exceedance, Tockner et al., 2003) and Vermigliana 1.82 m^3 s^{-1} ($\sim$median flow, Q_{48}: 48% exceedance). The water level was monitored during all surveys and no changes in flow stage were identified. Reynolds number was between 10^5 and 10^6 for the Vermigliana; and 10^4–10^5 for the Tagliamento and Frome rivers. Froude number was above 1 (supercritical flow) for 54% of the measurements for the Vermigliana, 41% for the Tagliamento and 20% for the Frome. Reynolds and Froude number were computed from high frequency velocity measurements (see below for details).

The Vermigliana is a tributary of the Noce River in north-east Italy, characterized by a pluvio-nival hydrological regime. The study reach is located within a confined valley setting, with high channel bed gradient (0.032) and a step-pool morphology. The dominant substrate is boulders and cobbles (particle size range 63–630 mm; ISO, 2004). The Tagliamento is a near-pristine gravel bed braided river in north-east Italy (side channel study location bed gradient = 0.012). The dominant substrate is fine gravels (particle size range 6.3–63 mm; ISO, 2004). The study reach is a meandering anabranch of the main channel characterized by a riffle-pool morphology. The Frome (UK) is a lowland groundwater-fed chalk stream in the south of England (study reach bed gradient = 0.004). The study reach is sinuous with a vegetated riparian zone. Channel morphology comprises riffle, pool and glide geomorphic units but submerged aquatic plants (*Ranuculus spp*) represent a major roughness element (Gurnell & Grabowski, 2016). The dominant substrate is fine gravels (particle size range 2–6.3 mm; ISO, 2004).

2.2 | High frequency velocity measurement and post-processing

At each site, velocity was measured in three dimensions (streamwise, lateral and vertical) at high frequency (32 Hz) for 120 s using a

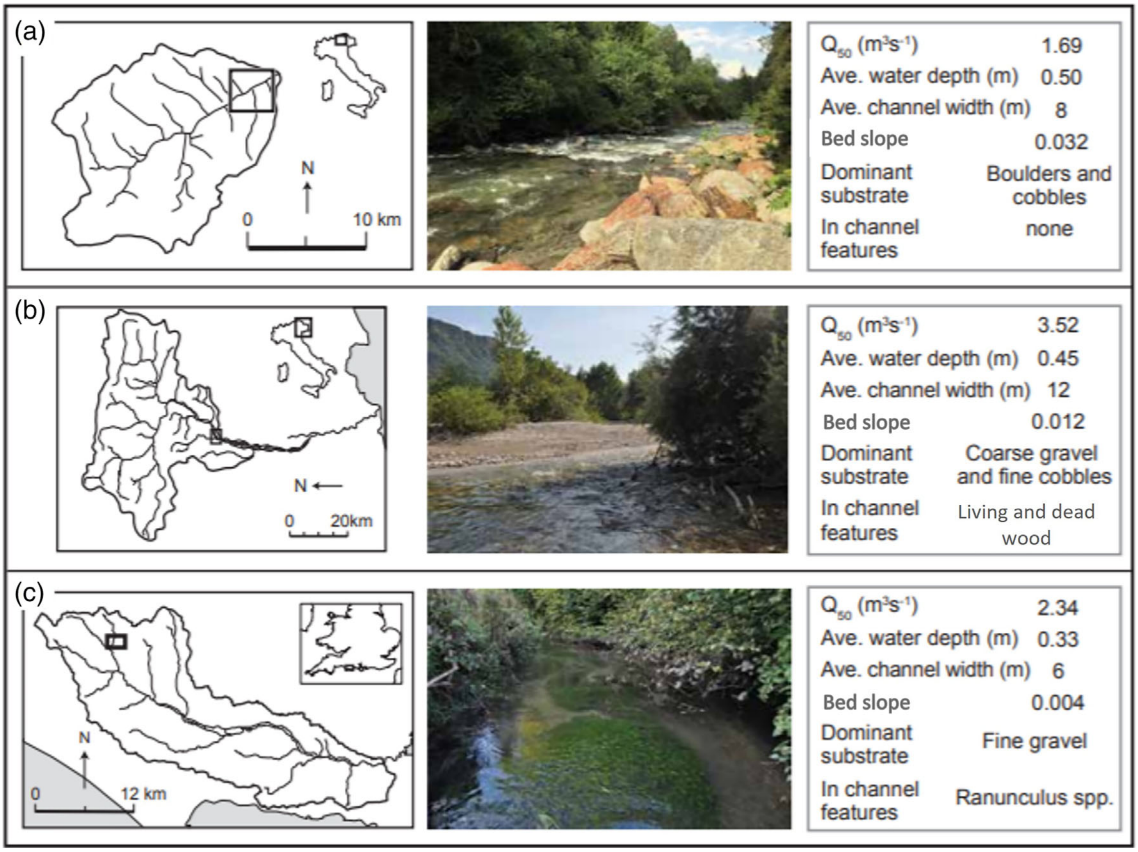
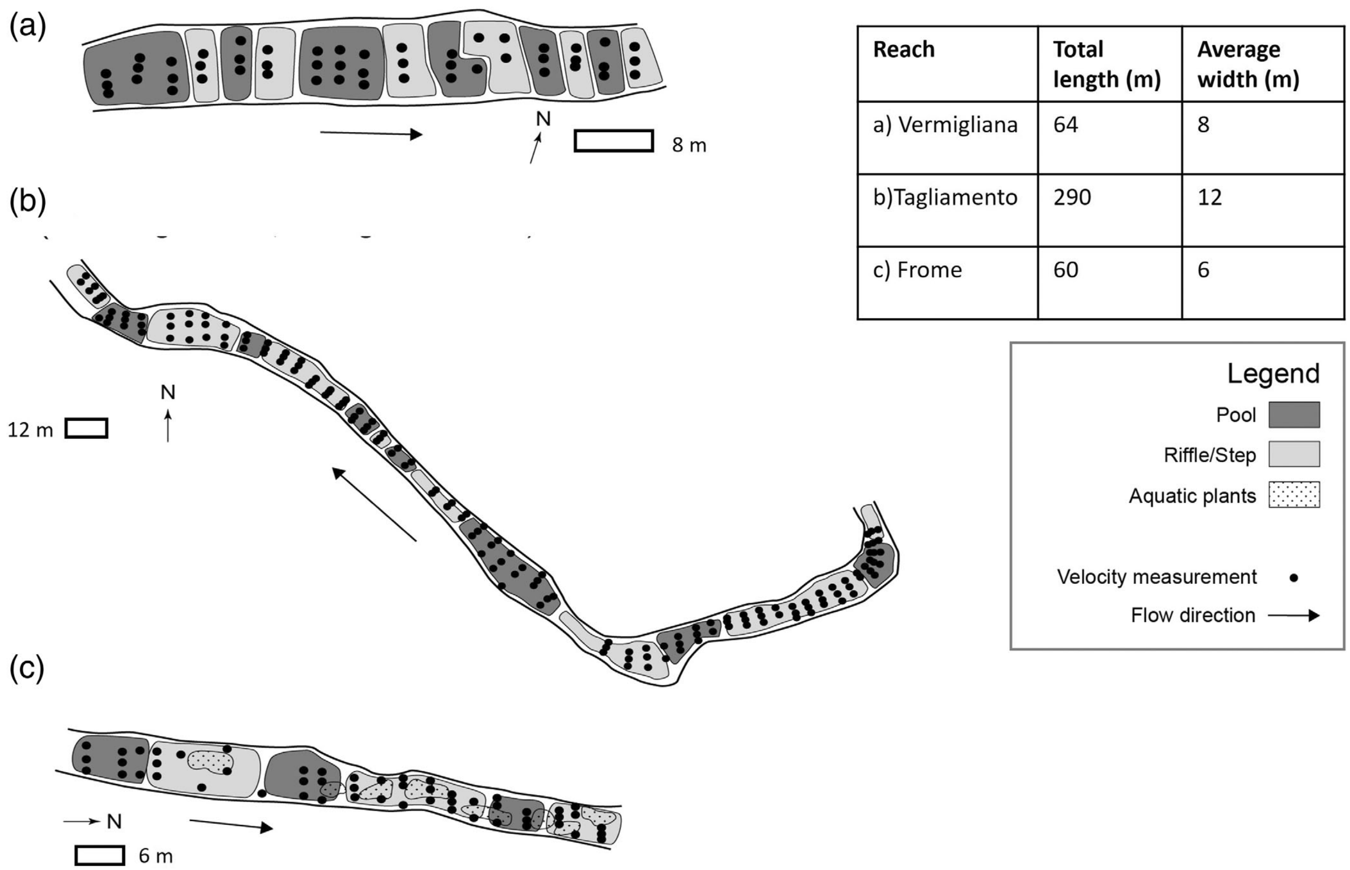


FIGURE 1 Field site locations and contextual information: (a) high gradient step-pool reach, River Vermigliana, Italy (Manning coefficient = 0.040); (b) intermediate gradient riffle-pool reach - River Tagliamento, Italy (Manning coefficient = 0.022); (c) low gradient riffle-pool reach with aquatic macrophytes (*Ranuculus* spp.) – River Frome, UK (Manning coefficient = 0.015). Q_{50} is the median flow (flow percentile which is equalled or exceeded 50% the period of flow record [Color figure can be viewed at wileyonlinelibrary.com]

Nortek/YSI (Vector) Acoustic Velocimeter (ADV). This frequency and record length has been proposed as optimal for turbulence measurements in natural channels (Buffin-Bélanger & Roy, 1998; Buffin-Belanger & Roy, 2005; Wilkes et al., 2013). The ADV was attached to a moveable mounting structure designed to vertically suspend the ADV in the flow while minimizing flow disturbance from the mounting. Each velocity measurement was captured at 0.6 of the water depth from the surface, a standard protocol in habitat studies to indicate average conditions (Emery et al., 2003; Moir & Pasternack, 2008). Conditions at 0.6 depth may be less representative of average conditions where characteristic logarithmic velocity profiles are altered by the presence of roughness elements such as aquatic plants or boulders but the method enabled a standardized approach across our study sites that is comparable with published literature. Flow velocity was sampled at three locations (30, 50, 70% of channel width) along equally spaced cross sections (scaled on channel width) in order to capture variability along the channel centreline and more marginal locations (17, 58 and 19 cross sections were sampled for the Vermigliana, Tagliamento and Frome rivers, respectively). Cross sectional spacing was 3 m for the Vermigliana and Frome reaches, and 5 m for the Tagliamento. Transverse spacing of cross sectional measurements was approximately 2 m for the Vermigliana, 3 m for the Tagliamento and 1.5 m for the Frome. This "mesoscale" spatial resolution with 1.5–5 m spacing of sample points (see Figure 2) is conventional in aquatic habitat applications and enables reach-level coverage but does not permit detailed analysis of secondary circulations or the microstructure of eddies (Webb & Cotel, 2010). To avoid bias in turbulence results arising from probe orientation, sampling frequency, Doppler noise floor, and aliasing of the Doppler signal (Lane et al., 1998), visual observation of time series plots was used to explore velocity variability and identify possible spikes (Chatfield, 2003). Spikes were replaced using phase-space thresholding (PST) where they did not meet quality requirements identified by the Signal to Noise Ratio (SNR > 20) and correlation (COR > 70%) (Lane et al., 1998; Goring & Nikora, 2002; Chatfield, 2003). In addition, stationarity tests were performed for each time series and non-stationary series were detrended using linear or second order polynomial regression (Clifford et al., 1993; Harvey & Clifford, 2009) to remove the influence of larger-scale (e.g., secondary) flow circulation outside of the turbulent range.

2.3 | Geomorphic unit classification

The sampling design enabled sufficient replication of measurements within the key Geomorphic Units (GUs) characteristic of each reach.



Reach	Total length (m)	Average width (m)
a) Vermigliana	64	8
b)Tagliamento	290	12
c) Frome	60	6

FIGURE 2 Schematic diagrams to illustrate the spatial organization of geomorphic units and velocity point measurements for the three study reaches: (a) Vermigliana, (b), Tagliamento, (c) Frome. Black arrows represent flow direction

GUs were identified visually in the field following Belletti et al. (2017) focusing on instream units only. Each measurement location in the surveyed reach was assigned to one GU under stable flow conditions (riffles and pools for the Frome and Tagliamento reaches, and steps and pools for the Vermigliana reach). The spatial location of geomorphic units for each reach is shown in Figure 2 together with the location of velocity point measurements. For the river Frome aquatic macrophyte stands were also present and these were predominantly associated with riffle locations (see Figure 2).

2.4 | Computation of IPOS turbulence parameters

Turbulence parameters for each of the four IPOS categories (intensity, periodicity, orientation, scale) were computed for each velocity point measurement. Dimensionless variables were computed in order to allow comparability across rivers (Table 1). Intensity parameters incorporated the instantaneous turbulent fluctuations (u', v' w'), turbulent kinetic energy (TKE) and Reynold shear stress in each plane (uv, vw, uw). For periodicity, kurtosis of the velocity fluctuations was used alongside the condition for pseudo-periodicity derived from autoregressive models fitted to time series (Clifford et al., 1993). For orientation, quadrant analysis was used to identify turbulent event structure and assign contributions to the total shear stress to four event types (inward interactions (Q1), ejections (Q2), outward interactions (Q3) and inrushes (Q4)) following Lu and Willmarth (1973). For scale, eddy length scales were used in u, v and w velocity planes. Eddy length scales may be computed by fitting second order autoregressive (AR[2]) models to time series and, assuming Taylor's (1938) hypothesis (that a sequence of changes in velocity are representative of an unchanging pattern of turbulence at that location), the eddy length is given by the product of mean velocity and the integral time scale calculated using the AR(2) model (Clifford et al., 1993). Use of Taylor's hypothesis is appropriate under stationary flow conditions as during the study period (Clifford & French, 1993). Details on the computation of turbulence properties are provided in Table 1. Raw velocity data and computed turbulence parameters are provided in Appendix S1 (Trinci, 2017).

2.5 | Data analysis

Principal Component analysis (PCA) was used to identify the key gradients in turbulence properties. To identify redundant variables and high correlation between variables, Kaiser-Meyer-Olkin (KMO) and Barlett's test of Sphericity were examined to identify the variables to

TABLE 1 Summary of the IPOS variables (intensity, periodicity, orientation, scale) identified by Lacey et al. (2012) and Trinci et al. (2017) and their dimensionless forms. Bold text represents the reduced variables of the PCA. RL is the record length (120 seconds). Shear velocity is defined as the square root of the total shear stress (τ, in N/m^2) divided by the water density, and was computed, under the hypothesis of uniform flow at reach scale, as the square root of the product of the longitudinal bed slope (S), the hydraulic radius (R, ratio between the cross-sectional area and the wetted perimeter) and the gravitational acceleration (g). x = u, v, w velocity components, N = number of observations and d = water depth. Instantaneous turbulent fluctuations (x' = x – X) are represented by u', v' and w' and mean velocities by U, V, W. Modified from Trinci et al. (2017), with permission

	Parameters	Formula	Dimensionless variables
Intensity	Turbulence intensity (absolute)	$RMS_x = \sqrt{\frac{1}{N}\left(x'^2_1 + x'^2_2 + \ldots + x'^2_N\right)}$	$\frac{RMS_x}{u^*}$
	Turbulence intensity (relative)	$TI_x = \frac{\sigma_x}{U}$	-
	TKE	$TKE = \frac{1}{2}\rho\left(RMS^2_u + RMS^2_v + RMS^2_w\right)$	$\mathrm{TKE} = \frac{1}{2}\rho\left(\frac{RMS^2_u}{u^*} + \frac{RMS^2_v}{u^*} + \frac{RMS^2_w}{u^*}\right)$
	Reynolds shear stress	$\boldsymbol{\tau_{uv}} = \rho\overline{u'v'}\tau_{uw} = \rho\overline{u'w'}\boldsymbol{\tau_{vw}} = \rho\overline{v'w'}$	$\frac{\tau_{uv}}{u^{*2}}\frac{\tau_{uw}}{u^{*2}}\frac{\tau_{vw}}{u^{*2}}$
Periodicity	**Kurtosis**	$K = \frac{\sum_1^N \left(\frac{x_i - \bar{x}}{\sigma}\right)^4}{N}$	-
	AR(2) models applied and the condition for pseudo-periodicity derived.	$ITS_{u,v,w} = \int_0^\infty R(t)dt$ (where R[t] is the normalized autocorrelation function and t is the time lag).	$\frac{ITS_x}{RL}$
Orientation	**Skewness**	$K = \frac{\sum_1^N \left(\frac{x_i - \bar{x}}{\sigma}\right)^3}{N}$	-
	Event structure	Duration and/or contribution to stress of each type of "event": Q1 (u' > 0, w' > 0; outward interactions), Q2 (u' < 0, w' > 0; ejections of fluid away from the bed), Q3 (u' < 0, w' < 0; inward interactions) and Q4 (u' > 0, w' < 0; inrushes of fluid towards the bed).	$\frac{t_1}{RL}\frac{t_2}{RL}\frac{t_3}{RL}\frac{t_4}{RL}$
Scale	**Eddy length scale**	$L_x = X * RL$ Where L represents an average eddy length using mean velocity (X) along the three components and RL (record length).	$\frac{L_x}{d}$

include in PCA. PCA was performed on 11 dimensionless hydraulic variables that satisfied the Kaiser Meyer Olkin (KMO) and Barlett tests (KMO 0.61; $\chi^2_{critical}$ 230.15, $p < 0.005$) (Table 1): turbulent kinetic energy (TKE), shear stress on the uv and uw planes; kurtosis (u and w); pseudo-periodicity (u) and (w); magnitude of flow event structure derived from quadrant analysis (ejections (Q2) and inrushes (Q4)) and eddy scales (L_u and L_w). All variables were not normally distributed (Shapiro–Wilk: $p < 0.001$) and therefore non-parametric statistical tests were used. Kruskall–Wallis (KW) and Mann–Whitney (MW) were used to explore statistically significant differences in PC scores between groups (reaches (3 groups) and Gus (2 groups)). Semi-variograms were computed to explore the spatial organisation of PC scores following Clifford et al. (2005) and Legleiter (2014). Semi-variance is a geostatistical approach used to explore the spatial correlation of a variable (in this case PC scores) between measured points located at various distances apart in space. The approach is based on the concept of a "regionalized variable", which assumes that points that are close to one another are more similar in terms of their attributes. GU membership of turbulence point data was related to the extracted principal components using generalized linear models (multiple logistic regression using a logit link and binomial error distribution). Generalized linear models (logistic regression) can be used to predict the probability of a sample or observation falling within a category of a binary response based on a set of explanatory variables (Hosmer & Lemeshow, 2004). In this case, the four derived Principal Components (PCs) were used as explanatory variables, in order to predict the GU response variable (riffle/pool or step/pool) depending on the reach. Multiple logistic regression was applied to each site individually. Models were also constructed using the standard hydraulic dimensionless variables of depth and velocity that were computed by dividing each depth and velocity by the reach average depth and shear stress, respectively, and used to compare with the models based on PCA. ROC (Receiver Operating Characteristics) curves were used to check the performance of each model and its accuracy is represented by the area under the curve (AIC). The Hosmer-Lemeshow test was used to evaluate the goodness of fit.

3 | RESULTS

3.1 | Statistically derived turbulence gradients

The results for the PCA on 11 dimensionless turbulence properties are provided in Table 2 and Figure 3. The first four derived PCs had eigenvalues >1 and cumulatively explained 60% of the variance in the data and variable loadings (Table 2) were used to describe and

TABLE 2 Principal Component (PC) loadings for the turbulence variables and corresponding interpretations of the PCs derived across the three reaches

		Principal components			
	Dimensionless variables	**PC1 (intensity)**	**PC2 (periodicity/scale)**	**PC3 (combined)**	**PC4 (orientation)**
Intensity	$\frac{RMS_u}{u^*}$	**.761**	.051	−.453	−.147
	TKE	**.756**	−.175	−.204	.248
	$\frac{\tau_{uv}}{u^{*2}}$	**.810**	−.296	.435	.117
	$\frac{\tau_{uw}}{u^{*2}}$	**.721**	.061	−.515	−.244
Periodicity	Kurtosis u	.237	−.229	.417	−.224
	Kurtosis w	.227	−.244	**.581**	−.047
	Pseudo-periodicity u	.129	**.638**	−.069	.196
	Pseudo-periodicity w	.214	**.559**	−.029	.286
Orientation	Q2(%)	−.284	−.051	.063	**.691**
	Q4(%)	.160	.149	**.589**	**.562**
Scale	$\frac{L_u}{d}$	−.314	.061	−**.581**	.043
	$\frac{L_w}{d}$	.210	−**.543**	.375	.381

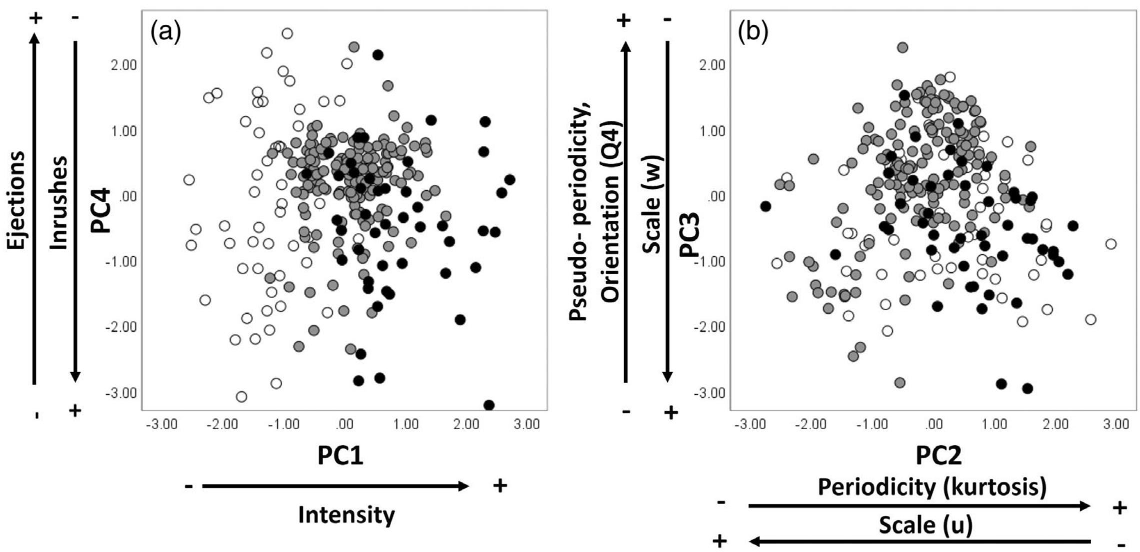


FIGURE 3 Scatterplots showing Principal Component (PC) scores for the four PCs derived for the analysis of 11 dimensionless turbulence parameters across the three reaches. (a) PCs scores for intensity (PC1) and orientation (PC4); (b) PCs scores for periodicity/scale (PC2) and combined gradient (PC3). Marker symbology represents the reaches: Vermigliana (closed black circles), Tagliamento (closed grey circles), and Frome (open circles)

characterize the gradients in turbulence properties that the derived Principal Components 1–4 represent. PC1 was interpreted to represent a gradient of increasing turbulence *intensity*, with high positive variable loadings for RMSu, shear stress on the uv and uw planes and TKE. PC2 was interpreted to represent a gradient in *periodicity* and *scale* of turbulence with higher scores indicating a more periodic flow structure and smaller characteristic eddy lengths. PC3 is a combined gradient that has high loadings in variables from the periodicity, orientation and scale categories and therefore is the least distinct component. Lower scores on PC3 indicate lower contributions of inrushes, higher kurtosis in turbulent residuals and smaller eddy sizes. PC4 was interpreted to reflect an orientation gradient, with highest loadings for cumulative stress contributions of ejections and inrushes of fluid. As expected, the dimensionless turbulence intensity increases across the three reaches from lower to higher bedform roughness and the differences in PC1 scores between the reaches were statistically significant (KW: $p < 0.01$). PCs 2 and 3, representing periodicity and scale and the combined gradients, respectively, showed greater overlap in PC scores among the reaches although the Tagliamento and Vermigliana reaches were statistically distinct on both gradients, and the Frome and Vermigliana reaches were distinguished by PC3 (KW: $p < 0.001$). Scores for PC4 are highly variable across all three reaches

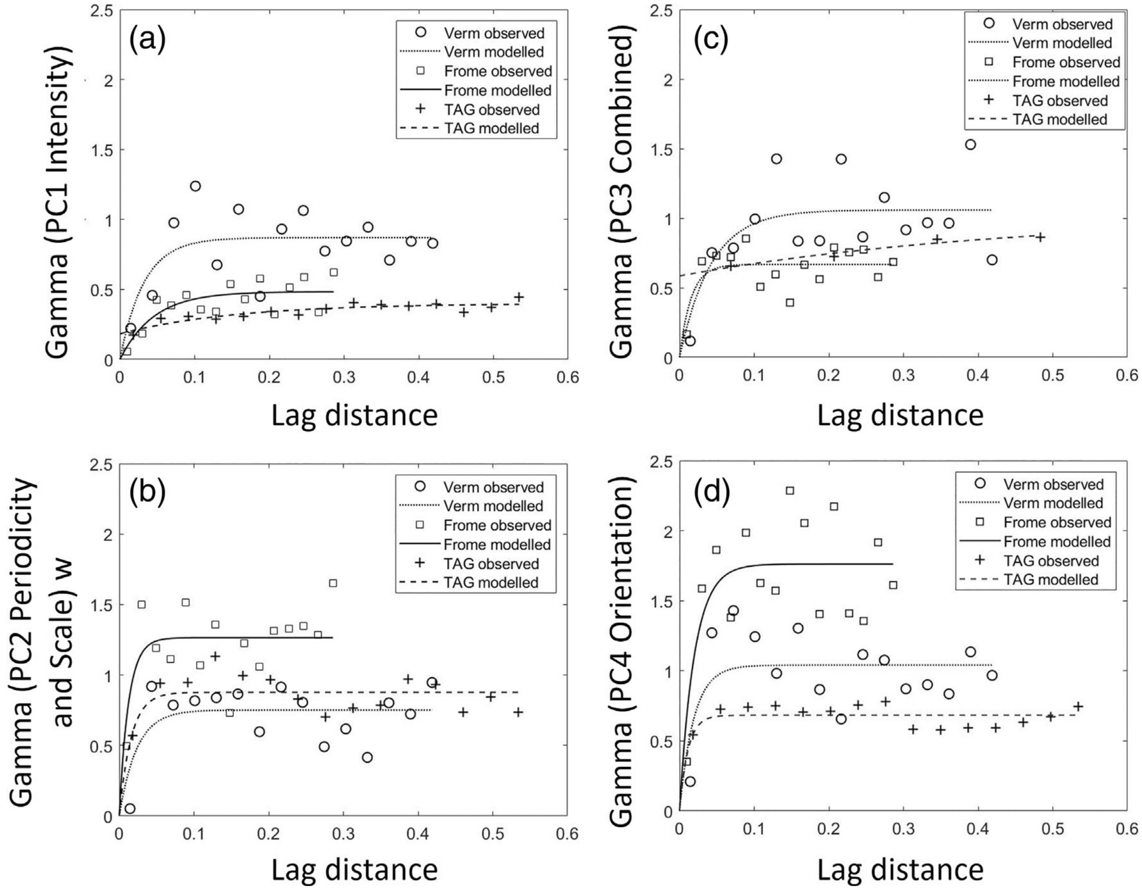


FIGURE 4 Experimental and modelled semivariograms to illustrate the spatial autocorrelation of intensity, periodicity, orientation and scale turbulence parameters for each. Markers represent the semivariance computed for pairs of sample locations at increasing distances apart (experimental variograms) and lines represent the modelled variograms fitted to aid interpretation of the key aspects of variogram form (nugget, sill and range). Marker and line symbology reflects the three reaches: Vermigliana reach (open circles and dotted lines), Tagliamento reach (crosses and dashed line), Frome reach (open squares and solid line). Each lag distance has been divided for the appropriate river total length. Lag scale: Frome: 0.1 lag = 6 m; Tagliamento 0.1 lag = 30 m; Vermigliana: 0.1 lag = 6.4 m) Reach spacing: macrophyte (Frome) = 3 m; riffles/pools (Tagliamento) = 30 m; steps/pools (Vermigliana) = 3 m

and there were no statistically significant differences between reaches (KW: $p > 0.01$).

3.2 | Spatial organization of derived turbulence gradients

Figure 4 shows semivariograms for the PC scores for PCs 1–4 for each river. The majority of modelled variograms were characterized by a relatively small range (i.e., the variogram flattens out at a short lag distance, indicating a lack of spatial autocorrelation) and a steep climb to the sill (the semivariance at which the range occurs). All four PCs exhibited this style of variogram form for the step-pool (Vermigliana) and low gradient riffle-pool (Frome) reaches indicating spatial autocorrelation among turbulence data for samples spaced less than 6 m apart. In contrast, the intermediate gradient riffle-pool reach (Tagliamento) exhibited a nugget effect, indicating spatial autocorrelation at scales smaller than the sampling interval (3–5 m), and a less pronounced sill for PC1 and PC2 indicating spatial autocorrelation at greater distances. There is some evidence of periodic dips in semi-variance at multiple lag distances, although these are subtle in most cases. Dips in semi-variance indicate increased similarity of turbulence properties at that lag distances and these broadly align with approximate bedform spacing or multiples thereof: 0.1–0.2 reach length lag (6–12 m) for the Vermigliana reach (bedform spacing ~10 m), 0.1 reach length (6 m) for the Frome reach (bedform spacing ~10 m, macrophyte spacing ~5 m) and 0.3 reach length (90 m) for the Tagliamento reach (bedform spacing ~30 m).

3.3 | Derived turbulence gradients and geomorphic units

Most PCs show some difference in median values between GUs for each river, but with overlap in PC scores among all GUs (Figure 5). For intensity (PC1), the Frome and Tagliamento reaches both follow an

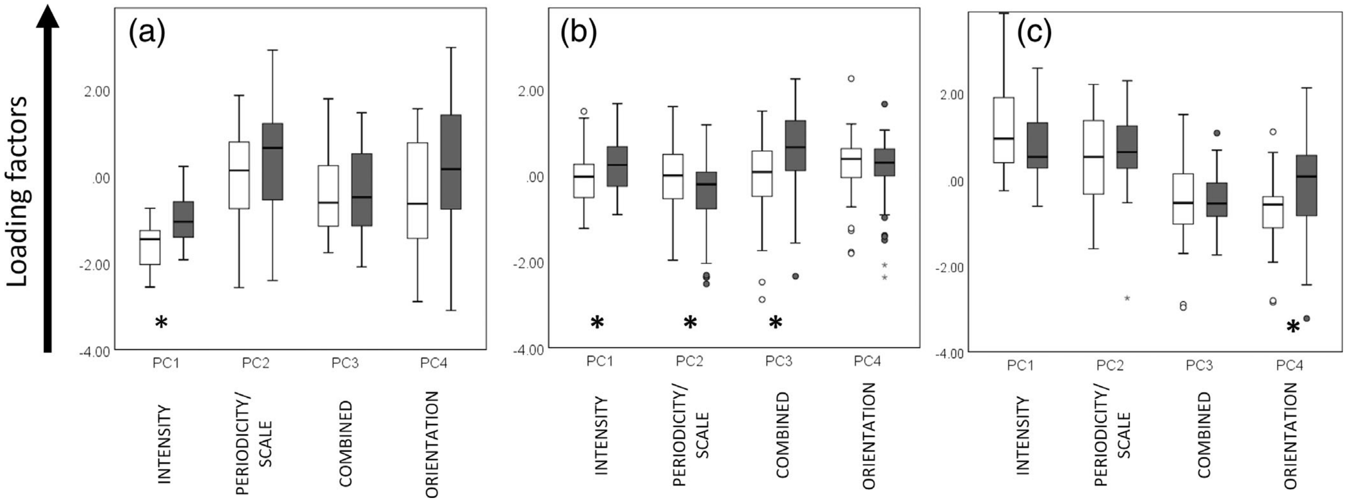


FIGURE 5 Boxplots for PCs score of the three rivers: (a) Frome, (b) Tagliamento and (c) Vermigliana rivers grouped by pools (white box) and riffles/steps (dark grey box). PCs scores represent intensity (PC1), Periodicity and scale (PC2), the combined gradient (PC3) and Orientation (PC4), respectively. Boxes and whiskers show median, interquartile range and minimum and maximum values. *denotes statistically significant differences between groups (Mann–Whitney U *p* value < 0.01)

TABLE 3 Parameters of the logistic regression models used to explore the relationship between derived Principal Components (PCs) and geomorphic units for each reach. Values in brackets are the parameters for predicted pools

Gradient reach	Descriptions	Values	Standard error	p	Odds ratio
Vermigliana	Constant	0.70 (−0.70)	0.51	0.17	1.98
	PC1: Intensity	−0.41 (0.41)	0.32	0.22	0.68 (0.16)
	PC2: Periodicity/scale	−0.15 (0.15)	0.33	0.65	1.11 (0.29)
	PC3: Combined	1.28 (−1.28)	0.39	0.45	1.32 (1.02)
	PC4: Orientation	0.70 (−0.70)	0.31	0.04	1.87 (1.02)
Tagliamento	Constant	−0.13 (0.13)	0.21	0.57	0.87
	PC1: Intensity	0.59 (−0.59)	0.33	0.05	1.81 (0.91)
	PC2: Periodicity/scale	−0.95 (0.95)	0.27	0.00	0.39 (0.83)
	PC3: Combined	1.07 (−1.07)	0.24	0.00	2.91 (0.80)
	PC4: Orientation	−0.08 (0.08)	0.25	0.77	0.93 (0.76)
Frome	Constant	3.50 (−3.50)	1.12	0.02	33.77
	PC1: Intensity	2.42 (2.42)	0.77	0.02	11.30 (5.30)
	PC2: Periodicity/scale	0.07 (−0.07)	0.31	0.81	1.12 (1.12)
	PC3: Combined	0.39 (−0.39)	0.40	0.31	1.45(1.45)
	PC4: Orientation	0.45 (−0.45)	0.25	0.12	1.46 (1.46)

expected trend of higher intensity within riffles compared to pools, while other gradients show contrasting relationships between riffle and pool GUs across both rivers. GU-based differences in the turbulence gradients are most pronounced for the Tagliamento reach where PCs1, 2 and 3 show statistically significant differences between riffle and pool GUs (KW: $p < 0.01$). In contrast, there was a statistically significant difference between steps and pools (Vermigliana) for PC4 (orientation) and between riffle-pools (Frome) for intensity (PC1).

Logistic regression models were constructed for each reach data set using the derived PCs (Table 3) to identify which PCs were most useful in predicting GUs (riffles/steps and pools). Models were also constructed using the standard hydraulic variables of (dimensionless) depth and velocity commonly employed in habitat assessment and modelling for comparison. Standard depth and velocity models were statistically significant for the river Frome ($X^2 = 11$; $p < 0.05$, AIC $= 59$) but not for the Tagliamento or Vermigliana, while the models based on derived PCs were statistically significant for the Frome and Tagliamento ($X^2 = 21$ and 36; $p < 0.05$) but not the Vermigliana ($p = 0.111$). The Akaike information criterion (AIC) was 71.05, 63.59 and 191.13 for the Frome, Tagliamento and Vermigliana reaches, respectively, indicating the best model fit for the intermediate riffle-pool reach (Tagliamento).

For the river Frome, the model based on turbulence PC gradients explained 36% and 43% of the variance for pools and riffles, respectively, compared with the standard velocity-depth model which explained 24% and 39% of the variance for pools and riffles respectively (Nagelkerke R^2). For the Tagliamento reach the model based on PCA-derived turbulence gradients explained 45% and 53% of the variance for pools and riffles respectively (Nagelkerke R^2), and the velocity-depth model was not statistically significant. For the Frome reach, the turbulence intensity gradient (PC1) was significant, and for Tagliamento reach both the intensity (PC1) and periodicity/scale (PC2) gradients were significant.

4 | DISCUSSION

The results provide the first application of the IPOS turbulence framework across multiple rivers and bedform types in natural environments. Importantly, three of the gradients objectively derived from the data set through PCA were aligned with the four IPOS categories, with derived PCs interpreted to represent intensity (PC1), periodicity-scale (PC2), and orientation (PC4), in order of contribution to the variance in the data. These gradients all showed statistically significant differences between rivers and/or geomorphic units. This provides statistical validation for the IPOS framework and an efficient and transferable approach for characterizing diverse turbulent properties across rivers. PC3 was least distinct and represented a combination of IPOS properties, and it was also generally less useful for distinguishing between geomorphic units. One limitation was that most of the periodicity variables did not meet statistical assumptions of the multivariate analysis and this category was therefore represented by two periodicity variables rather than the full suite. Two IPOS categories (periodicity and scale) were jointly represented by one gradient, whereby increasing periodic flow structure was associated with decreasing eddy size. This relationship is consistent with cascade energy theory and energy dissipation processes (Franca & Brocchini, 2015).

The individual reaches showed expectedly high levels of variability along the gradients of intensity-scale, periodicity and orientation. Inter- and intra-reach variability naturally reflects the interacting influences in river systems, where the turbulent properties at a particular location will reflect a combination of locally derived and upstream-inherited flow structures (Hardy et al., 2009) influenced by the flow stage and the morphology of the channel (Legleiter et al., 2007). The intensity gradient accounted for the highest variance among the gradients and most pronounced inter-reach differences, underlining the significance of turbulence intensity metrics which are the mostly commonly captured in ecohydraulics research (Lacey et al., 2012). Turbulence intensity is known to have wide-ranging and contrasting effects on aquatic biota, for example by contributing to prey detection in some environments (Ferner & Weissburg, 2005), or negatively impacting fish through downstream displacement, higher swimming costs and reduced stability (Lupandin, 2005; Enders et al., 2003; Cotel et al., 2006;). In contrast, the scale, periodicity and orientation properties of turbulent flow are less well-studied in geomorphological and ecohydraulics research. By revealing the statistical coherence of these gradients in multivariate space, and their links with geomorphic units as a fundamental unit of river habitat, our analysis emphasizes the need to capture all four dimensions of turbulence identified in the IPOS framework. For instance, the periodicity-scale gradient revealed statistically significant differences between pairs of reaches. Both scale and periodicity metrics are known to be important influences on energy costs and stability in fish. For example, fish can exploit flow periodicity to reduce energy costs (Liao, 2007; Liao & Cotel, 2013) and the magnitude of eddy length scales in relation to fish length are an important determinant of stability and energy costs (Webb & Cotel, 2010; Silva et al., 2012;). Uncovering the variation of scale, periodicity and orientation properties, in addition to turbulence intensity, among geomorphic units in different river types therefore provides a more holistic understanding of hydraulic habitat available for aquatic organisms. The analysis also highlights the importance of explicit consideration of the three-dimensional nature of flow velocity: parameters associated with the three velocity planes (u, v, w) were sometimes separated in multivariate space (e.g., scale on the u and w planes), emphasizing the importance of capturing the full 3-dimensional velocity structure (MacVicar & Roy, 2007b; Wilcox & Wohl, 2007).

Overall, the derived IPOS gradients were more useful in distinguishing geomorphic units compared to standard velocity and depth variables (albeit to varying degrees), but different gradients were important for different rivers and geomorphic unit combinations. Gradients in both intensity and periodicity-scale were significant predictors of geomorphic units in the Tagliamento reach and there was a more marked improvement in prediction of geomorphic units when the PC model was used compared to the standard velocity-depth model. In contrast, one gradient was helpful in the prediction combinations of geomorphic units for the Frome (intensity) and improvement in prediction when using the PCs was observed but to a lesser degree. The orientation gradient individually revealed statistically significant differences between steps and pools, but neither the PC or velocity-depth model was significant for the Vermigliana. Orientation parameters such as turbulent event structure have been shown to influence dislodgement of benthic invertebrates (Blanckaert et al., 2013) and fish (Tritico & Cotel, 2010), but are much less commonly addressed in fluvial geomorphology and ecohydraulics research compared to intensity variables (Lacey et al., 2012). Our results provide clear evidence that all four dimensions of turbulence should be routinely considered in ecohydraulics and hydromorphology research to allow a full understanding of the differences in hydraulic conditions among geomorphic units and hence habitats. Turbulence characteristics of different geomorphic units were most distinct for the Tagliamento reach where bedform morphology was most prounounced, reflecting strong topographic forcing of flow structure (Lacey & Roy, 2007; Stocchino & Brocchini, 2010). While natural rivers possess a diverse range of geomorphic unit configurations, the assemblages sampled in this study are representative of a significant proportion of those found in temperate environments (Henshaw et al., 2020). The discrete categories used in traditional river habitat assessment methods (including geomorphic units) necessarily impose blunt boundaries onto the hydraulic continuum that exists in natural river channels (Emery et al., 2003; Tonolla et al., 2010; Wallis et al., 2012) and therefore some variation in the statistical distinctiveness of geomorphic units is to be expected. Marginal and transitional areas are likely to account for some of the "overlap" in hydraulics among the geomorphic units. Given this, the effectiveness of the ecologically relevant IPOS turbulence gradients in distinguishing between the geomorphic units is in fact surprisingly pronounced, supporting the concept of geomorphic units as a fundamental unit of habitat in river systems.

The sampling design employed was designed to capture low-flow reach-scale variations across multiple sites in the mid-flow region that has traditionally been the focus of hydraulic habitat research. The sampling resolution therefore reflects the need for spatial coverage across multiple geomorphic units within a restricted time frame to ensure stationarity in flow stage. As a result, detailed analyses of turbulence at microscales (e.g., around individual boulders, aquatic plant stands or individual aquatic organisms such as fish) or across the vertical plane (with flow depth) are beyond the scope of the paper but provide opportunities for further research and application of the IPOS framework.

5 | CONCLUSIONS

Field data on turbulence are required for developing our understanding of geophysical processes and eco-hydraulic interactions, but are rarely captured across multiple rivers and geomorphic units. Our statistically derived gradients in turbulence field data align with the four turbulence categories of intensity, periodicity, scale and orientation and are capable of distinguishing between different river reaches and geomorphic units. The findings therefore connect the ecologically defined IPOS categories of turbulence properties with river types and with geomorphic units, the fundamental building blocks of aquatic habitat in river systems. The analysis also reveals the statistical coherence of the four categories or "dimensions" of turbulence in multivariate space. This shows that the IPOS framework can provide a link between morphology, hydraulics and ecology in river systems and facilitate a more holistic understanding of the turbulence conditions of different habitat units. Our field data show that turbulence signatures of natural channel morphology are expressed across all four 'dimensions' of turbulence, emphasizing the importance of considering all four aspects of turbulent flow and a diverse range of turbulent properties in ecohydraulics research. Turbulence gradients offered better prediction of geomorphic units compared to standard velocity and depth variables, although to varying degrees according to river type. Further research may explore the use of IPOS to investigate turbulence at microscales (e.g., around individual flow obstructions), with changing flow stage, with the seasonal growth of aquatic vegetation and in relation to geophysical processes such as sediment transport.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Giuditta Trinci https://orcid.org/0000-0001-8124-0978
Walter Bertoldi https://orcid.org/0000-0003-1158-2379

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