Velocity and depth distributions in stream reaches: testing European models in Ecuador

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Velocity and depth distributions in stream reaches: testing European models in Ecuador.

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Abstract

We tested how European statistical hydraulic models developed in France and Germany predicted the frequency distributions of water depth and point-velocity measured in 14 reaches in Ecuador during 25 surveys. We first fitted the observed frequency distributions to parametric functions defined in Europe and predicted the parameters from the average characteristics of reaches (e.g. discharge rate, mean depth and width) using European regressions. When explaining the frequency of three classes of velocity and three classes of depth among reach surveys, the fitted and predicted distributions had a low absolute bias (< 3%). The residual variance of fits relative to the mean class variance was < 18%. The residual variance of predicted frequencies was 30-61% for velocity classes and 20-36% for depth classes. Overall, the European models appeared appropriate for Ecuadorian stream reaches but could be improved. Our study demonstrates the transferability of statistical hydraulic models between widely-separated geographic regions.

CE Database subject headings: Rivers and streams; Velocity and depth distributions; Model tests; Stochastic models; Hydraulic models.

Authors keywords: Statistical hydraulic model; Frequency distributions; Tropical alpine region

Introduction

The knowledge of the distribution of point hydraulic variables (e.g. shear stress, velocity or water depth) in natural stream reaches is of interest for hydraulic engineers (Chiu and Tung 2002), fluvial geomorphologists (Rosenfeld et al. 2011) and stream ecologists (Mérigoux et al. 2009). Deterministic numeric models are frequently used to predict and map hydraulic patterns within reaches, but are still difficult to apply in complex flow conditions (Legleiter et al. 2011). Statistical hydraulic models that predict the frequency distribution of point hydraulic variables have been proposed as a simple alternative. They are based on the observation that point hydraulic variables have comparable frequency distributions in many natural reaches (Lamouroux et al. 1995; Stewardson and McMahon 2002). These frequency distributions can be fitted to parametric probability functions, and the parameters can be predicted from average reach characteristics (e.g. discharge, mean depth, mean width, mean particle size; Lamouroux et al. 1995; Schweizer et al. 2007; Saraeva and Hardy 2009). Consequently, knowledge of mean depth-discharge and width-discharge relationships in reaches (i.e. at-a-reach hydraulic geometry relationships, Lamouroux 2007) can be used to predict the distributions of point hydraulic variables at various discharge rates using statistical hydraulic models.

The univariate statistical models for at-a-point velocity (time-averaged but not depth-average along a vertical profile) and water depth initially developed by Lamouroux et al. (1995) and Lamouroux (1998) in small to large French and German reaches have been calibrated in rivers with slopes < 4% and relative roughness (i.e. average particle size relative to average reach depth) averaging 0.57 (Table 1). Saraeva and Hardy (2009) tested these models in small streams in the lowland part of a temperate watershed (British Columbia in North America) where mean annual flows are less than 3.5 $m^3.s^{-1}$. They concluded that the statistical approach was applicable to their rivers, but that the parametric models and their relationships with average reach characteristics had to be adapted. Stewardson and McMahon (2002) and Schweizer et al. (2007) proposed further developments of statistical models, including bivariate models that predict the joint distributions of depth and depth-averaged velocity.

In this study, we test the transferability of the velocity and depth distribution models of Lamouroux et al. (1995) and Lamouroux (1998) (hereafter European models) in 14 Ecuadorian reaches, and propose improved models for tropical Andean streams (> 3500 m a.s.l.). Ecuadorian tropical highlands streams have morphologic and climatic characteristics that often differ from the European ones (Boulton et al. 2008). They have variable morphologies due to recent volcanic and glacial activities (Jacobsen 2008). Glacial-streams, generally characterized by straight high-gradient channels and torrential flows, contrast with streams in moorland valleys with low gradients, deep and sinuous channels (Jacobsen 2008). Precipitation averages between 500 and 3000 $mm.year^{-1}$ (Buytaert et al. 2011). Stream hydrology is characterised by diel discharge variations, partly due to snowmelt, but a low seasonal variability due to porous soils (ash deposits) that smooth out base flows (Buytaert et al. 2011).

The existing European models

The univariate European models of Lamouroux et al. (1995) (Eq. (1)) and Lamouroux (1998) (Eq. (2)) concern respectively f_u (the distribution of the relative velocity u/U; where u is the point velocity and U its reach average, see Notations) and f_h (the distribution of the relative depth h/H, where h is total depth and H its reach average).

$$f_u(x=u/U,s)=s\cdot\left\{3.33\cdot\exp\left(-\frac{x}{0.193}\right)+0.117\cdot\exp\left[-\left(\frac{x-2.44}{1.73}\right)^2\right]\right\}+(1-s)\cdot\left\{0.653\cdot\exp\left[-\left(\frac{x-1}{0.864}\right)^2\right]\right\} \quad (1)$$

$$f_h(x=h/H,t)=t\cdot\exp(-x)+(1-t)\cdot\left\{0.951\cdot\exp\left[-\left(\frac{x-1}{0.593}\right)^2\right]\right\} \quad (2)$$

Each model is a mixture of two extreme distributions, one centred around the mean value and one decentred, corresponding to more heterogeneous distributions. The mixing parameters s (Eq. (1)) and t (Eq. (2)) vary between 0 and 1 and were the only parameters fitted to the observed distributions in a reach in the current study. We did not alter the other constants in Eq. (1) and (2), that originate from fits to the average observed distribution in Europe. Lamouroux et al. (1995) proposed three equations of increasing complexity to predict s as a function of average characteristics of reaches (Table 2). Lamouroux (1998) predicted changes in t across discharge rates, i.e. he predicted t at a mean depth H knowing t_0 at a mean depth H_0. Both models reflected that the distributions tended to normalize with increasing discharge rates.

Data collection

We sampled 14 reaches (length ~ 20 wetted width) in seven rivers, at two surveys except for three reaches (one survey only). Reaches had catchment areas between 6 and 105 km^2 and altitudes between 3900 and 4500 m a.s.l. They were situated in three sub-regions: Papallacta's streams are only fed by subsurface runoff from rainwater, whereas Antizana (close to glacier) and Cotopaxi (far from glacier) receive additional glacial inputs. Width:depth ratio varied between 4 and 46 (mean ~14), sinuosity varied between 1 and 2.8

(mean ~1.7). Reaches were on average faster-flowing, shallower and narrower than European reaches (Table 1). Woody debris were absent but a few emergent boulders were observed.

On each survey, we measured discharge rate Q according to the velocity-area method. We sampled hydraulic variables on a grid composed of regularly-spaced cross sections along the reach, and regularly-spaced verticals along the cross-sections, whose number depended on the reach heterogeneity. Finally, we sampled an average of 90 verticals [minimum 42, maximum 135] situated along 25 cross-sections [12 - 40] per reach. For each cross-section, we measured the wetted width w. At each vertical along the cross section, we measured h, a number of point velocities (u) along the vertical, and bed particle size (d). We measured u with a propeller at two cm and at $0.4h$ above the bed along each vertical. Additional measurements at heights of $0.2h$ and $0.8h$ were made when $h > 30$ cm. Instantaneous velocities were averaged over a 30 s period, reduced to 15 s in 8 surveys where discharge rate was variable.

Data processing and analyses

We derived observed f_u and U after interpolating u measurements every cm along verticals. We assigned 0 for the velocity at the bottom, and the velocity measured at the higher point along the vertical for the velocity at the surface. Linear and spline interpolations were tested considering that velocity profiles can differ from the logarithmic theoretical shape in natural reaches (e.g. Wiberg and Smith 1991). Results were comparable and only those associated with linear interpolation are described here.

We compared the observed distributions of velocity and depth in Ecuador with fitted distributions (where s and t, noted s_{fit} and t_{fit}, are fitted using maximum likelihood criteria), predicted distributions (where *s* and *t*, noted s_{pred} and t_{pred}, are predicted from characteristics of reaches using the unmodified European regressions, Table 2) and improved predictions (where *s* and *t*, noted s_{impr} and t_{impr} , are obtained by new regressions fitted in Ecuador, Table 2). For improved predictions (models 4 and 6 in Table 2), the candidate explanatory variables were those already used for velocity in Europe (model 3), to which we added the reach bottom slope (*i*) and the Reynolds number (*Re*, see Notations) as suggested by Stewardson and McMahon (2002) and Schweizer et al. (2007). Note that our improved depth model did not use to knowledge of t_0 at one calibration discharge rate, thereby simplifying the European model.

We quantified how fits, predictions and improved predictions explained the observed frequencies of three classes of velocity and depth (low, $u/U < 1/2$, $h/H < 1/2$; intermediate, $1/2 < u/U < 2$, $1/2 < h/H < 2$; and high values, $u/U > 2$, $h/H > 2$).

Results

The unexplained variance associated with the fits (*UV*, calculated as the ratio between the residual variance and the variance of observed frequencies) was < 18% for all depth and velocity classes, and the average bias was < 3% in absolute value (see Fig. 2). Therefore, *UV* of fits were comparable with their equivalents in Europe (< 19% in the original publications), i.e. the parametric functions defined in Europe were suitable in Ecuador. Consequently, we did not try to adapt the European parametric functions and focused on the predictability of the mixing parameters.

The *UV* associated with the predicted frequencies of velocity classes was 30-61% across models 1-3 (see examples for model 2 in Fig. 2), and the bias was < 3%. Therefore the three unmodified European model predicted some variation of observed frequencies in Ecuador, though *UV* in Ecuador was sometimes higher than *UV* obtained in Europe (30-43% in Lamouroux et al. 1995). Accordingly, *s* values in Ecuador were predicted by the three European models nearly as well (r^2 between 0.66 and 0.69, $P < 0.001$, Table 2) as in Europe (r^2 between 0.61 and 0.78 in Lamouroux et al. 1995). For depth distributions, the *UV* associated with predictions was satisfactory (20-36%, Fig. 2), slightly higher than *UV* obtained in Europe (5-35% in Lamouroux 1998). Accordingly, *t* values in Ecuador were very well predicted by the European models ($r^2 = 0.85$, $P < 0.001$, Table 2).

The *UV* associated with our improved models of velocity distribution had lower values than those obtained with the European regressions (between 26 and 41%, see examples for model 2 in Fig. 2). The prediction of *s* was also improved ($r^2 = 0.79$, Table 2). Concerning depth, our improved model had comparable *UV* (19-31%) as the European predictions, and predicted *t* comparably ($r^2 = 0.82$, Table 2). However, our improved depth model demonstrated the possibility to predict depth distribution without calibration of *t* at one discharge rate.

Discussion

Two of our results further demonstrate the generality of statistical hydraulic models, in tropical Andean streams and likely in other geographic regions (e.g. Stewardson and MacMahon 2002). First, the European statistical models performed nearly as well in Ecuador as in Europe, with a low bias and slightly higher residual variance. Second, the European velocity model involving only *Fr* performed well in Europe and in Ecuador, supporting that this variable is an important predictor of hydraulic distributions within reaches. This result is consistent with previous studies made at scale of reaches (Schweizer et al. 2007) or geomorphic units (Rosenfeld et al. 2011). High *Fr* values generate more homogeneous velocity distributions, due to the homogenisation of riffle-pool patterns (Jowett 1993). The relative roughness, identified as a useful predictor in Europe, was not included in our improved models in Ecuador, likely due to the reduced range of particle size in Ecuador (Table 1). Indeed, the effect of relative particle size on hydraulic distributions has been observed in other studies (Schweizer et al. 2007) and *D/H* influences the shape of velocity profiles (e.g. Hoover and Ackerman 2004; Rhoads et al. 2003).

Our improved velocity model slightly increased the variance explained by the European model, and our improved depth model showed the possibility to predict depth distribution without calibration at one discharge rate. These results indicate the potential of refining the statistical approach in particular geographic contexts. Further improvement of the models could be obtained by including variables describing bank composition (Rhoads et al. 2003), bank stability (Millar and Quick 1993), the relative submergence of bedforms (Wilcox and Wohl 2007) or the variability of bed elevation (Aberle and Smart 2003). Investigating such effects would benefit from additional data collection in contrasting geomorphologic contexts (e.g. streams with very large relative roughness, steep slopes, tropical regimes).

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Notation

The following symbols are used in the paper:

Functions and parameters

f_u = distribution of relative velocity *u/U*
f_h = distribution of relative depth *h/H*
s = mixing parameter for velocity distributions
t = mixing parameter for depth distributions

Reach characteristics

Q = discharge rate ($m^3.s^{-1}$)
U = reach averaged velocity ($m.s^{-1}$)
H = reach averaged depth (m)
D = reach averaged particle size (m)
W = reach averaged wetted width (m)
σw = standard deviation of wetted width among cross-section (m)
Fr = Froude number defined as $U/\sqrt{(g.H)}$
Re = Reynolds number $(U.H)/\upsilon$. Multiplied by 10^{-6} throughout this paper
i = reach slope (%)

Local hydraulic variables

u = point velocity (time-averaged but not depth-averaged) ($m.s^{-1}$)
h = water depth (m)
d = bed particle size (m)
w = cross-section wetted width (m)

Constants

g = gravitational acceleration ($m.s^{-2}$)
υ = water kinematic viscosity, considered as equal to 10^{-6} ($m^2.s^{-1}$)

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LIST of TABLES

Table 1. Minimum, mean and maximum values of reach-averaged characteristics for the Ecuador and European data sets considered. Data from Europe were extracted from Lamouroux et al. (1995, velocity model) and Lamouroux (1998, depth model). When the comparison was possible (*) indicates a different mean value in Europe (velocity data set) compared to Ecuador (Wilcoxon rank sum test, $P < 0.05$).

Table 2. European predictions and improved models for velocity and depth distribution in stream reaches (mixing parameters *s* and *t* of Eqs. (1) and (2)). Models 1-3 are the European velocity models of Lamouroux et al. (1995). Model 4 allows additional explanatory variables, selected using a stepwise procedure based on Akaike Information Criterion, and shown in the order the entered the regression. Model 5 is the European depth model of Lamouroux (1998). Model 6 excludes t_0 and H_0 from explanatory variables but allows additional explanatory variables, shown in the order they entered the regression. See Notations for variable definitions. The coefficient of determination r^2 corresponds to the regression between best fits in Ecuador and predicted or improved values. N = 25 for all models except model 5 (N = 11), which predicts *t* at one discharge from the knowledge of t_0 at a lower discharge. All P-values associated with regressions were < 0.001. Standard errors of coefficients are provided in parentheses.

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Reach characteristic	Ecuadorian data				European velocity model			European depth model	
	minimum	mean		maximum	minimum	mean	maximum	minimum	maximum
Catchment area (km^2)	6.5	35.4		104.3					
Sinuosity (-)	1.0	1.7		2.8					
Q (m^3.s^{-1})	0.060	0.450	*	1.851	0.060	2.513	20.160	0.003	1110.000
W (m)	1.4	3.6	*	11.5	5.1	17.2	109.4	1.0	293.0
U (m.s^{-1})	0.14	0.41	*	0.78	0.03	0.29	0.62		
H (m)	0.17	0.27	*	0.36	0.19	0.37	0.94	0.11	3.80
D (m)	0.022	0.099	*	0.159	0.020	0.192	0.520		
i (%)	1.2	2.2		3.0			4.0		
Fr (-)	0.09	0.25	*	0.44	0.01	0.12	0.41		
D/H (-)	0.08	0.40		0.75	0.04	0.57	1.58		

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Model	Equation	r^2
velocity		
1	$s_{pred} = -0.15 - 0.252(\pm 0.068) \cdot \ln(Fr)$	0.69
2	$s_{pred} = -0.275 - 0.237(\pm 0.057) \cdot \ln(Fr) + 0.274(\pm 0.131) \cdot (D/H)$	0.66
3	$s_{pred} = -0.346 - 0.224(\pm 0.055) \cdot \ln(Fr) + 0.273(\pm 0.124) \cdot (D/H) + 0.411(\pm 0.361) \cdot (\sigma w/W)$	0.69
4	$s_{impr} = -0.426 - 0.253(\pm 0.044) \cdot \ln(Fr) - 0.072(\pm 0.029) \cdot i + 0.437(\pm 0.261) \cdot (\sigma w/W)$	0.79
depth		
5	$t_{pred} = t_0 - 0.7 \cdot \ln(H/H_0)$	0.85
6	$t_{impr} = -0.233 - 0.593(\pm 0.366) \cdot Re - 0.184 \cdot (\pm 0.087) \cdot \ln Fr + 1.495(\pm 0.394) \cdot (\sigma w/W)$	0.82

LIST of FIGURES

Figure 1. Examples of observed (grey bars), fitted (large solid line) and predicted (fine solid line, models 2 and 5 in Table 2) frequency distributions of *u/U* at two discharges in one reach (a and b) and *h/H* in another reach (c). Improved distributions were very close to predicted ones and are not shown for readability. All distributions are shown as frequency distributions of 20 regular classes of relative velocity and depth ranging between *u/U* = *h/H* = 0 and *u/U* = *h/H* = 5. Frequencies of velocities and depth falling outside this range were assigned to the relevant extreme class.

Figure 2. Observed frequencies of three velocity classes as a function of fitted frequencies (a), predicted ones (b, model 2 in Table 2), and improved predictions (c, model 4 in Table 2). Similar graphs for depth models (d: fitted frequencies; e: predicted ones, model 5; f: improved ones, model 6). The three classes of velocity and depth frequencies correspond to (●) low values, (○) intermediate values and (□) high values. *UV* is the unexplained variance.

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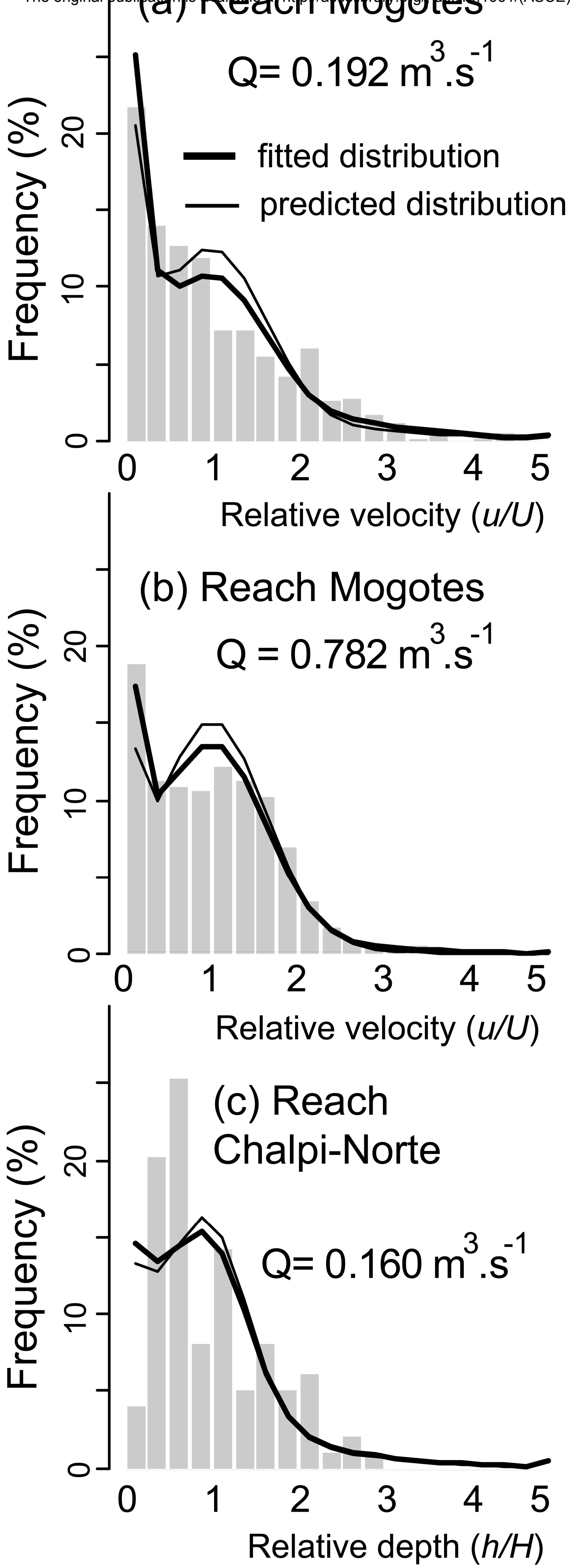

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