Testing the performance of a statistical hydraulic model in Andean streams

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Academic year: 2008-09
Over the last 40 years, the habitat simulation method has become a useful tool, used worldwide to support decision-making in the effort to define environmental flows. It combines physical habitat structure modelling with habitat preferences for targeted species to provide a suitable habitat values.

In the last decade various developments of the habitat model have been accomplished. The conventional approach ends up often in complex models to reflect the natural flow pattern, whereas a statistical approach suggests reach synthetic parameters to simplify the input of data required to implement the method. Nowadays, the scientific stakes in this domain are the validation and the generalization of the relation between habitat and ecology, within and between stream-reaches which still remain low.

Following this path, the study suggests to test the performance of a statistical hydraulic model, established for French rivers, in Andean streams of Ecuador. In particular, the test is focused on the velocity pattern across representative stream-reaches of a specific biogeoclimatic area in Ecuadorian Andes (glacier input, low rain seasonality, volcanic soil, short and scarce vegetation).

It concludes that the distributions of velocity predicted by the model matches well with the observed one (more than 60% of the variability is explained) over the whole 17 selected streams. Furthermore, the prediction is better than for the French rivers due to less heterogeneity in the river range.

An adaptation in the Andean high-altitude streams to obtain more accuracy could be done by introducing in the model other hydraulic variables, averaged at the reach-scale. Although the substrate size classified into 6 classes (from silt to boulder) was not identified as a determinant factor, further improvement could be done by a more precise measurement of the particle size and by integrating dimensionless and more complex parameter such as the Reynolds number.

Keywords: Velocity distribution; Habitat simulation method; Transferability; Highland streams; Ecuador.
ACKNOWLEDGEMENTS

Firstly, I want to thank the energetic and fresh IRD team in Ecuador – Roger, Patrick, Charlotte, Guillaume, Marion and Jean-Christophe – always present to help me and collaborate in the field data collection with enthusiasm and guts despite of the difficult conditions. Without them, I never could do the work.

I would like to express my gratitude to Patrick Le Goulven, my supervisor in Ecuador, to give me the double opportunity of participating, undertaking such projects in Ecuador, and also for his support to achieve this work.

I am especially thankful to Roger Calvez for his patience, his both precious time and help along the project, and with whom I learned a lot.

I thank also the partnership EMAAP Quito and in particular, Carlos Guayta, Marie-Elena Gordillo, Jose Villacis and Benjamin for their support and their help on the field.

I am also grateful to Nicolas Lamouroux, my supervisor in France, for offering me his precious time, for sharing his wisdom in the domain, and for his supervision.

I would like to thank the team from Cranfield University as my supervisor Tim Hess and Monica Rivas Casado who give me valuable advices to complete my thesis.

I would like to thank also Lauriane and Odile for their reading and those people who I haven’t mention expressively, who supported me in different phases of the thesis.

This work was enable to do thanks the financial, logistical and technical support of GEAU-IRD, Cemagref Lyon, EMAAP-Q and FONAG.

I would like to wink at Jacques for his poem “Le matin”.

Finalmente, quiero dedicar esta tesis a nuestra Pachamama, que me da cada día la inspiración para creer en un mundo poblado de humanidad y en particular a las comunidades indígenas que continúan la lucha para protegerla...

....« Sumak Kawsay »
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NOMENCLATURE

Institutions
EMAAP-Q: Sanitation and Drinking water Plant of the Quito District (Empresa Metropolitan de Alcantarilla y Agua potable de Quito)
IRD: Institution of Research for the Development
FONAG: the Quito Water Fund (FONdo para el AGua)

Software
PHABSIM: PHysical HABitat SIMulation
EVHA: Evaluation de l’Habitat – Evaluation of Habitat
RHYHABSIM: River HYdraulic HABitat SIMulation

Variables
Q: Discharge \( (m^3/s) \)
H: Water depth \( (m) \)
U: Mean velocity \( (m/s) \)
u/U: Relative velocity
W: Width \( (m) \)
Fr: Froude number
D/H: Relative roughness equal to the ratio of particle size over the water depth
i: Slope \( (m/m) \)
IS: Sinuosity
L: Length \( (m) \)
Scatch.: Surface area of the catchment \( (km^2) \)
Alt. catch.: Mean altitude of the catchment \( (m) \)

Statistical Analysis
MCA: Multiple Component Analysis
PCA: Principal Component Analysis
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1 INTRODUCTION

The increasing demand for water supply in a context of growing population and threat of climate change becomes a recurrent and complex issue for water resources managers (Poff et al., 2003). The competition between water consumption for households and for irrigation, representing respectively about 15% and 70% of the global consumption, is therefore enhanced. To address these issues, intensification of water transfers and development of hydraulic constructions have been done at the expense of the protection of rivers. The major impact is a drop of native biodiversity and ecosystem function. For example, the implementation of large dams leading to a homogenisation of natural flow regime (Poff et al., 2007). Water managers are aware of the ecological importance of flow and the need of compromise when planning projects. They are looking for tools to satisfy the water demand and achieve ecological objectives (Poff et al., 1997).

Environmental flow is a term to define which flow has to be maintained downstream from the hydraulic structures with the objective of having a sustainable use of water resources, preserving ecosystem functions and maintaining its benefits for the society. The respect of environmental flows became recently a legislative standard (e.g. Water Framework Directive in Europe), and various practices have emerged since 1960 to support decision-making (Dunbar et al., 2004). There are about 200 reviewed methods used in more than 44 countries (Tharme, 2003). However, uncertainties remain to find the balance between the water demands and ecological requirements. Scientific efforts are expected to overtake the two main limitations: the ecosystem complexity which does not have a linear-response to alteration of flow and the scale up from local and specific studies to large cases solving issues of limited resources (expertise, human, finance...).

Reach-scale efforts have already been done to rehabilitate rivers (Peter et al., 2005), but efforts have to be pursuit in terms of predictions of geomorphological process and ecosystem impacts (Reichert et al., 2007) as well as generalisation of habitat- models (Poff et al., 1997).
1.1 Context in Quito, Ecuador

The delegated plant, to supply water to the capital, EMAAP-Q, has plans until 2015 that will extend the current water supply network up to the Amazonian catchment basin in order to fulfil the increasing water demands of the population. Although water resources are abundant within this area, the capital is located in a sensitive area where the glaciers, already seriously impacted by the climate change (Francou et al., 2000), and the Páramos (bioclimatic stage characteristic of Andes – Girard, 2005), play a key role for the hydro-system regulation (Figure 1). In this context, EMAAP-Q with the support of other key stakeholders as Institution of Research for the Development (IRD-Quito) and the Quito Water Fund (FONAG) have launched a common project to provide a technical tool to support the discussion defining environmental flow. A part of their roles are to achieve this objectives, they plan to implement the habitat simulation method.

The habitat simulation method benefits of a large scale implementation across the world and represents 28% of the methods used to assess environmental flows (Tharme, 2003). The method associates a hydraulic-habitat model with biological preferences in order to provide a suitable habitat value for the targeted species in the process of conservation. Since its origins the method was adapted and developed. In particular, a statistical approach emerged facilitating the use of habitat model (only a few input data are required) and the up-scaling of habitat model from local to regional scale (Lamouroux and Jowett, 2005).

1.2 Aim and objectives

In this context, the aim of this thesis is to assess the performance of a habitat-hydraulic model, developed for temperate watercourses in France, in the Andean highland streams of Ecuador defining by a different geomorphological features and climatic conditions. Its implementation elsewhere has required:

1) to select representative stream-reaches of the studied catchment basin,
2) to collect hydraulic parameters from those reaches and for different discharges,
3) to apply the statistical model to the velocity distribution,
4) to compare modelled output data with observed data,
5) and in case of invalid model outputs, to propose different ways of investigations to perform the model.

Figure 1: Catchment of Quito and its supplying surrounded watershed
The dark frame indicates the three studied areas. Sources – GoogleMap and IRD-Quito (2009)
2 Literature review

2.1 Environmental flow methods

At this date, around 200 methodology types (Figure 2) have been listed to define environmental flows, which could be grouped into four main methods categories (Tharme, 2003): hydrological, habitat simulation, hydraulic and holistic methods.

![Figure 2: Main categories of methodologies implemented in the world – Source: (Tharme, 2003)](image)

2.1.1 Hydrological method

The hydrological method was the first to be implemented to determine environmental flows and has largely influenced the standard of minimum flows. The general principle is to define the environmental flows as a percentage of a given flow, which could be the mean annual flow as suggested for the methods of Tennant (Tennant, 1976) or again low flow and mean monthly flow. Then, a level of alteration corresponds to those flows’ classes of percentage.

It still represents 30% of used methods with new approaches. For example, the Range of Variability Approach (RVA) (Richter et al., 1997) is based on a statistical analysis with 32 indices of alteration encompassing the magnitude, the frequency, the timing and the seasonality of the flow regime. Theses methods are based on measures of the difference between natural flows and the flow chosen as a metric to take into account the hydrological variability define as decisive for aquatic communities (e.g. Richter, 1996).
From the outset, development of hydrological methods has been confirmed by numerous studies showing ecological responses to hydrological patterns (Poff et al., 1997). But it still remains inconsistent and there are uncertainties as to how the biological communities are affected by the different aspect of the flow regime (Biggs and Jowett, 2007). Finally, the method has the advantage to be easily implemented in case of availability of hydrological data.

2.1.2 Habitat simulation method
During the seventies, the habitat simulation method fulfilled the needs to quantify the impact of the altered discharge on the aquatic ecosystem.

This method consists in an association of a hydraulic model and biological model for species and specific life stage to estimate the instream habitat suitability at the habitat scale (Figure 3). The hydraulic model predicts local parameters, (depth, and velocity and substrate size) defining the microhabitat structure according to the discharge; the biological model is basically a combination of habitat preferences for targeted species. Each preference curves shows the link between density of species and a habitat variable (Bovee, 1982). The habitat simulation model provides also a habitat value at the scale of the microhabitat according to the flow for a targeted species (Bovee et al., 1998).

The pioneer in this field was the Cooperative Instream Flow of the United States Fish and Wildlife Service (USFWS). They undertook a large program of investigation resulting in the Instream Flow Incremental Methodology (IFIM), which provides several tools for water management. It was largely used in North America (Reiser et al., 1989) and extended worldwide (Tharme, 2003). In particular, the major component is its PYysical HABitat SIMulation (PHABSIM) software (Bovee, 1982). Despite several criticism as the lack of biological validation and a complex hydraulic model (Souchon and Capra, 2004), the software has been largely adapted, for example in France (EVHA) and New Zealand (RHYHABSIM), keeping in line with the principle of the method (Figure 4, frame in dashed line), and updating it with the integration of more complex hydraulic models (2D and 3D) and the extend of biological preferences.
Figure 3: General principle of the habitat simulation method

The left frame presents the hydraulic model, the top one at the right presents biological preferences curves and the bottom one at the right is the habitat values according to the discharge.

Figure 4: Evolution and adaptation of the pioneer habitat model

*Dashed frame: conventional approach. Blues lines: stochastic approaches (Non exhaustive liste).*

The habitat simulation method has also been simplified according to statistical approaches (Figure 4, *frame in full blue lines*). These approaches are based on the
statistical properties of hydraulics variables between stream-reaches (e.g. STATHAB\textsuperscript{1} concerning the velocity and the depth) as well as the available habitat values for areas using already an conventional approach (e.g. ESTIMHAB\textsuperscript{2}).

2.1.3 Hydraulic method
The hydraulic method represents only 11% of the methods (Tharme, 2003) and was developed in the USA during the 70’s to ensure the production of salmonids. The principle is to get focused on the conservation of hydraulic parameters which vary according to the flows, as for example the wetted perimeter or the minimal water level. This involves making measurement on a limited cross-section at different discharges. Although this method makes the link between both morphological and hydrological parameters of the river, the method supposed that aquatic organism response is mainly controlled by hydraulic features. In short terms, the method is easy to undertake but the impact of the integration on the ecosystem is limited. Finally, the method has received less attention than the previous one, but the hydraulic geometry consideration has been integrated in the statistical approach of habitat simulation to simplify the collection of data.

2.1.4 Holistic methods
The holistic method has emerged where the implementation of habitat simulation method turns out to be expensive or difficult by lack of material means. Developed at the end of the 1990’s in South of Africa and Australia, it suggests a global approach of the aquatic ecosystem without the choice of targeted species. It links pluri-disciplinary knowledge as hydrology, hydraulic conditions of habitat, geomorphology, water and biological quality. In particular, it is based on the critical hydrological events to define environmental flows monthly. The two pioneer methods grouped under the name Building Block Methods (BBM) are the Australian Holistic Approach (Arthington and Zalucki, 1998) and the South Africa Building Block (Tharme and King, 1998). However, the results remain qualitative and require developing more efficient monitoring and a high degree of expertise.

\textsuperscript{1} STATHAB is a free software from Cemagref (France) composed of statistical hydraulic models
\textsuperscript{2} ESTIMHAB is also a free software from Cemagref based on the generalization of the habitat values
To sum up, the existing methods present pros and cons emphasizing the fact that there are different suitable methods, any perfect, to define environmental flows. The implementation of one of these methods depends on the context (data available) and the objectives (acceptable socio-economically) of the management for a sustainable use of ecosystems (Richter et al., 2003). This put also in evidence the necessity to know the natural variability of hydrosystem across the space and the time, to provide adequate prediction in the hydraulic project.

2.2 Habitat models

2.2.1 The physical habitat as a limiting factor
The impact of altered discharge on aquatic organism requires modelling the habitat at a micro-scale corresponding to the species selection (Scruton and Gibson, 1995). But, the abundance of fish and macro-invertebrates’ communities depends on four main hydro-systems components leading the dynamic processes (Karr and Dudley, 1981): the discharge, the structure of the physical habitat (as geomorphologic aspect), water quality (oxygenation, pollutants, temperature...), and energetic inputs from the catchments as nutrients.

In fact, the complex interaction of theses components determines the both primary and secondary production. Accordingly, it is important to identify the main factors which are influencing on aquatic communities’ distributions. Then, the use of the habitat simulation is valid when the habitat structure becomes a limiting factor (Statzner, 1988). In the literature, this approach is known as the micro-habitat method.

2.2.2 Variables to define the habitat structure
The physical habitat can be split at least into two major zones: flow column and boundary layer. The micro-habitat method attempts to make the link between processes occurring at these two compartments and focus on the variability of the relevant physical variables for organisms.

A simplistic approach was to consider that a suitable habitat for aquatic communities is mainly defining by three local parameters: water depth, flow velocity...
and particle size (Bovee, 1982). However, the combination of these three parameters create different hydraulic conditions at a small-scale playing a determinant role (Brooks et al., 2005), as for instance fish populations showing preferences for some combination of depth and velocity (Beecher et al., 2002).

In order to represent complex hydraulic interaction, various efforts were done to improve direct and indirect measures of physical variability. For example, a direct measure of shear stress method based on the use of FST hemisphere, (Statzner and Müller, 1989) was provided, putting in evidence that the constraint at the bottom bed is a determinant factor for the macro-invertebrate distribution (Mérigoux and Dolédec, 2004). Then, ratio and dimensionless hydraulic variables as relative roughness, Froude number and Reynolds number have been also used as synthetic factor of the local physical process to model the habitat (Statzner, 1988; Brooks et al., 2005). The two latter parameters present the advantages to generalize local preferences across stream-reaches.

2.2.3 Hydraulic models to estimate the habitat variables

The hydraulic model as a component of the habitat simulation method computes the distribution of these local parameters vs. to the discharge rate. Two categories of hydraulic model exist.

The conventional approach to establish the habitat-hydraulic model (e.g. included in PHABSIM) is based on general hydraulic equations. A 1D model is usually used. In this case, the model is limited by the resolution of physical equations, becoming less suitable with complex and heterogenic channel geometry (Kondolf et al., 2000). In fact, the accuracy to estimate local parameters decreases with an increasing turbulence and the complexity of channel’s morphology (Guay et al., 2001). Sophisticated models (modelling in 2D or 3D) have been applied, but present disadvantages to require a huge quantity of data to describe the geomorphologic structure and to fit the existing conditions (Souchon et al. 2003).

The second approach is statistic and has emerged in France, in the last decade, to simplify the input field data (See frame in blue line on the Figure 4). In fact, the statistical hydraulic model puts in relation micro-scale hydraulic variations with mean
channel characteristics, which requires fewer and simpler data sampling (Church, 1992). For example, models require the measurement of 100 depths and 20 widths along the reach to provide unvaried distribution of the depth, the velocity and the shear-stress (Figure 5). Two approaches exist to establish statistical hydraulic model. The first generation of statistical model is based on a direct empirical approach of the observed distribution (e.g. STATHAB and FSTRESS) whereas the second one (e.g. ESTIMHAB) consists in a generalization of the habitat values curves provided by a conventional habitat simulation model (Souchon and Capra, 2004).

![Figure 5: Shape of frequency distributions for velocity, depth and shear stress](image)

Extract from Lamouroux (2008) – histograms represent distributions of the observed frequencies and lines correspond to the modelled distributions.

Finally, the statistical approach appears to be enough accurate to predict local hydraulic parameters in comparison with the limitations from the determinist models and it appears as a cost-efficient alternative regardless of the efforts involved (Lamouroux, 2008). Moreover, statistical models have an advantage to put in evidence key hydraulic factors for aquatic organism distribution and should facilitate their use worldwide for the habitat-hydraulic studies as pointed up by the results of investigations in France and New-Zealand (Souchon and Capra, 2004).
2.3 Statistical hydraulic models

2.3.1 Principle

✓ Define the function of distribution

Statistical modelling is based on the characteristic distributions of local velocity, depth and shear stress.

In the case of both water depth and velocity, their observed distributions shift from a positively skewed (exponential) to a symmetric (normal) distribution when the flow is increasing (Lamouroux et al., 1995; Lamouroux, 1998). For example, in a French model STHATHAB, Lamouroux et al. (1995) suggests to combine a decentred and a centred model to describe the velocity distribution (Figure 6), where the mixing parameter $s$ varies from 0 to 1. So the bimodal distribution reflects the alternative of low and high velocity through the stream-reach.

![Figure 6: Principle to model the function of distribution of the relative velocity](image)

From Lamouroux et al., 1995 – The parametric model of the observed distribution results from an association of a decentred model and a centred model and depends on the mixing parameter $s$ in this case.

✓ Estimate the mixing parameter

The mixing parameter of the bimodal distribution could be estimated by the maximum likelihood criterion which is commonly used to infer statistical parameters. Then, in the purpose to simplify the input data, Lamouroux et al (1995) suggested to estimate the mixing parameter through mean channel variables as the observed discharge ($Q$), the mean water depth ($H$) and the mean width ($W$) over the stream-reach. In particular, the general shape of the bimodal distribution benefits of a better fitting when dimensionless variables as combinations of these channel characteristics are used.

The choice of these channel characteristics comes from the identification of the three sources of the bimodality. The first comes from the transversal variation and the preferential flow paths. Then, the longitudinal heterogeneity regardless the sequence of rapid and slow zone, the constraints exerted by the bottom bed and the bank on the flow influence also the hydraulic variables’ patterns.
For the velocity distribution model, the best way to fit the mixing parameter depends on the Froude number (Fr) and the relative roughness (ratio of particle size over the water depth, D/H) (Lamouroux et al., 1995). In fact, the increase of Froude, equivalent to velocity one, results in a decrease of transversal heterogeneity (Dingman, 1989). Moreover, the roughness element has a little impact on the flow at the reach-scale for the moderate-gradient and gravel-bed river (Lamarre and Roy, 2005). But, when the particle size is in the order of the flow depth, the gross particles control the flow patterns at the reach-scale (Legleiter et al., 2007). Therefore, the shape of the velocity distribution depends on the flow resistance generated by the coarse particle (Wiberg and Smith, 1991; Lawless and Robert, 2001).

Another channels characteristics were also considered as the slope and the river width variability (expressed as the standard deviation of width over the width, \(\sigma W/W\)) to integrate respectively longitudinal and transversal variability (Lamouroux et al., 1995). However, they are not often used behind the objectives to provide simplest modelling and regardless the few provided explanations.

✓ Prediction of the hydraulic geometry's variables

The estimation of the mixing parameter through hydraulic geometry's parameters becomes particularly interesting to develop predicting model. The temporal evolution of the mean channel variables is given by empirical formulas (Equation 1) (Leopold et al., 1964):

\[
H = a \cdot Q^b \quad W = c \cdot Q^d \quad (1)
\]

Where:
- \(H\) is the mean depth at the reach scale (m)
- \(W\) is the mean width at the reach scale (m)
- \(Q\) is the discharge (\(m^3/s\))

Accordingly, sampling at two different discharges leads to compute the parameters \(a\), \(b\), \(c\) and \(d\) for each reaches. Prediction of the mean channel variables is therefore available for any discharges, providing by the predicting model (Figure 7).
Figure 7: Phases of simulation
Phase 1: Sampling data at 2 different discharges. Phase 2: resolution of the both formulas. Phase 3: For any discharge, H and W are known to use the function of distribution modelling at the specific reach.

2.3.2 Range of application and perspectives

✓ Limits
The models suggested by Lamouroux et al. (1992, 1995 and 1998), were the precursory researches to describe statistically univariate distributions of depth, velocity and shear stress. The validity of theses models comes from the different applications so far. In the case of the velocity distribution, the model was based on the analysis of data from a large range of rivers in France and was validated for rivers whose discharge was inferior to 20 m$^3$/s (e.g. Rhône river) and for changing discharge in the same river (e.g. Ardèche river) (Lamouroux et al., 1995).

Then, the domain of accuracy is limited because statistical approach put in evidence the common point of rivers within an area: hydraulic jumps as cascade are not taken into account in the generalization of the distribution. In particular, it is well adapted to natural rivers for preservation project.

Despite these limits, considering that currently specific and costly studies are unaffordable, where hydrological data are limited and emergent situation appears with new regulation, the statistical approach appears to be a powerful tool to target water management objectives.
The statistical models could be currently associated to habitat preferences models for aquatic communities (Lamouroux et al., 1998), but some efforts must be done to provide multivariate models and open larger perspectives to develop habitat simulation method.

Besides, until know no validation has been done beyond temperate streams. For example, a generalized model was validated in New-Zealand on 99 stream-reaches (Lamouroux and Jowett, 2005) showing a reliable estimation of habitat values from simple hydraulic variables. Tests of statistical models should go on in different regions to find key hydraulic variables and describe regional patterns.

### 2.4 Andean highland streams in Ecuador

#### 2.4.1 Andean hydrosystems

The regional constraints on the local stream habitat permit to identify hydro-ecological area according to their geology, climate, topography and vegetation (Frissell et al., 1986; Allan and Johnson, 1997).

Geological parameters having the strongest influence on the physical habitat are the catchment area, the proportion of lacustrine clay in the soil and glacial outwash materials (Richards et al., 1996). Then, several flows parameters, as bankfull discharge, have been identified across hydrological region to have an important influence of the stream equilibrium (Souchon et al., 2002). Finally, the hydraulic geometry parameters of the channel as the slope, the width and the meanders are also determinant factors on the distribution of geomorphologic units (Church, 1992).

The knowledge of the main feature of a region has a particular importance to understand and predict the interaction of physical and biological processes (Souchon et al., 2002).

The studied streams are located in the Páramo area which is a biogeoclimatical landscape situated at an altitude from about 3500 to 4600 m (Ortiz, 2003).
The average precipitation is around 800-900 mm, in general abundant and relatively constant during the year. The regime of rainfall is unimodal: one raining season from July to August due to a high Intertropical Convergence Zone\(^3\) which provokes strong seasonal wind and one dry season around December-January. However, the change between higher and lower rainfall is not drastic. Furthermore, the Páramo is characterised by a high humidity.

The geomorphology in this area depends especially on the high volcanic activity and the presence of glacier. So landscape are marked by slope from slow to strong gradient, valley with marsh, canyon designed by streams (Ortiz, 2003).

The permeability of the soil depends on the evolution of it alteration. The soil is able to retain a high quantity of water and presents a high permeability. The type of soil is compounded of volcanic ash, considered recent (< 10,000 years) called Andosols. The alteration with the time shapes up in the landscape round and smooth. The latter is especially important for the development of the vegetation and the soil is also less impacted by erosion process.

The permanent vegetal cover is generally short, located at the ground level and is dominated by grasses (\textit{e.g.} Cortaderia nitida), lichens and moss (\textit{e.g.} Sphagnum), helpful in our case to determine the limit of our studied area.

The ecosystem of Páramos is usually considered as a hydroclimatical regulator (Francou et al., 2000).

2.4.2 Stream geomorphology in Ecuadorian Andes

Three areas in the Páramo are concerned in my study: Papallacta which is located at the east of the capital, Quito, and the two glacier areas, Antizana and Cotopaxi, at the south-east (Figure 1).

According to Jacobsen (Jacobsen, 2008), tropical highland stream are characterised by steep slope, straight channel, turbulent flow and coarse substrate, but also by deep, narrow and incised channel and a fine substrate in low gradient. Although theses streams present a certain morphological variability, they have common features which are slightly different from temperate streams in high altitude.

\(^3\) Intertropical Convergence Zone (ITCZ): it defines the convergence zone of the North-East and South-East trade winds (Wikipédia, 2009).
(Ward, 1994). The main difference might be a lower seasonal predictability due to a strong influence from daily glacial melt (Jacobsen, 2008).
3 Methodology

3.1 Criteria of selection for stream-reach

Because there is little knowledge about the catchment processes in the region, three areas – Papallacta, Antizana and Cotopaxi – were identified as a potential study area, according to the hydrological input (rainfall and glacier input) and their diversity of geomorphological aspect (based on the classification of rivers of Rosgen, 1994, Figure 8). Moreover, these areas are concerned by the hydraulic project “Rios Orientales”. The both Antizana and Cotopaxi’s area are in the foothills of the volcanoes, respectively named as previously cited.
To make a link with the potential redistribution of the hydrological input by the catchment, the surface area of the basin was measured with ArcGIS’s tools (See Appendix 1 for details of hypsometric curves).

Various shape and channel characteristics of rivers in each region were considered and visually appreciated to select the stream-reaches. Then, topographic data (elevations and angle) were collected from another experiment to calculate what were visually observed, in particular the sinuosity and the slope. The slope (i) was obtained by averaging the difference of elevation between cross-sections, and the sinuosity (IS) represents the ratio between the real length over the direct distance between the stream’s extremes; higher is the value of IS, higher is meandered the reach.

The limits of the reach were chosen to ensure that the reach includes several geomorphic units generally found in those streams (riffles, rapid and pool – Figure 9). Limits were located at the limits of representativeness of the geomorphic units (Ginot and Souchon, 1998). Because the units roughly alternate on average every 5-6 times the channels width (Grant et al., 1990; Church, 1992), reach length was chosen as superior or equal to 12 times the mean width according to the variability of the geomorphological units and the access.

Figure 9: Illustration of the both pool-step and pool-riffle sequences
3.2 Sampling
To analyze the statistical distribution of point velocities and depth in reaches, these variables were measured across reaches using a systematic sampling grid (referenced into the manual of ESTIMHAB software). This systematic protocol was chosen to minimize subjectivity and involve defining regular spaces between cross-section and between points of measurement.

In each reach, approximately 20 regularly spaced cross-sections were chosen for measurements, and five regularly spaced measurement points were chosen along this cross-section (regular spacing for the whole reach, that is why there are more measurement points along a large cross-section). This method provides reliable estimation of the average value of depth (H) and width (W) (Church, 1992; Stewardson, 2005). In practice, the length (L) of the reach was approximately determined – one step was assumed equal to one meter – as well as the visually approximate width (W_approx). Then, the space between two cross-section was equal to L divided by 20, and the space between each measure point was equal to the W_approx divided by five (Figure 10).

Figure 10: Field sampling procedure
It consists to define the space between each cross-section – SpCS – then each sampled point – SpSP. Source: ESTIMHAB manual (Cemagref Lyon, 2009).

At each transect, the wetted width (W) was measured with a tape measure from the one side to the bank to another one. When there was emerging particle of substrate
along the cross-section, the width of the substrate particle is subtracted to the total width

![Figure 11: Measure of wetted width](image)

At each point, water depth, substrate and velocity were measured. The velocity was measured with a micro current-propeller C2 (n° 141702 from IRD) at different point of the vertical: at two centimetres from the bottom (minimum depth available with the instrument), then if the water depth (h) was superior to 30 cm, the measure was taken at 20, 40 and 80% of the total depth or else it was measured at 40% (h< 30 cm). The time of measure was variable (15, 20 or 30 s) and depending on the flow strength. When the flow was low a more accurate measure of the velocity was taken longer as a low flow allowed for a longer time to measure the velocities. The appreciation of the substrate was a visual estimation of the particle size at the bottom of the vertical, according to the classification adapted of Wentworth scale (11 classes from Silt to Bedrock, as defined in (Malavoi and Souchon, 2002).

In the particular case where the point was located out of the water due to the substrate, the next measured point was reported according to the regular space between measured points. When the measure point was located in the bank, it was reported to the next cross-section according to emerged distance which remained. When the measure was impossible (the general case was the presence of dug bank), a visually estimation of the velocity on average was done according to the previous one.

For each sampling date, the discharge was measured with the micro current propeller according to the velocity area method. The velocity data were computed with the software HYDRACCESS\(^4\) (IRD, 2000).

---

\(^4\)developed by P. Vauchel for the Institute of research for the development (IRD)
During the first sampling at a reach, a staff gauge was installed to see for another campaign of measurement if the stage has changed as a quick estimation of the discharge (Figure 12). Actually, another measure in the same reach would have been interesting if the difference between the sampling of the discharge between both sampling dates was visible. When the difference on the staff gauge was at least 10 cm, the measure was retaken.

![Comparison of two stages at two different dates in the reach SFD.](image)

**Figure 12: Comparison of two stages at two different dates in the reach SFD**

At the left, the flood recovers the staff gauge showing clearly the increase of the stage.

The mean value of width (W), depth (H), velocity (U) and Froude number (Fr) were computed from the field measured point. The determination of the mean diameters \( d_{50} \) and \( d_{84} \), which represents respectively the mean diameter of the 50% and 84% of the particles into the reach, allows characterizing the substrate over the reach. The method to define \( d_{50} \) and \( d_{84} \) is graphical and the determination of substrate class comes from the reading of their cumulative frequency per reach (See Appendix 2). Finally, the mean of the class limits gives the value in meter for mean diameters.

### 3.3 Test the statistical model developed in France

Only the test of the statistical model of velocity distributions is described here, that of depth distribution requiring more measurements at several discharges (Lamouroux, 1998).
All calculations on velocity distributions were made on relative velocity and discrete values (in 20 classes of relative velocity from 0 to 5) to simplify graphics, optimization procedures and shorten computing time. The analysis was based on the distributions of the relative velocity (u/U) (where U is the reach-averaged velocity and u the mean velocity on a vertical) because relative distributions are more comparable among streams and U is a known variable in applications of statistical hydraulic models. To test the statistical model of velocity distributions from (Lamouroux et al., 1995), the observed distributions were compared with the distributions provided by this model.

3.3.1 The observed relative velocity distribution
An observed distribution by reach represents the frequency of the relative velocity (u/U) which is expressed as a percentage of the total number of measurement.

To compute the velocity distribution and the average velocity, each point velocity has to be weighted by the surface unit that it represents in the cross section (Figure 13).

![Figure 13: Point velocity weighting](image)

Cross-section on a river where several point of velocity are taken on a vertical (dark line) – the point velocity, represented by a green point, is weighted by the surface unit dS.

But, in this case of sampling it was required to weigh the velocity only according to the depth because of the grid sampling method over the whole reach.

The first step consisted of making a regular interpolation of the local sampled velocity along the vertical\(^5\). This was done with a linear function between each point. From those established functions, the velocity was interpolated every cm along the vertical. The average velocity (u) over the vertical results from the mean of all those computed velocities. Finally, each average velocity was divided by the reach averaged velocity U to provide the relative velocity (u/U). The observed distribution of (u/U) was plotted according 20 regular classes scaled from 0 to 5.

\(^5\) Note that the measure of velocity at the bottom (at two cm) was initially planned to be used to model the shear stress distributions.
For each class of relative velocity, the probability $\text{OP}(\text{class})$ associated to each velocity's class is the relative frequency ($\gamma$) of $u/U$ in the class (Equation 2) (The sum of $\gamma$ is equal to 1 across class).

$$
\text{OP}(\text{class}) = \frac{\gamma\left(\frac{u}{U},\text{class}\right)}{\sum_{\text{class}=1}^{20} \gamma\left(\frac{u}{U},\text{class}\right)} \quad (2)
$$

### 3.3.2 The predicted relative velocity distribution

To build the predicted distribution, (Lamouroux et al., 1995) proposed the function of distribution $f$ (Equation 3), which is an association of a decentred model (exponential law) and a centred model (normal law). The bimodal distribution depends on the mixing parameters $s$, which varies from 0 to 1. The mixing parameter $s$ is specific to a reach. It is expressed as a linear function of the logarithm of the Froude number of the reach ($\ln Fr$) (Equation 4). The Froude number depends on the both reach-average velocity ($U$) and water depth ($H$) (Equation 5).

The both water depth and relative velocity were averaged over the reach. Then, the Froude number was computed from these values to determine the reach-specific parameter $s$, noted further $s_{\text{predicted}}$, and thus the function of distribution (Equation 3) was defined.

$$
f(x = \frac{u}{U}, s) = s \cdot \left[3.33 \cdot \exp\left(-\frac{x}{0.193}\right) + 0.117 \cdot \exp\left(-\left(\frac{x-2.44}{1.73}\right)^2\right)\right] + (1-s) \cdot \left[0.653 \cdot \exp\left(-\left(\frac{x-1}{0.864}\right)^2\right)\right] \quad (3)
$$

$$
s_{\text{predicted}} = -0.15 - 0.252 \cdot \ln(Fr) \quad (4)
$$

$$
Fr = \frac{U}{\sqrt{gH}} \quad (5)
$$

Where:

- $f$ is the function of distribution of the relation velocity $u/U$,
- $s$ the mixing parameter,
- $U$ is the average velocity,
- $H$ is the mean depth.

The predicted distribution represents the values of the integral for each class of velocity. The integral of the function was computed over each class of velocity to
obtain the corresponding density of probability $PP(class, s)$ (Equation 6). The integral of the negative values from the centred model was included in the first velocity’s class.

$$PP(x = \text{class, } s = s_{\text{predicted}}) = \int f(x, s) \cdot dx$$ \hspace{1cm} (6)

### 3.3.3 The fitted relative velocity distribution

To test the relevance of the prediction of $s$ using Equation 4, previously chosen amongst ones proposed by Lamouroux et al. (1995), an optimal $s$ value was also computed using a maximum likelihood criterion.

Let $\gamma(class)$ be the frequency of relative velocity $(u/U)$ in the class. The probability $P(class, s)$ to find a relative velocity is the same for all velocity in the class. So, the associated probability to the frequency class is the probability of each relative velocity to the power of the $\gamma(class)$ (Equation 7).

$$\prod_{i=1}^{\text{class}} P(class, s) = P(class, s)^{\gamma(class)}$$ \hspace{1cm} (7)

The likelihood $(V)$ is the product of this probability of frequency over all the classes (Equation 8); that could be transformed into the natural logarithm of likelihood $(\ln V)$ (Equation 9).

$$V(s) = \prod_{i=1}^{\text{class}=20} P(class, s)^{\gamma(class)}$$ \hspace{1cm} (8)

$$\ln[V(s)] = \sum_{\text{class}=1}^{\text{class}=20} \gamma(class) \cdot \ln[P(class, s)]$$ \hspace{1cm} (9)

The estimator $\hat{s}$ is obtained for the maximum of the log-transformed likelihood $(\ln(V))$, when $s$ varies from 0 to 1 (Equation 10).

$$\max_{s \in [0,1]}[\ln(V)] \Rightarrow \hat{s} = s_{\text{fitted}}$$ \hspace{1cm} (10)

The process to compute the fitted distribution is the same as the predicted distribution, except that $P(class, s)$ is dependant of the previously obtained parameter $s$, noted $s_{\text{fitted}}$, instead of the $s_{\text{predicted}}$ (Equation 11).
\[ FP(x = \text{class}, s = s_{\text{final}}) = \int f(x, s) \cdot dx \]  

(11)

3.3.4 Test of comparison

Observed, predicted and fitted distributions were compared by several means.

At first, all distributions were plotted together to provide visual appreciation of fits.

Secondly, the frequency of three classes of relative velocities 
\( \frac{u}{U} \in [0; \frac{U}{2}], \left[ \frac{U}{2}; 2U \right], \left[ 2U; +\infty \right] \) were compared by linear regression between observed vs. predicted and observed vs. fitted frequencies. In each case, the coefficient of correlation \((R^2)\) and the p-value \((p)\), according to the Fisher test, were provided. Then, the performance of the models for each case was also estimated, by calculating the variance of the residual (noted UV) between observed vs. predicted and observed vs. fitted frequencies, expressed as a percentage of the variance of the observed frequencies.

Thirdly, the predicted \( s \) parameter was also compared by linear regression with the fitted one to identify both relevance of prediction and potential for improvement.

All computations and graphs were done in the statistical programming language and computing environment R (Ihaka and Gentleman 1993)\(^6\).

3.4 Exploratory analysis to improve the model

To find which parameters have the most important influence on the velocity distributions over the studied reaches, a normed principal component analysis (PCA) was undertaken.

The PCA was in order to identify which parameter at the reach and basin scale could be a determinant factor. Six variables were analysed: surface area of the catchment, slope, mean width, sinuosity, and discharge and mean Froude number as a synthetic parameter of the mean depth and mean velocity. The mean values were

\(^6\) The functions used were: \texttt{approx()} for linear interpolation, \texttt{rminb()} for optimizing the likelihood and \texttt{integrate()} for numeric integrative.
obtained across the reach. Then, just the first campaign per reach was considered to avoid giving more weight for the reaches sampled twice regardless the larger-scale variables. So, it was considered only 12 reaches.

Then, dimensionless and complex parameters were tested by multiple regressions to improve and provide an adapted model for the predicted parameter $s$.

All computations and graphs were done under R with the package ade4 (Chessel et al., 2004)\textsuperscript{7}.

\textsuperscript{7} The functions used were: \texttt{dudi.pca()} for principal component analysis and \texttt{inertia.dudi()} to obtain the details of the analysis.
4 Results

4.1 Description of the selected reaches

The catchment’s surface of Papallacta, Antizana and Cotopaxi (See Figure 14) are respectively around 20, 35 and 75 km² (Table 1, Appendix 1), at an altitude between 3900 and 4500 m. Only Papallacta is strongly impacted by human activities (pasture and weir for water supply point). At the top of Papallacta, there are natural lake systems and steep slopes further downstream. The Cotopaxi and Antizana areas present large floodplains up against their respective volcano. Streams close to the Antizana glacier are dug and strongly perturbed by diary glacial flood.

Table 1: Characteristics of the rivers at the catchment scale

<table>
<thead>
<tr>
<th>River</th>
<th>Mogotes</th>
<th>Chapli</th>
<th>Chapli</th>
<th>Salve Facha</th>
<th>Antizana1</th>
<th>Antizana2</th>
<th>Tambo</th>
<th>Tambo-yacu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>MD</td>
<td>CNA</td>
<td>CNB</td>
<td>SFD/SFP</td>
<td>AHA/AHB</td>
<td>AHC/AHD</td>
<td>TBA</td>
<td>TBB</td>
</tr>
<tr>
<td>Scatch. km²</td>
<td>17.27</td>
<td>6.47</td>
<td>9.38</td>
<td>24.83</td>
<td>34.66</td>
<td>33.32</td>
<td>104.28</td>
<td>13.59</td>
</tr>
<tr>
<td>Alt. catch. m</td>
<td>4018</td>
<td>3949</td>
<td>3954</td>
<td>4077</td>
<td>4438</td>
<td>4061</td>
<td>4017</td>
<td>4194</td>
</tr>
</tbody>
</table>

The representative stream-reaches in the region have a width varying from 1 (zone of Antizana and Papallacta) to 11 meters (zone of Cotopaxi) in average.

Table 2: Physical characteristics of the rivers at the reach scale

<table>
<thead>
<tr>
<th>Code</th>
<th>L (m)</th>
<th>i (m/m)</th>
<th>IS</th>
<th>Phi</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>60</td>
<td>-0.030</td>
<td>1.55</td>
<td>F. Cobble/Boulder</td>
</tr>
<tr>
<td>CNA</td>
<td>71</td>
<td>-0.027</td>
<td>2.06</td>
<td>F. Cobble/Boulder</td>
</tr>
<tr>
<td>CNB</td>
<td>73</td>
<td>-0.023</td>
<td>2.26</td>
<td>C. Cobble/Boulder</td>
</tr>
<tr>
<td>SFD</td>
<td>89</td>
<td>-0.013</td>
<td>2.83</td>
<td>Coarse pebble</td>
</tr>
<tr>
<td>SFPA</td>
<td>39</td>
<td>-0.024</td>
<td>1</td>
<td>F. Cobble/Boulder</td>
</tr>
<tr>
<td>SFPB</td>
<td>62</td>
<td>-0.013</td>
<td>1.52</td>
<td>F. Cobble/Boulder</td>
</tr>
<tr>
<td>AHA</td>
<td>64</td>
<td>-0.020</td>
<td>1.05</td>
<td>C. Pebble /C. Cobble</td>
</tr>
<tr>
<td>AHB</td>
<td>45</td>
<td>-0.024</td>
<td>1.16</td>
<td>C. Cobble/Boulder</td>
</tr>
<tr>
<td>AHC</td>
<td>46</td>
<td>-0.027</td>
<td>1.09</td>
<td>C. Cobble/Boulder</td>
</tr>
<tr>
<td>AHD</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>Cobble/Boulder</td>
</tr>
<tr>
<td>TBA</td>
<td>95</td>
<td>-0.017</td>
<td>1.06</td>
<td>F. Cobble/Boulder</td>
</tr>
<tr>
<td>TBB</td>
<td>145</td>
<td>-0.012</td>
<td>2.34</td>
<td>F. Cobble/Boulder</td>
</tr>
<tr>
<td>TY</td>
<td>57</td>
<td>-0.023</td>
<td>1.04</td>
<td>F. Cobble/Boulder</td>
</tr>
</tbody>
</table>

L: length, i: slope, IS: sinuosity; Phi: particle size classes observed and associated to d50&d84 
F.:fine, C.: Coarse, See Appendix 2 for substrate size classes
They are mainly defined by a coarse substratum, (dominance of boulder and cobble), a moderate gradient (\(i \in [1; 3]\%\)) and a low Froude number (\(F_{\text{average}} \in [0.1;0.4]\)). The sinuosity (IS) is variable (from 1 to 2.83) (Table 2, See Appendix 3 for details to calculate IS and i). It appears visually that streams are dominated by riffles and rapids with some episodic pools (Figure 9).

The length of reach-stream varies from 39 to 145 m. The reach-average depth varies from 14 to 27 cm, and the reach-average velocity varies from 0.16 to 0.46 m/s (Table 3).

Table 3: Hydraulic and geomorphologic characterization of the sampled reaches

<table>
<thead>
<tr>
<th>Date</th>
<th>Code</th>
<th>Q  (m³/s)</th>
<th>W  (m)</th>
<th>U  (m/s)</th>
<th>H  (m)</th>
<th>Fr</th>
<th>Nbr. Section</th>
<th>Nbr. Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>22-may-09</td>
<td>MD1</td>
<td>0.229</td>
<td>3.01</td>
<td>0.31</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>07-july-09</td>
<td>MD2</td>
<td>0.871</td>
<td>3.68</td>
<td>0.64</td>
<td>0.34</td>
<td>0.35</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>28-may-09</td>
<td>CNA1</td>
<td>0.200</td>
<td>2.49</td>
<td>0.39</td>
<td>0.21</td>
<td>0.27</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>17-june-09</td>
<td>CNB1</td>
<td>0.058</td>
<td>2.16</td>
<td>0.21</td>
<td>0.14</td>
<td>0.18</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>08-july-09</td>
<td>CNB2</td>
<td>0.307</td>
<td>2.99</td>
<td>0.33</td>
<td>0.22</td>
<td>0.23</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>04-june-09</td>
<td>SFD1</td>
<td>0.077</td>
<td>1.77</td>
<td>0.24</td>
<td>0.22</td>
<td>0.16</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>22-may-09</td>
<td>SFD2</td>
<td>0.083</td>
<td>1.75</td>
<td>0.24</td>
<td>0.2</td>
<td>0.17</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>03-june-09</td>
<td>SFPA1</td>
<td>0.102</td>
<td>3.00</td>
<td>0.24</td>
<td>0.21</td>
<td>0.17</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>22-july-09</td>
<td>SFPA2</td>
<td>0.487</td>
<td>3.07</td>
<td>0.49</td>
<td>0.33</td>
<td>0.27</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>05-june-09</td>
<td>SFPB1</td>
<td>0.147</td>
<td>3.45</td>
<td>0.16</td>
<td>0.27</td>
<td>0.10</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>11-june-09</td>
<td>AHA1</td>
<td>0.706</td>
<td>1.48</td>
<td>0.77</td>
<td>0.34</td>
<td>0.42</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>15-july-09</td>
<td>AHA2</td>
<td>0.332</td>
<td>1.38</td>
<td>0.73</td>
<td>0.27</td>
<td>0.45</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>25-june-09</td>
<td>AHB1</td>
<td>0.464</td>
<td>1.91</td>
<td>0.77</td>
<td>0.34</td>
<td>0.42</td>
<td></td>
<td>25</td>
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<tr>
<td>26-june-09</td>
<td>AHC1</td>
<td>0.227</td>
<td>2.82</td>
<td>0.42</td>
<td>0.24</td>
<td>0.27</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>15-july-09</td>
<td>AHD1</td>
<td>0.364</td>
<td>2.44</td>
<td>0.45</td>
<td>0.3</td>
<td>0.26</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>01-july-09</td>
<td>TBA1</td>
<td>1.660</td>
<td>7.20</td>
<td>0.58</td>
<td>0.36</td>
<td>0.31</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>19-june-09</td>
<td>TBB1</td>
<td>1.789</td>
<td>11.28</td>
<td>0.56</td>
<td>0.29</td>
<td>0.33</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>18-june-09</td>
<td>TY1</td>
<td>0.676</td>
<td>2.74</td>
<td>0.74</td>
<td>0.33</td>
<td>0.41</td>
<td></td>
<td>32</td>
</tr>
</tbody>
</table>

<table>
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<th></th>
<th>min</th>
<th>average</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>0.058</td>
<td>0.488</td>
<td>1.789</td>
</tr>
<tr>
<td>W</td>
<td>1.38</td>
<td>3.26</td>
<td>11.28</td>
</tr>
<tr>
<td>U</td>
<td>0.16</td>
<td>0.46</td>
<td>0.77</td>
</tr>
<tr>
<td>H</td>
<td>0.14</td>
<td>0.27</td>
<td>0.36</td>
</tr>
<tr>
<td>Fr</td>
<td>0.10</td>
<td>0.28</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Reaches are codified according letters and figures indicate sampling date: 1 represents the first sampling date and 2 the second one. Q: measured discharge; the mean values across the reach are W
(mean width), \( U \) (mean velocity), \( H \) (mean depth), Fr (Froude number). Number of cross-section (Nbr. Section) and vertical point (Nbr. Vertical) are also given.

The extremes of the sampled discharge belongs to the range of the statistical model of (Lamouroux et al., 1995), corresponding to \([0.06 ; 20.16]\) m³/s. Nevertheless highland Ecuadorian reaches present in average smaller width (# 3.26 vs. 17.2 m), higher velocity (# 0.46 vs. 0.29 m/s) and lower water level (# 0.27 vs. 0.37 m).

Figure 14: Map of the region with the location of sampled points

In total, between May and July, 18 samplings have been done over 13 stream-reaches of seven rivers (Figure 14, See Appendix 4 for photos of reaches). The field samplings were done at two different discharges for 5 stream-reaches. Between 12 and 40 cross-section by site were collected (in average 25, Table 3). Overall, between 45 and 160 point measurements were made by reach which represents in total 1660 verticals (See Appendix 3 for details). The time expended per sampling was about four hours.
4.2 Comparison of frequency distributions

The bimodal character of distributions is visually conforming in streams of the region and fitted frequencies are generally close to the predicted ones. An overview of the distribution shape shows the observed frequency match well those predicted, and to a lower extend for the reach SFD1 (Figure 15).

In the first hand, the most frequent velocities – from 50 to 70% - are those included in the intermediate class, between 0.5 and 2 m/s. Whereas, the lower and the higher velocity’s classes represent respectively between 20 and 40%, and inferior to 20% of the frequency.

Observed vs. predicted and fitted frequencies are well correlated for the three classes of velocity (respectively, $R^2$ is superior to 74 and 90%, Figure 16). The proportion of the unexplained variance (UV) by the predicted frequencies is less than 40% while it is less than 6% by fitted ones. The best explanation is for the intermediate class of velocity (UV ≈ 0.70 for the predicted distributions and UV ≈ 0.98 for fitted one). The bias (e.) provided by the model remains low, less than 5% and in the same proportion for both predicted and fitted distributions and the three classes of velocity.
Figure 15: Relative velocity frequency distributions for 17 reaches

Observed points (bars), predicted values (point line), and fitted values (red line). Qobs: discharge at which the sampling was done (m$^3$/s). See Table 3 for abbreviations of streams. See Tables 1, 2 and 3 for the details of the reaches.
Figure 16: Observed vs. predicted and fitted frequency for the three relative velocity classes
(1rst column): Observed vs. predicted frequency - (2nd column): Observed vs. fitted frequency of the three relative velocity classes. The “SFD1” is excluding of the analysis, see explanation in chapter 4.3. Solid line represents the equation y=x, and the dashed line represents the linear regression. (UV) and (e.) represent respectively the unexplained variance and the average error as a percentage of the variance of frequencies for the 17 reaches and the mean frequency. $R^2$ and P-value are the statistics of the regression between observed frequencies and predicted or fitted ones.
4.3 Analysing the prediction of the mixing parameter
The predicted values of the mixing parameter $s$ explain almost 75% of the fitted parameter. The particular point SFD1 give a bias to the correlation (Figure 17a). A better correlation is obtained if this point is eliminated ($R^2 = 0.80$). So in the following analysis the point SFD is eliminated.

The rivers of the studied area cover a range of $s$ between 0 and 0.45. The highest values are attributed to Papallacta area and the lowest to volcanoes’ zone (Figure 17b).

The variation of $s$ between reaches of a same river is relatively low, despite it is more pronounced for the river in Papallacta area and Antizana2’s river (Figure 17b).

Figure 17: Fitted vs. predicted mixing parameter
All the figures represent fitted vs. predicted. Figure a: the point SFD1 is suspicious respect to the others points. (full line: $x=y$; dashed line: linear regression line). Figure b: circles show homogenous values of $s$ between reach of a same river, AHD1 and AHC1 from the river Antizana2 are an exception. Figure c: variation of $s$ between 2 sampling discharges for the same reach, the head of the arrow indicates the higher discharge.
For the reaches from the volcanoes’ area, excepted for the Antizana2’s river, only $S_{predicted}$ varies slightly whereas $S_{fitted}$ remains almost constant (Figure 17c).

For the four reaches sampled twice, there is a shift of the parameter $s$ between the two sampling discharges (Figure 17c). The amplitude of the change is about two for the both $s$ predicted and fitted, excepted in the case of CNB and AHA for which the amplitude of change is lower. When the discharge increases the value of $s$ decreases, excepted for CNB. Due to the low contribution of CNB, it can be neglected the opposite evolution of the mixing parameter $s$ according to the discharge.

Finally, the unexplained variance by the predicted parameter $s$ is around 30%.

4.4 Potential explanatory variables at the river scale

4.4.1 Explorative analysis
The main information is represented on the two first axes of the Principal Component Analysis according to the eigenvalues. The first axis is mainly defined by the discharge, the surface area of the catchment and the mean width, whereas the second axis is defined by the Froude number and the index of sinuosity (Figure 18): they are negatively correlated and the higher absolute contribution on the axis 2 is given by the Froude number.

![Diagram](image)

**Figure 18:** Exploratory analysis (PCA) to estimate the mixing parameter $s$
At the left, factorial map E1xE2 with the projection of the rivers; at the right, circle of correlation and the studied variables (Froude number (Fr), discharge (Q), Width, Slope, Sinuosity and Area of the catchment).
On the first hand, the Tambo River is well distinct from the others according to the first axis. On the other hand, the ordination of rivers is made along the second axis. Higher Froude number being characterized by the Tamboyacu and Antizana1 rivers, and the higher sinuosity by one of the reach from Salve Facha River.

4.4.2 Explicative analysis
The natural logarithm of Froude number explain by 80% the predicted parameter $s$, in an interval of confidence close to 3% (given in brackets)(Equation 12).

$$s_{\text{fitted}} = -0.326 \pm 0.090 - 0.395 \pm 0.062 \cdot \ln(\text{Fr})$$

$$R^2 = 0.80$$

Additional parameters were added in the linear regression to improve the model (in total, 15 variables, See Appendix 5 for details of the regression). Only the addition of the slope presents a better coefficient of correlation than the previous one from Equation 12, with $R^2$ equal to 0.91.
5 Discussion

5.1 Reach selection and data collection
The extreme values of the sampled variables belong to the range of the statistical model of (Lamouroux et al., 1995). However, Ecuadorian highland reaches are characterized by smaller width, higher velocity, lower water level and lower discharge (See Appendix 6 for French data). Only the Tambo River presents reaches with higher width and discharge.

The stream-reach SFD1 had a curious position in the graphical analysis. It presents the same average characteristics as SFD2 (same stream-reach but sampled at a different date) but the observed distribution differs especially for low velocities between the two sampling dates. There was apparently a dead zone in the stream-reach which was taken into account in one field sampling and not in the other. Moreover, the considered reach widens downstream and the velocity decreases fast. The boundaries of the reach being different in one case, a higher number of low velocities might be included. Those two changes have increased the number of low velocities in the sampling, which could explain the SFD1 position relatively to SFD2.

5.2 Performance of the model
The blind test of the transferability of the statistical hydraulic model from (Lamouroux et al., 1995) shows that it applies well to the highland Ecuadorian streams. Actually, the unexplained variance of relative velocity classes is in the same order or even lower than those obtained in France for the high velocity class (UV equal 43% in French rivers vs. 37% in Ecuadorian streams). In this last case, it could be explained by a low representativeness of this velocity class in Ecuador.

The lower variance of residuals might be due to the fact that the field teams were generally the same in Ecuador, hence generating less errors from measurements (that was not the case in France), that the Ecuadorian protocol was based on regular grid (the French exercise used data from conventional hydraulic 1D model) and that studied rivers may cover a narrower range of heterogeneity. In fact, according to (Poff et al., 2006), small channels present a higher similarity between catchments than mid-
sized to larger rivers. The reach samplings in France cover the three categories of rivers whereas those in Ecuador are limited to the small and intermediate rivers excepted in the Cotopaxi zone where dimension of the stream are higher. This last distinction was observed with the principal component analysis.

Besides, the accuracy of the predictions depends also on the way to interpolate and extrapolate velocities and the number of measurement points (Rivas Casado, 2006). In the analysis of the dataset, one extra velocity point was available and it was taken from the bottom and designated for another purpose.

Despite of good correlation between the observed distributions, an adapted model for highland Ecuadorian streams is proposed that can reduce residuals.

The principal component analysis shows a distinction between reaches according the discharge, the surface area of the catchment and the width. The Tambo river, whose hydraulic characteristics are higher amongst those of the other sampled reaches, is not ordinate according to the Froude number. This involves the following hypothesis: either the consideration of larger reaches with higher flow (> 1 m³/s) could undermine the previous relation used between the mixing parameter and the Froude number, or the difference of the sampling density for each river could undermines the estimation of the parameter s. Actually, in this last case, the pieces of information collected in small streams is denser than those collected in the large ones, and more accurate to describe local variability.

According to the observations from the correlation’s circle of the PCA, the estimation of the specific-stream parameter s could be therefore improved considering another hydraulic parameters such as slope, width, observed flow (already considered in bivariate distribution of velocity and depth, e.g. (Stewardson and McMahon, 2002). Then, the sinuosity is observed negatively correlated to the Froude number according to the PCA. Its contribution to the axis 2 which is determinant for the rivers’ ordination, suggests the consideration the sinuosity amongst other potential explanatory variables in further analysis.
The exploratory analysis confirms that the slope plays an important role and its consideration allows improvements in the estimation of the parameter $s$. In a lower level, the consideration of the relative width also enables improvements in the coefficient of correlation. However, the analysis does not show that the substrate has a determinant role between reaches ($R^2$ remains around 80% in the multiple linear regression) as it could be expected in streams where the particle size has a depth close to the water depth (Lamarre and Roy, 2005). This leads to consider two possibilities for further research: either the pieces of information collected are not accurate enough to describe the substrate distribution or the substrate has no direct influence at all in the estimation of the mixing parameter $s$. The first hypothesis is most likely to be true, as it has been proved already that the roughness plays a role in the calculation of the hydraulic parameter’s distribution (Lamouroux et al., 1995; Schweizer et al., 2007). Then, the scale to classify the substrate is well adapted of biological understanding but less relevant when substrate classes are compared with reach-scale parameters. Moreover, the range of the substrate size class is narrow. Thereby, the consideration of the substrate should be done through more precise measurement of the particle diameter, at least for those whose size is almost the same than the water depth. It is also shown that the consideration of sinuosity does not allow any reduction of the residual variability.

5.3 Field limitations
First, the material and human resources were a limiting factor to choose representatives reaches due to a difficult access to removed and private areas. Moreover, the cold temperature and the duration of the sampling were factors that lead to simplify the protocol initially predicted (substrate size classification was chosen rather than particle size measurement, and less than 20 cross-section per reach were sampled for some campaigns). However, the consequences of a variable number of cross-sections are not observable because the number of sampled points was not identified has an issue during the analysis, and the estimation of Froude number does not undermine the prediction of $s$. 
Secondly, the rainy season began in the middle of the field time with higher discharge occurring. In this case, the equipment available to measure velocity (micro current propeller) was in its limit of use.

Finally, the catchment restitution process of the rain is unknown and the instantaneous stage sampling is inexistent, often causing useless trips during the second campaign to measure at different flows. The knowledge about hydrological variability in the three areas in terms of discharge range available is also limited, adding incertitude when choosing targeted stream-reach.

5.4 Limitations of the analytical methods
The interpolation of the velocity on a vertical, the extrapolation of the measure point of velocity when only two measures were available and the “visual” estimation of velocity and depth on the field when the conditions did not allow measurements generate errors in the prediction of velocity frequencies and parameter \( s \). Thus, the limit of this analysis is an evaluation of error propagation.

The consequences of the sampling density were also not taken into account to compare reach distributions. However, the anomaly observed between SFD1 and SFD2 shows an influence of the sampling procedure. Also, the behaviour of the Tambo TBB reach-sampling raises the question of the accuracy of the model to represent local conditions.

Linear regression suggesting an adapted model to Andean streams would have to be supported by a more robust statistical analysis (e.g. checking residuals, model assumptions). Furthermore, the adapted model suggested for the Andean streams are given as a guideline but should be validated before being used with an independent data set.

Testing the influence of the discharge to improve the model would require more details of the flow regime which is not available in the region.

Finally, testing the performance of the model would require the sampling of more data at different discharge to see the impact of the stage evolution in one river.
6 Conclusions

This study supports the idea that the statistical hydraulic model from (Lamouroux et al., 1995) could be applied to the Ecuadorian highland streams and that the Froude number is a well adapted variable to summarize the channel morphology across rivers. It is important to remember that the statistic models were applied to non-affected (or little affected) morphologies and within a range of discharge between 0.06 and 1.78 m$^3$/s.

The future efforts to extend the range of application of the statistical habitat model could be done in different ways for both biological and hydraulic model and the generalization of the habitat value.

Prospects of investigations already exist to find determinant factors to link local and regional scales: by considering the Reynolds number as indicator of flow evolution (Lamouroux et al., 1999) and a parameter taking into account the particle size, and considering the channel stability, which is a determinant ecological factor (Asmus et al., 2009; Jacobsen, D. unpublished) (e.g. the bank stability as part of it could be a potential explanatory variables). The variability of the channel morphology based on a cross-section analysis (Western, 1997) could also be considered because it links width, slope and discharge and, as it was noticed previously, this combination have an influence on the reach scale.

Another step would consist in testing the model for more contrasted geomorphologies (bedrock stream) and extreme climates as it can be found under the tropics, where the discharge may vary fast (e.g. in 1970 in Guadeloupe: in one minutes it had rained 38 mm), or even in Mediterranean regions.

Then, the establishment of a multivariate distribution could improve the prediction of habitat values. Actually, variation of velocity and depth across a stream-reach are strongly dependant and there are two major hydraulic variables responsible for organism distribution (Church, 1992; Quinn and Hickey, 1994). Research has already been done to provide joint distribution of velocity and depth to model the
spatial pattern (Stewardson and McMahon, 2002; Schweizer et al., 2007). And in this case, it appears that hydrological parameter, defined for example as the ratio of surveyed flow over the mean flow, is also a good estimator of the parametric model (Schweizer, 2007).

Finally, it has been shown that biological response to the reach-scale is well up-scaling despite the influence of others parameters (e.g. temperature, nutriments) which provides a large perspective for multivariate development in statistical models (Lamouroux and Cattanéo, 2006).
7 Recommendation

The statistic models were applied to natural and little impacted streams. Nevertheless, these models can facilitate the implementation of habitat models in Ecuador and therefore in the Andean part of South America for basin management guiding.

The use of the French hydraulic statistical model to predict velocity distribution in the Andean stream requires few extra validations as demonstrated previously. It could be interesting to extend the investigations to different discharge rates and contrasted rivers across the region to complete the data set from Ecuador and thus, to perform prediction of the mixing parameter. For example, it could be useful to sample river with higher width than the average observed in the region (around 3 m). Besides, because the hydrological process of the region is not well known, another sampling should be done at a different season (higher discharge sampling on a same river). Then, the adapted model suggested for Andean stream gives a better relation between $s$ and Froude number. Even if the consideration of slope provides a better correlation, its use implies to measure one extra parameter and is recommended if the data are already available or easy to obtain (especially material to measure at disposal). More accurate measurement of the particle size could also improve the predictions. However, the simplest correlation given so far is satisfying enough to predict velocity distribution.

For further investigations and completion of the current data set, some precautions have to be taken during data collection both regarding channel particularities (such as dead zone) and keeping a homogeneous density sampling.

Although biological preference models are under development in highland streams in Ecuador (hydraulic preferences were identified for some characteristic macro-invertebrates of the region, Girard, 2008 unpublished), this work broadens the perspectives of providing habitat values by coupling the models. For this purpose, further research has to be done regarding both depth and shear stress distributions to provide the hydraulic model of the habitat simulation method. Furthermore, efforts should be done to provide habitat preferences of the macroinvertebrate’s
communities considered as indicators of the good ecological state in the Andean highland streams.
REFERENCES


Tennant, D. L. (1976), "Instream flow regimens for fish, wildlife, recreation and related environmental resources", *Fisheries*, vol. 1, no. 4, pp. 6-10.


APPENDIX 1

Hypsometric curves of the studied river’s catchment
APPENDIX 2

Distributions of the cumulative frequency for 12 reaches

Method used to define the mean diameter $d_{50}$ and $d_{84}$.

**Substrate size class**

- **C1**: Herbs/Detritus
- **C2**: Silt < 0.1 mm
- **C3**: Sand < 1 mm
- **C4**: Gravel < 16 mm
- **C5**: Fine pebble > 16 mm
- **C6**: Coarse pebble > 32 mm
- **C7**: Fine cobbles > 64 mm
- **C8**: Coarse cobbles > 128 mm
- **C9**: Boulder > 256 mm
- **C10**: Bedrock > 1025 mm
- **C11**: Rock > 1025 mm

$c_1$ to $c_{11}$: 84% to 50%
APPENDIX 3

- Topographic data are available on CD under “Topo_Data.pdf”

Abbreviation included in the topographic data file
Topographic data: there are 4 data for each measured point (3 elevation and 1 angle, called azimuth)
Coord. X and Y: this is the coordinates of the measured point in a space (X,Y)
Delta water depth (m): represents the difference of water elevation between the first cross-section and the last one
Real distance (m): represents the sum of the different length between two successive cross-section
Direct distance (m): represents the length between the first and the last cross-section
Slope (%): is the ratio between the delta water depth and the real distance
Sinuosity: is the ratio between the direct and the real distance

- Field data are available on CD under “Field_Data.pdf”

Abbreviation included in the field data file

**code** River and number of campaign
- **q** Discharge
- **w** Wetted width
- **h** Water depth
- **vf** Velocity at 2cm from the bottom
- **v1** Velocity at 20% of the water depth
- **v2** Velocity at 40% of the water depth
- **v3** Velocity at 40% of the water depth
- **EH** If there is an estimation visual of the depth, the value equal 1, otherwise the value equal 1
- **EV** If there is an estimation visual of the velocity, the value equal 1, otherwise the value equal 0
- **ExV** If there is an extrapolation of the velocity according to the mean velocity profil, the value equal 1, otherwise the value equal 1
- **EL** If there is an estimation visual of the width, the value equal 1, otherwise the value equal 0
- **S** Substrate size class
- **ES** If there is an estimation visual of the substrate, the value equal 1, otherwise the value equal 0
APPENDIX 4

Figure 1: AHa – Small channel straight and incised

Figure 2: AHb – Small channel irregular meandered and incised

Figure 3: AHc – Irregular meandered and intermediate channel

Figure 4: AHd – Straight and intermediate channel
Figure 5: CNa – Irregular meandered and small channel: (a) large view, (b) upstream in the curve

Figure 6: CNb – Small and Step-Pool channel: (a) upstream, (b) downstream after the curve

Figure 7: MD – (a) Narrow channel with enlargement downstream, (b) deep pool located upstream

Figure 8: SFD – Small channel narrow and with Riffle-Pool sequences, located 500 downstream a large weir
Figure 9: SFPa – Straight intermediate channel, (a) downstream, (b) upstream

Figure 10: SFPb – (a) deep channel upstream, (b) the large curve with bigger boulders upstream

Figure 11: TY – Intermediate channel, slightly curved and boulder bed

Figure 12: T8a – Straight/Intermediate channel: (a) view from upstream, (b) view to downstream
Figure 13: TBb – Intermediate channel, large with rock dispersed amongst boulders
APPENDIX 5

1/ Linear regression with ln(Fr)

Call:
lm(formula = tabletot$svrais ~ logfr)

Coefficients:

Estimate  Std. Error  t value  Pr(>|t|)
(Intercept) -0.32656     0.09064  -3.603   0.00483 **
logfr       -0.39550     0.06259  -6.319   8.7e-05 ***

---

Residual standard error: 0.09338 on 10 degrees of freedom
Multiple R-squared: 0.7997,
Adjusted R-squared: 0.7797
F-statistic: 39.93 on 1 and 10 DF,  p-value: 8.693e-05

2/ Linear regression with ln(Fr) and Sinuosity (is)

Call:
lm(formula = tabletot$svrais ~ logfr + tabletot$is)

Coefficients:

Estimate  Std. Error  t value  Pr(>|t|)
(Intercept) -0.318185    0.106105  -2.999   0.014986 *
logfr       -0.399605    0.069690  -5.734   0.000282 ***
tabletot$is -0.008891    0.049379  -0.180   0.861101

---

Residual standard error: 0.09825 on 9 degrees of freedom
Multiple R-squared: 0.8004,
Adjusted R-squared: 0.7561
F-statistic: 18.05 on 2 and 9 DF,  p-value: 0.0007086

2bis/ Linear regression with ln(Fr) and ln(is)

Call:
lm(formula = tabletot$svrais ~ logfr + logis)

Coefficients:

Estimate  Std. Error  t value  Pr(>|t|)
(Intercept) -0.32694     0.09535  -3.429   0.007520 **
logfr       -0.40053     0.07035  -5.693   0.000297 ***
logis       -0.01691     0.08345  -0.203   0.843970

---

Residual standard error: 0.0982 on 9 degrees of freedom
Multiple R-squared: 0.8006,
Adjusted R-squared: 0.7563
F-statistic: 18.07 on 2 and 9 DF,  p-value: 0.0007055

3/ Linear regression with ln(Fr) and Slope (i)

Call:
lm(formula = tabletot$svrais ~ logfr + tabletot$i)

Coefficients:

Estimate  Std. Error  t value  Pr(>|t|)
(Intercept)  -0.6010     0.1040   -5.780   0.000266 ***
logfr       -0.4260     0.0450  -9.467   5.63e-06 ***
tabletot$i  -11.0423     3.3033  -3.343   0.008621 **

---
Residual standard error: 0.06574 on 9 degrees of freedom
Multiple R-squared: 0.9107,
Adjusted R-squared: 0.8908
F-statistic: 45.86 on 2 and 9 DF, p-value: 1.905e-05

3bis/ Linear regression with ln(Fr) and log of slope (ln i)

Call:
  lm(formula = tabletot$svrais ~ logfr + logi)

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
  (Intercept)                 0.41728    0.25271   1.651   0.1331
  logfr                       -0.43021    0.04762  -9.034 8.28e-06 ***
  logi                        0.20270    0.06640   3.053   0.0137 *
---
Residual standard error: 0.06899 on 9 degrees of freedom
Multiple R-squared: 0.9016,
Adjusted R-squared: 0.8797
F-statistic: 41.23 on 2 and 9 DF, p-value: 2.941e-05

4/ Linear regression with ln(Fr) and relative width (w/h)

Call:
  lm(formula = tabletot$svrais ~ logfr + ratiow)

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
  (Intercept)                  -0.26705    0.09206  -2.901   0.0176 *
  logfr                        -0.39892    0.05822  -6.852 7.46e-05 ***
  ratiow                       -0.46864    0.29214  -1.604   0.1431
---
Residual standard error: 0.0868 on 9 degrees of freedom
Multiple R-squared: 0.8443,
Adjusted R-squared: 0.8096
F-statistic: 24.39 on 2 and 9 DF, p-value: 0.0002322

4bis/ Linear regression with ln(Fr) and log of relative width (ln(w/h))

Call:
  lm(formula = tabletot$svrais ~ logfr + logratiow)

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
  (Intercept)                  -0.49057    0.15778  -3.109  0.012534 *
  logfr                       -0.41725    0.06330  -6.592  0.000100 ***
  logw                        -0.06250    0.04986  -1.253  0.241624
---
Residual standard error: 0.09082 on 9 degrees of freedom
Multiple R-squared: 0.8295,
Adjusted R-squared: 0.7916
F-statistic: 21.89 on 2 and 9 DF, p-value: 0.0003491

5/ Linear regression with ln(Fr) and inverse of depth(1/h))

Call:
  lm(formula = tabletot$svrais ~ logfr + ratioz)

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
  (Intercept)                  -0.37060    0.10540  -3.516  0.006556 **
  logfr                       -0.36254    0.07429  -4.880  0.000872 ***
  ratioz                      2.19579    2.57324   0.853 0.415616

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Residual standard error: 0.09467 on 9 degrees of freedom
Multiple R-squared: 0.8147,
Adjusted R-squared: 0.7735
F-statistic: 19.79 on 2 and 9 DF,  p-value: 0.0005074

**5bis/ Linear regression with ln(Fr) and log of the inverse of depth(ln(1/h))**

Call:
`lm(formula = tabletot$svrais ~ logfr + logz)`

Coefficients:
```
             Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.2663     0.4419   0.603  0.56158
logfr        -0.3367     0.0738  -4.563  0.00136 **
logz          0.1580     0.1154   1.368  0.20437
```

Residual standard error: 0.08955 on 9 degrees of freedom
Multiple R-squared: 0.8342,
Adjusted R-squared: 0.7974
F-statistic: 22.64 on 2 and 9 DF,  p-value: 0.0003076

**6/ Linear regression with ln(Fr) and the relative roughness (d50/h)**

Call:
`lm(formula = tabletot$svrais ~ logfr + ratiodm)`

Coefficients:
```
               Estimate Std. Error t value Pr(>|t|)
(Intercept)    -0.33296    0.09802  -3.397  0.007910 **
logfr          -0.39188    0.06704  -5.846  0.000245 ***
ratiodm        35.95011  131.98893   0.272  0.791482
```

Residual standard error: 0.09802 on 9 degrees of freedom
Multiple R-squared: 0.8014,
Adjusted R-squared: 0.7572
F-statistic: 18.15 on 2 and 9 DF,  p-value: 0.000694

**6bis/ Linear regression with ln(Fr) and log of the relative roughness (ln(d50/h))**

Call:
`lm(formula = tabletot$svrais ~ logfr + logdm)`

Coefficients:
```
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  -0.02498    0.44397  -0.056  0.95636
logfr        -0.38428    0.06627  -5.798  0.00026 ***
logdm         0.03475    0.05002   0.695  0.50477
```

Residual standard error: 0.09589 on 9 degrees of freedom
Multiple R-squared: 0.8099,
Adjusted R-squared: 0.7677
F-statistic: 19.17 on 2 and 9 DF,  p-value: 0.0005693

**7/ Linear regression with ln(Fr) and the relative roughness (d84/h)**

Call:
`lm(formula = tabletot$svrais ~ logfr + logd)`

Coefficients:
```
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  -0.02498    0.44397  -0.056  0.95636
logfr        -0.38428    0.06627  -5.798  0.00026 ***
logdm         0.03475    0.05002   0.695  0.50477
```

Residual standard error: 0.09589 on 9 degrees of freedom
Multiple R-squared: 0.8099,
Adjusted R-squared: 0.7677
F-statistic: 19.17 on 2 and 9 DF,  p-value: 0.0005693
(Intercept) -0.290380  0.359437  -0.808 0.439993
logfr  -0.394560   0.066549  -5.929 0.000221 ***
logd     0.004888   0.046819   0.104 0.919139
---
Residual standard error: 0.09837 on 9 degrees of freedom
Multiple R-squared:   0.8
Adjusted R-squared: 0.7555
F-statistic: 18 on 2 and 9 DF,  p-value: 0.0007162

7bis/ Linear regression with ln(Fr) and log of roughness (ln(d84/h))

Call:
  lm(formula = tabletot$svrais ~ logfr + ratiod)

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)       -0.33646    0.10194  -3.301 0.009222 **
logfr               -0.38997    0.06881  -5.667 0.000307 ***
ratiod             19.04840   70.35759   0.271 0.792700
---
Residual standard error: 0.09803 on 9 degrees of freedom
Multiple R-squared:   0.8013
Adjusted R-squared: 0.7572
F-statistic: 18.15 on 2 and 9 DF,  p-value: 0.0006943

8/ Linear regression with ln(Fr) and log of Reynolds number (ln(Re*10^-7))

Call:
  lm(formula = tabletot$svrais ~ logfr + logRe)

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)    -0.563708   2.301999  -0.245  0.81204
logfr        -0.386957   0.105898  -3.654  0.00528 **
logRe          -0.006919   0.067105  -0.103  0.92014
---
Residual standard error: 0.09837 on 9 degrees of freedom
Multiple R-squared:   0.8
Adjusted R-squared: 0.7555
F-statistic: 17.99 on 2 and 9 DF,  p-value: 0.0007163

8bis/ Linear regression with ln(Fr) and Reynolds number (Re*10^-7)

Call:
  lm(formula = tabletot$svrais ~ logfr + Re)

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)    -3.406e-01  1.658e-01  -2.055  0.07009 .
logfr        -4.016e-01  8.851e-02  -4.537  0.00141 **
Re           1.889e+13  1.822e+14   0.104  0.91970
---
Residual standard error: 0.09837 on 9 degrees of freedom
Multiple R-squared:   0.8
Adjusted R-squared: 0.7555
F-statistic: 18 on 2 and 9 DF,  p-value: 0.0007163
### Table 1. General Characteristics of the Reaches and Values of the Physical Variables Used in the Modeling Procedure

<table>
<thead>
<tr>
<th>Reach</th>
<th>Stream Name, Reach Location</th>
<th>Morphology</th>
<th>Natural Discharge, m³/s</th>
<th>Stream Name, Reach Location</th>
<th>Natural Discharge, m³/s</th>
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</thead>
<tbody>
<tr>
<td>air</td>
<td>Allier Alleysas</td>
<td>N</td>
<td>A</td>
<td>3.6 26.3 0.43 0.14 1.04 0.46</td>
<td>1.62 0.31 0.15</td>
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<tr>
<td>pin</td>
<td>Allier Pâcles St-Etienne</td>
<td>N</td>
<td>N</td>
<td>9.5 19.9 0.22 0.57 0.37 2.45</td>
<td>-2.40 0.65 0.29</td>
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<tr>
<td>sap</td>
<td>Allier Le Sgnet</td>
<td>N</td>
<td>R</td>
<td>22.5 14.4 0.21 0.23 0.52 2.10</td>
<td>-2.12 0.58 0.17</td>
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<tr>
<td>jau</td>
<td>Allier St-Julien</td>
<td>N</td>
<td>A, H</td>
<td>6.5 35.5 0.26 0.37 0.69 3.23</td>
<td>1.96 0.25 0.46</td>
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<tr>
<td>anee1</td>
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<td>N</td>
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</tr>
<tr>
<td>anee3</td>
<td>Ance du Nord, 3a</td>
<td>N</td>
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<td>-3.80 1.10 0.25</td>
</tr>
<tr>
<td>anee4</td>
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<tr>
<td>arc</td>
<td>Arc, Modane</td>
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<td>H</td>
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<td>-2.25 0.36 0.08</td>
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<tr>
<td>bran1</td>
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</tr>
<tr>
<td>bran2</td>
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<tr>
<td>bran3</td>
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<td>A</td>
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<td>-2.66 0.56 0.33</td>
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<tr>
<td>pvdr</td>
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<td>R, H</td>
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<tr>
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<td>A, H</td>
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<td>N</td>
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<td>-1.63 0.25 0.11</td>
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<td>Pochen</td>
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<td>cham1</td>
<td>Chambron, St Maury</td>
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<td>N</td>
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<tr>
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<td>-2.86 0.45 0.26</td>
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<td>Chambron, Pr Bédane</td>
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<td>N</td>
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<td>dra</td>
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<td>R</td>
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<td>liog5</td>
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<td>yon4</td>
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<td>A</td>
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<tr>
<td>rlei2</td>
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<td>rlei3</td>
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<td>B</td>
<td>R</td>
<td>1400.0 109.4 0.48 0.40 0.11 19.75</td>
<td>-1.47 0.27 0.17</td>
</tr>
</tbody>
</table>

Minimum: 2.1 0.03 0.19 0.02 0.06 -4.28 0.94 0.08
Average: 17.2 0.29 0.37 0.19 2.51 -2.12 0.57 0.21
Maximum: 100.4 0.62 0.94 0.52 20.16 -0.88 1.58 0.62

*Extreme and average values are also indicated (see notation for the definition of the variables).

1N: natural; B: bed transformation; BA: bank transformation.

2R: natural; R: reduced; H: hydropeaking; A: alimentation at low flow.

3Mean annual value.