Determination of bed roughness parameters from field survey: application to the Cavaillon River, Haïti

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ABSTRACT: The *Cavaillon* is a Southern Haitian River causing considerable management problems since its behavior is uncertain and likely to cause serious damage to surrounding populations. Within the framework of a scientific cooperation project, our willingness is to improve the ability of local institutions to manage the river. Therefore, a methodology to construct a complete hydraulic model of the river is developed by implementing methods that require few resources. This paper presents the definition of the roughness parameters. Definition of the flow resistance evolution remains a key element in the characterization of a fluvial system in order to achieve a 1-D or 2-D modeling of the flow. Data were collected from a bed materials survey carried out for 84 cross-sections to predict the bed roughness parameters through the empirical equation proposed by Ferguson. The focus is on the determination of a parameter representing bed roughness variation along the sections, but also depending on the discharge. With these parameters, a stage-discharge relation is built for two monitoring sections, aiming the use of future available in-situ measurements. Finally, a distribution of the bed roughness along the 20km reach is proposed as a function of the flow discharge.

1 INTRODUCTION

Flood management is crucial for the Haitian territory. Haiti is one of the poorest countries in the Western Hemisphere and most of the population is dependent on the agricultural sector, thus very sensitive to river behavior. Flooding events that occur regularly during the cyclonic periods in Haïti may be disastrous for surrounding residents and dramatically affect the rivers morphology. As an example, in March 1986, a flood occurred in the Haitian subregion « Les Cayes » with a toll of 79 deaths and 98860 affected people. Also, in 2004, a disaster affected the locality of « Fonds Verettes »: floods occured in several valleys of the Haitian center region, some of which were inhabited and the consequences were huge since 2665 people died from a total affected population of 31283 (*www.emdat.com*).

In this context, sediment transport and bank erosion become a major issue since the catastrophic deforestation of river catchments increases again the dramatic consequences of flood event.

The present work is part of a broader study funded by the Belgian academic cooperation through its administration department, ARES-CCD (Académie de Recherche et d'Enseignement Supérieur, Commission de la Cooperation et du Développement).

Figure 1: Localization of the studied river reach

This project aims at improving the ability of Haitian institutions to better understand and manage their rivers and prevent potentials damages of flood event. Part of the work is devoted to the development of a methodology aiming at constructing simple and efficient hydraulic models for their rivers, based on the existing knowledge and on field surveys, using free modelling tools, considering the limited available resources in the country. This methodology is built using the case of the Cavaillon River, located in southern Haiti, in the department Les Cayes (Figure 1).

The bed roughness, discussed in this work, is an important parameter in this process. This paper focuses on the capitalization of a recent field survey lead the Cavaillon River.

Most common ways to represent uniform flow in an open channel are the Chezy, Manning-Strickler or Darcy-Weisbach approaches which relate cross-sectional average velocity to the slope, the hydraulic radius and a term representing the flow resistance. These formulations read

$$U = C\sqrt{RS_0} \tag{1a}$$

$$U = \frac{1}{n}R^{2/3}S_0^{1/2} \tag{1b}$$

$$U = \sqrt{\frac{8g\,RS_0}{f}} \tag{1c}$$

where U is the cross-section averaged velocity, C the Chezy friction coefficient ($m^{1/2}s^{-1}$), R the hydraulic radius, S_0 the bed slope, n the Manning friction coefficient ($m^{-1/3}s$), g the acceleration of gravity and f the Darcy-Weisbach friction factor, a dimensionless quantity.

These equations all depend on the square root of the bed slope, on the hydraulic radius, with varying exponent, and on a friction factor, C, n or f that represent each the same physical phenomenon. Arbitrarily, we choose the Manning coefficient, which is widely used in hydraulic modelling, to represent the bed roughness in this paper.

The work presented hereafter proposes a predicted evaluation of this Manning coefficient from measurable properties of the river, i.e. the bathymetry and the bed material size distribution of 84 sections surveyed along a 20km reach of the Cavaillon River.

Firstly the field campaign is briefly described and the data are presented in details for each section. Then, the method applied for the evaluation of the flow resistance is explained and the results are discussed. The conclusion focuses on the relevant outputs from this work for the global project and on the next priority steps.

2 DATA COLLECTION

2.1 *Cross sections measurement*

The studied reach of the river is located on the downstream part of the river (Figure 1). The *Dory* weir is defined as the upstream limit, represented by the section PK00.174, located immediately downstream of the spillway (Figure 2).

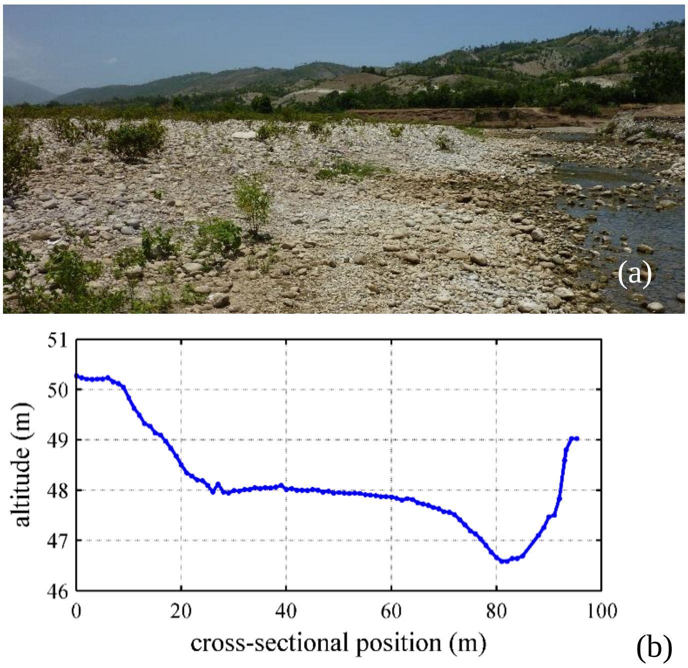


Figure 2: Upstream limit of the study reach (Section PK00.174): (a) general situation, (b) measured bathymetry.

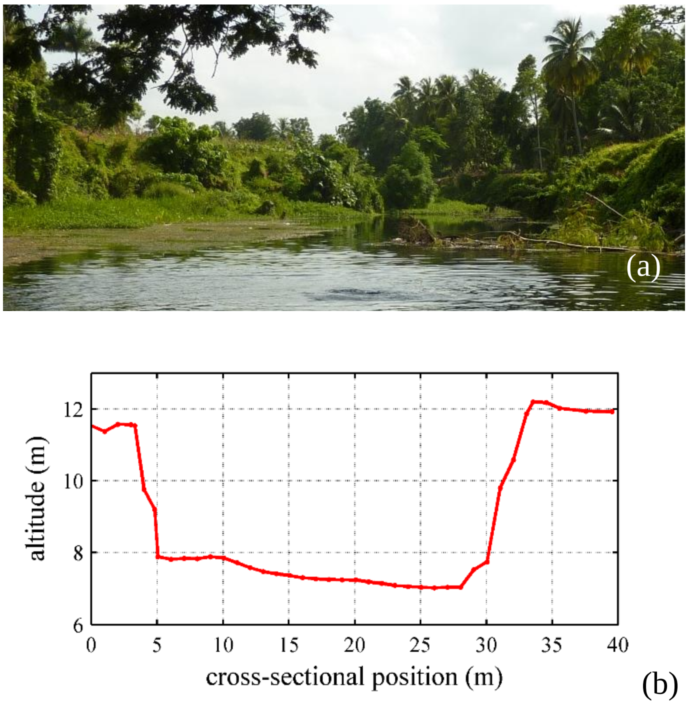


Figure 3: Downstream limit of the study reach (Section PK22.601): (a) general situation, (b) measured bathymetry

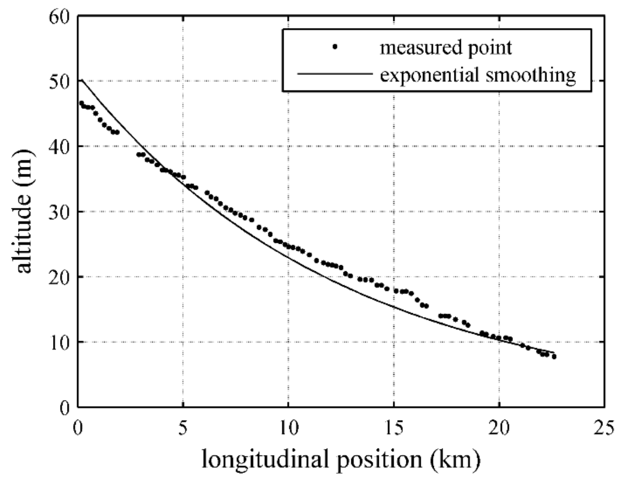


Figure 4: Bed profile of the Cavaillon River

The downstream limit is given by the last section on the river for which the *Caribbean Sea* has no influence on the water level. This section is represented by the point PK22.601, at the locality called *Grand-Place* (Figure 3). The length of the study reach is consequently about 23 km.

Along this distance 84 cross sections were measured with an inter-distance of about 200 m. For each section, a topographical survey has been conducted with total station and differential GPS technology. The width of the cross sections varies from 35 m to 155 m. The bed profile of the study reach is illustrated in Figure 4. More details can be found in (Joseph et al. 2015).

2.2 *Bed material size distribution*

The Pebble Count method (Wolman, 1954), based on a random sampling of sediment has been applied for the 84 sections along the reach of the river.

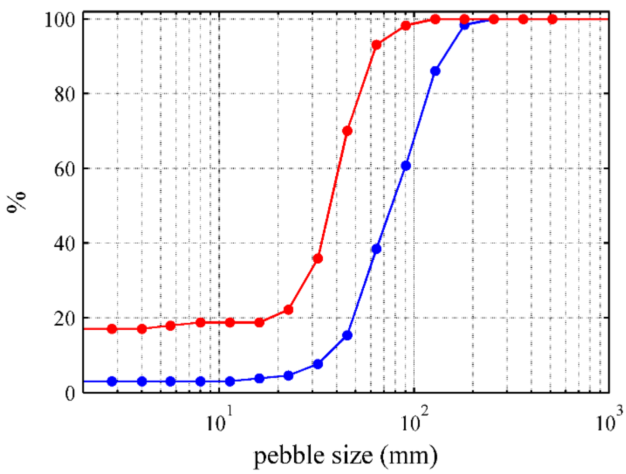


Figure 5: Bed material size distribution. Section PK00.174 and PK22.601. Blue curve: Dory. Red curve: Grand Place.

This method allows for the determination of the granulometric curve of coarse-bed rivers from simple field measurements as follows. Once a river cross-section is identified, more than 100 pebbles are randomly sampled, i.e. the first sample touched by the operator is picked-up and reported adequately in one of the 18 sediment size classes. A cumulative percentage of sediment for each class represents the percentage of them finer than the class identified. These values can be commonly reported on a semi-logarithmic cumulative graph to represent the samples distribution for each section, as illustrated in Figure 5 for *Dory* and *Grand-Place*. It must be recalled that this simple field survey method is suitable only for coarse-grain distribution, which is the case here. Indeed, sediment finer that 2 mm cannot be identified precisely. More details can be found in (Carlier d'Odeigne et al. 2015).

3 EVALUATION OF FLOW RESISTANCE

In uniform flow without presence of vegetation, the principal source of resistance is the bed material. Bedforms, which could be an important friction element, as observed in sand-bed rivers, are rare for gravel-bed. With grain sizes about 41 mm in the present case, bedforms are not the dominant friction parameter and will thus be neglected in this first evaluation of the bed roughness.

Nevertheless it will be necessary to distinguish several flow conditions, with different water levels. Indeed, as summarized by Ferguson (2010) from several sources, for large size bed material like the boulders observed here, the influence of the bed material on the flow resistance is expected to increase as the water depth decreases.

This phenomenon is classified in three ranges depending on the relative submergence characterized by the ratio h/D_{84} (Bathurst et al. 1981), where h is the mean flow depth and D_{84} the size of the medium axis of the grains larger than 84% of the bed material. The three ranges are summarized in Table 1.

Table 1. Scale-roughness ranges

Category	Limits mm
Large	$h/D_{84} < 1{,}2$
Intermediate	$1{,}2 < h/D_{84} < 4$
Small	$4 < h/D_{84}$

This classification is important for the choice of the predictive equations since their performances are depending of the relative submergence of the flow.

3.1 *Determination of the bed roughness parameters*

From the literature, several equations can be found to describe bed roughness parameters (C, n, f) from the pebble size distribution. Ferguson (2007) describes two standard ways, the Manning-Strickler approach which consists of a power law

$$\frac{1}{n} = a_1\, D^{1/6} \tag{2}$$

where a_1 is a constant depending on the characteristic diameter D used, and a logarithmic law, attributed to Keulegan (XXXX), written as

$$\frac{R^{1/6}}{n} = a_1 + a_2 \log\left(\frac{h}{D}\right) \tag{3}$$

where a_1 et a_2 are constants depending on the characteristic diameter D used.

A third approach described by Ferguson (2007) is the Roughness Layer principle. For large- and intermediate- scale roughness, the bed material affects all levels of the flow and disturbs the usual logarithmic velocity. In this case, none of the Manning-Strickler or Keulegan approaches can represent accurately the roughness effect which implies rather a linear resistance equation

$$\frac{R^{1/6}}{n} \propto \frac{h}{D} \tag{4}$$

where the proportionality is depending on the characteristic diameter D definition.

Ferguson (2007) assumes that the Manning-Strickler (MS) and the Roughness Layer (RL) can be regarded as two limit behaviors of the flow resistance depending of the relative submergence. Consequently, he proposed to synthetize the two approaches through a variable power law equation (VPE) which uses a combination of MS and RL depending of the relative submergence.

$$\frac{1}{n} = \frac{a_1\, a_2\, R^{5/6} / D_{84}}{\sqrt{a_1^2 + a_2^2 \left(R/D_{84}\right)^{5/3}}} \tag{5}$$

where a_1 = 6.5 and a_2 = 2.5 as proposed by Rickenmann & Recking (2011).

Equation (5) proposes a simple bed roughness parameter evaluation valid for both shallow and deep water depth conditions that provides, following Rickenmann & Recking (2011), the best overall performance for flow resistance prediction. This approach is consequently chosen for the evaluation of the bed roughness of the Cavaillon River.

3.2 *Field data presentation*

Some relevant values are presented for each of the 84 cross sections studied along the river. Each cross-section is identified by its kilometer point as *PK*XX.XXX, measured from the Dory spillway. The level indicated is that of the thalweg, given as an absolute value with the zero level corresponding to the mean sea level at Morancy, at the mouth of the river. The slope is defined from the exponential function fitted through all thalweg points at the ad-hoc PK. The diameters D_{50} and D_{84} represent the sediment size for which respectively 50% and 84% of the samples are smaller than those values, and the standard deviation of the bed-material size distribution, given by σ = log(D_{84} / D_{50}) following Bathurst et al. (1981), indicates the uniformity coefficient.

Table 1. Relevant data for each section

Section	Level m	Slope %	D_{50} mm	D_{84} mm	σ
PK0.174	46,58	0,35	78	125	0,21
PK0.285	46,1	0,35	56	101	0,26
PK0.481	45,95	0,34	51	91	0,25
PK0.693	45,924	0,34	38	75	0,30
PK0.847	45,005	0,33	46	87	0,28
PK1.050	44,028	0,33	42	87	0,31
PK1.260	43,249	0,32	48	83	0,24
PK1.480	42,715	0,32	42	84	0,30
PK1.661	42,198	0,32	49	98	0,30
PK1.863	42,116	0,31	52	84	0,20
PK2.890	38,69	0,29	57	90	0,20
PK3.096	38,696	0,29	40	65	0,21
PK3.296	37,933	0,28	41	69	0,23
PK3.511	37,691	0,28	43	69	0,21
PK3.766	37,135	0,27	43	79	0,27
PK4000	36,349	0,27	64	98	0,18
PK4.400	36,276	0,26	2	42	1,32
PK4.600	36,098	0,26	41	78	0,28
PK4.800	35,596	0,26	41	71	0,24
PK5.000	35,575	0,25	17	52	0,48
PK5.200	35,247	0,25	66	107	0,21
PK5.400	33,895	0,25	44	71	0,21
PK5.600	33,876	0,24	39	90	0,37
PK5.800	33,629	0,24	26	90	0,55
PK6.200	32,88	0,23	2	85	1,63
PK6.400	32,228	0,23	2	45	1,36
PK6.600	31,928	0,22	25	90	0,56
PK6.800	31,199	0,22	49	90	0,26
PK7.000	30,543	0,22	2	61	1,48
PK7.200	30,221	0,21	39	72	0,27
PK7.400	29,714	0,21	70	121	0,23
PK7.600	29,43	0,21	2	43	1,33
PK7.800	29,042	0,20	37	62	0,22
PK8.000	28,703	0,20	47	84	0,25
PK8.200	27,57	0,19	47	73	0,19
PK8.400	27,234	0,19	44	97	0,34
PK8.600	26,508	0,19	43	83	0,29
PK8.800	25,536	0,18	54	89	0,22
PK9.000	25,345	0,18	58	162	0,44
PK9.200	24,924	0,18	75	127	0,23
PK9.400	24,579	0,18	57	113	0,30
PK9.600	24,475	0,17	17	42	0,38
PK9.800	24,289	0,17	30	93	0,49
PK10.000	23,912	0,17	69	129	0,27
PK10.200	23,364	0,16	68	112	0,22
PK10.400	22,494	0,16	51	97	0,28
PK10.800	22,131	0,16	33	58	0,24
PK11.000	21,868	0,15	10	41	0,63
PK11.200	21,767	0,15	45	76	0,23
PK11.400	21,648	0,15	35	77	0,34
PK11.600	21,39	0,15	45	68	0,18
PK11.800	20,48	0,15	45	97	0,33
PK12.000	20,128	0,14	40	65	0,21
PK12.400	19,588	0,14	20	67	0,52
PK12.600	19,513	0,14	36	75	0,32
PK12.800	19,476	0,13	47	91	0,29
PK13.000	18,69	0,13	51	86	0,23
PK13.200	18,716	0,13	47	79	0,23

Table 1 (continued). Relevant data for each section

Section	Level m	Slope %	D_{50} mm	D_{84} mm	σ
PK14.000	17,697	0,12	2	65	1,51
PK14.200	17,749	0,12	27	71	0,42
PK14.400	17,41	0,12	6	90	1,15
PK14.600	16,469	0,11	21	70	0,52
PK14.800	15,673	0,11	58	89	0,19
PK15.000	15,506	0,11	46	72	0,20
PK15.600	13,994	0,11	52	80	0,18
PK15.800	14,017	0,10	34	57	0,22
PK16.000	13,955	0,10	53	83	0,19
PK16.200	13,438	0,10	43	78	0,26
PK16.600	13,013	0,10	59	94	0,20
PK16.800	12,567	0,10	70	95	0,13
PK17.600	11,375	0,09	53	78	0,17
PK17.800	11,188	0,09	50	82	0,22
PK18.000	10,834	0,09	65	89	0,14
PK18.200	10,646	0,09	3	57	1,26
PK18.400	10,678	0,09	2	70	1,55
PK18.600	10,453	0,08	56	86	0,19
PK19.000	9,498	0,08	41	66	0,20
PK19.200	9,095	0,08	53	78	0,16
PK19.600	8,558	0,08	50	68	0,14
PK19.800	8,117	0,08	31	53	0,23
PK20.000	8,055	0,07	38	56	0,17
PK20.200	7,768	0,07	37	57	0,18

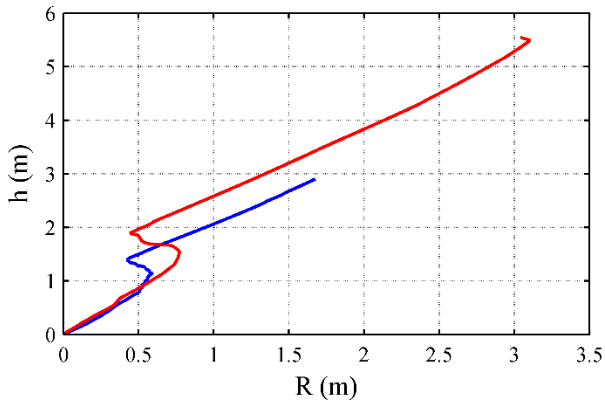
3.3 *Bed roughness evaluation for Cavaillon River*

For each section, for which the bathymetry is defined and the bed material size distribution is evaluated, a three-step sequence is systematically applied, assuming uniform flow conditions.

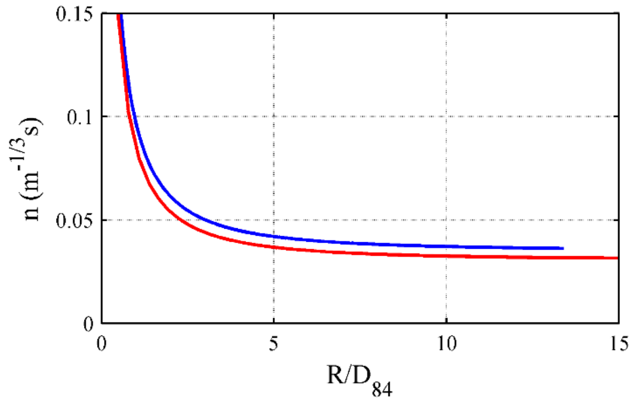
The first step consists in defining a relation between the water level and the hydraulic radius simply based on the geometry of the section $R = A/P$. This is illustrated in Figure 6a for two sections of the considered reach, located at PK00.174 – "*Dory*" and PK22.601 – "*Grand-Place*".

The second step is the direct application of the Ferguson equation (3). A relation between the characteristic diameter D_{84}, the hydraulic radius R and the Manning coefficient n is built for each section. Figure 6b shows this relation for the same two section used in Figure 6a: it can be observed that the flow resistance, represented by the Manning coefficient n, decreases for increasing R/D_{84}. In other words, the flow resistance induced by the bed material is decreasing when the water depth increases. The curves in Figure 6b also suggest the Manning coefficient converges towards a constant value for large water depths.

The last step involves the use of the uniform flow equation (1) to build a stage-discharge relation. From the previous definition of the bed roughness, it is possible to estimate the river discharge as a function of the water depth taking into the influence of the variation of the bed roughness with the depth. Considering the typical range of observed discharges in the Cavaillon River from 1 m³/s to 300 m³/s, we obtain a relationship between the discharge and the roughness coefficient as illustrated in Figure 7 for the 84 sections. Similarly to the Figure 6b, it can be observed that the Manning coefficient tends towards a constant value for all sections as the discharge is increasing. Also, it shows that the variation of the friction coefficient is definitely significant for the range of commonly observed discharges since the Manning coefficient varies by a ratio of about 2:1 or even more.



(a)



(b)

Figure 6: (a) Step 1: Hydraulic radius – water depth relation, (b) Step 2: R/D_{84} – Manning coefficient relation. Blue line representing section PK00.174 and red line representing PK22.601.

Another way to represent the bed roughness variation is illustrated in Figure 8. By representing the Manning coefficient along the river for several discharges (1, 10, 50, 150 m³/s), we also observe the same decreasing trend of the Manning roughness coefficient from upstream to downstream, which corresponds to a typical downstream fining of the grains.

This presentation of the results shows also that a pure implementation of the three-step sequence is not sufficient to be consistent with our willingness to obtain input for further numerical simulation. The variation of the roughness between several sections is too sharp and uncertain since the difference between two consecutives sections could suggest that a different section sampling could lead to different conclusion.

Nevertheless, some general patterns are emerging. An increasing flow reduces the bed material roughness influence and the Manning coefficient value presents a decreasing trend along the 23 km long river reach.

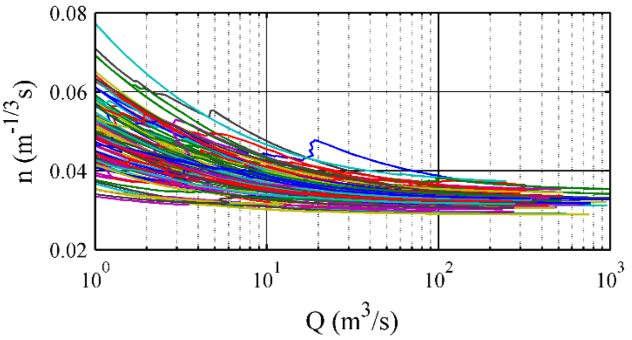


Figure 7. Relation between the discharge and the Manning coefficient 84 sections.

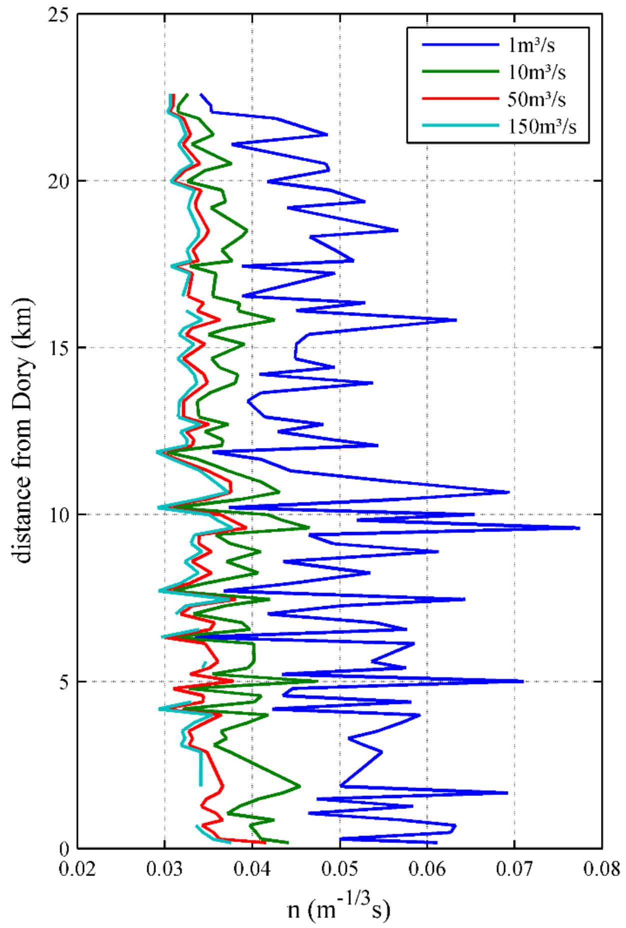


Figure 8. Evolution of the Manning coefficient along the Cavaillon River

3.4 *Relevant results for future investigations*

The analysis presented in section 3.3 provides results that can be useful as input for furthers applications.

3.4.1 *Stage-discharge relations*

The first one is our willingness to build stage-discharge curves for some key sections in the river. Especially, sections PK00.174 and PK22.601 are two sections for which in-situ measurement stations have been recently installed.

The current progress of the project does not enable us to compare theoretical stage-discharge relations with field data. However, the future field missions should allow for the collection of more measurements.

Nevertheless, following conclusions by Rickenmann and Recking (2011), it is expected that a VPE approach as (5) would be more accurate than a simple MS relation such as (2). Figure 9 illustrates the stage-discharge relations obtained with these two approaches for the sections of interest. The MS equation (2) is used with a_1=26 and D_{84} as characteristic diameter. The differences between the two approaches are significant especially for PK22.601 (red line) and require field observation to be confirmed.

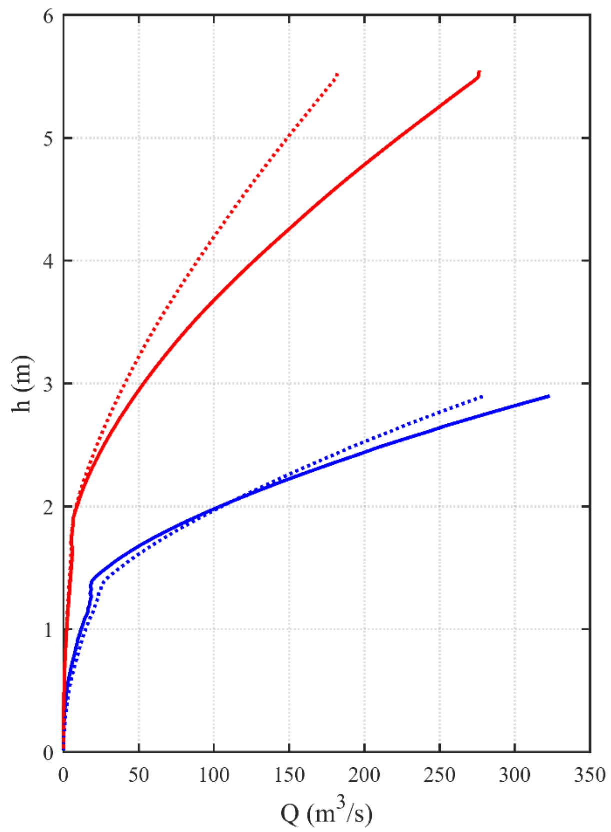


Figure 9. Water depth – discharge relation for PK00.174 (blue) and PK22.601 (red) obtained with Ferguson (line) and MS (dots) approach.

3.4.2 *Stage-discharge relations*

The second relevant result concerns the determination of the flow resistance parameters needed to run numerical simulations. Figure 8 shows the variation of the Manning coefficient along the river reach and also as a function of the discharge. This is also illustrated in Figure 7.

From these results, relations linking the roughness coefficient to the discharge could be derived and used in numerical simulations. Such a relation should also account for the decreasing trend of the bed roughness parameter along the river, as illustrated in Figure 10 obtained from an exponential decreasing curve fitting of the results of Figure 8.

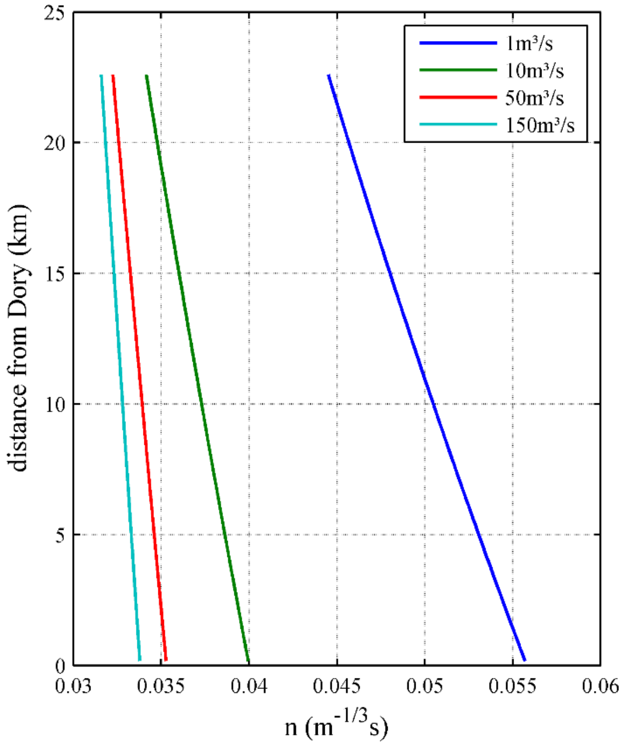


Figure 10. Exponential fitting of the Manning coefficient evolution along the river.

4 CONCLUSIONS AND FUTURE WORK

The work presented in this paper aims at helping to build a complete hydraulic model of the Cavaillon River. It focuses on the different steps required to obtain a parametric representation of the bed roughness from a bed material measurement field survey, with a methodology that can be easy implemented in a context as Haitian rurality.

The application of the combined MS-RL approach proposed by Ferguson (2007) gives an interesting knowledge about the river behavior and the specific features of the cross sections. In particular, the decreasing trend of the Manning coefficient from the upstream end to the downstream end of the study reach could be observed, as well as the influence of the discharge.

Further field campaigns and investigations on the river will include a survey of the floodplains topography and in-situ measurements of the discharge and water depths. These additional data will contribute to the construction of a hydraulic model of the river that could be used for flood managemet purposes.

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