Characterization of Blue-Nile (Abbay) conveyance at Ethiopian/Sudanese border

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Introduction

In the stretch of Blue Nile flowing towards the Ethiopian/Sudanese border the presence of vegetation clearly indicates the maximum flood level normally reached over the past few years (Fig. 1). Rock outcrops are clearly visible over the entire area.

Fig. 1 – View of Blue Nile's river bed during dry (left) and wet season (right)

During the dry-season, the bed is limited to a 'gorge', i.e., a steep-sided, deep and narrow canal carved out of rock masses by the erosive power of the river. This canal is homogeneously characterised along its length by variations in width and shape of its cross sections, and by occasionally emerging rock pillars and groynes of great size (Fig. 2 left). The river banks, together with the 'gorge', represent the overall rainy-season bed and are characterised by massive gneiss, irregular rock-masses and very large boulders. The wide and shallow sand deposits (Fig. 2 right) that appear on these banks during the dry-season are the result of the seasonal sedimentation that took place when the progressively decreasing discharge and the consequent drop in flow velocity reduced the river transport capacity.

Fig. 2 – Example of emerging rock pillar (left) and dry-season sand deposits (right)

A strong effort to effectively characterise the conveyance of this stretch of the river has been undertaken in the context of the GERdp (Great Ethiopian Renaissance dam project). Besides visual, topographic and bathymetric surveys, a direct measurement campaign of discharges (at two sections) and surface water-levels (at several river sections) has been carried out in order to collect a dataset representative of the whole seasonal range of the river flow. This dataset has been used to evaluate the river's roughness-variability with stage/discharge, and to verify the rating curves at monitored sections resulting from one-dimensional (1D) steady-flow river-hydraulics numerical models of the considered river stretch.

The present paper presents criteria and results of such a characterization.

1. Surveys and measurement campaign

Specific surveys were carried out to obtain the actual topography and bathymetry of the Blue-Nile at GERdp site. The topography of the stretch of Blue-Nile extending from GERdp site to the Ethiopian/Sudanese border was previously obtained from the Shuttle Radar Topography Mission (SRTM) SHUTTLE V4.1 and then from a specific Laser Scanning Survey carried out in October 2010. A bathymetric survey of a 5500 m long river-stretch encompassing GERdp site was carried out in February 2012. The resulting bathymetry was linked to topography by means of a specific survey carried out between March and April 2012.

Fig. 3 - TP2 vessel during measurement (left) and GERdp bridge (right)

Discharge measurements were carried out by means of the River-Surveyor M9 system by SonTek. The system consists of an Acoustic Doppler Profiler (ADP), a Power Communication Module (PCM), a real time kinematic (RTK) global positioning system (GPS) and a TP2 vessel (Fig. 3 left). Discharges were initially measured at the Blue-Nile Bridge (also known as 'Chinese Bridge'), located around 30 Km upstream the GERdp site, and then at GERdp Bridge (Fig. 3 right), about 600 m downstream dam axis and completed in September 2012.

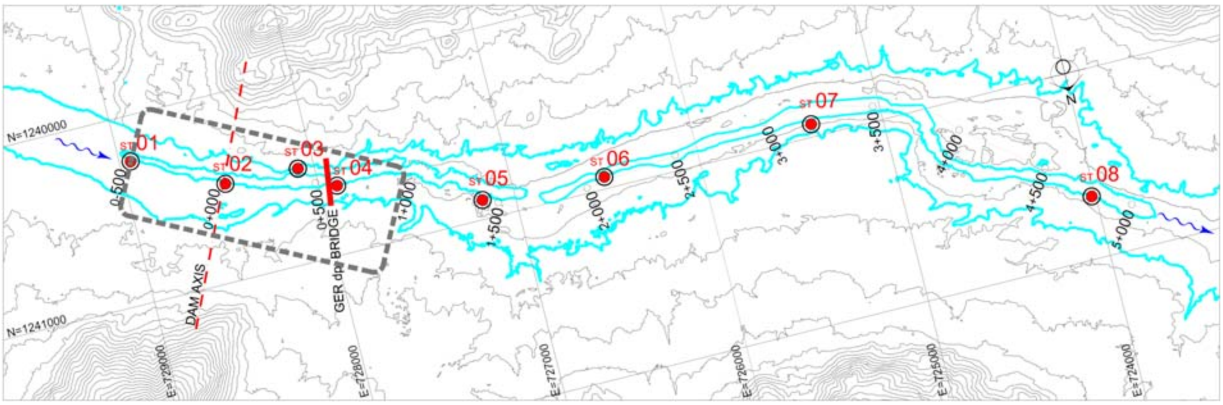

Fig. 4: Location of water level measurement stations

Water elevations were observed at the same time as discharge measurements by reading hydrometric staffs located at selected sections along the considered river stretch. Fig. 4 reports the location of each station in a general plan of the investigated river stretch. Fig. 5 shows a particular of Fig. 4, providing both the thalweg profile and the velocity distribution at selected locations. As expected, the gorge deepening around chainage 0+300 results in a reduction of mean flow velocity. Furthermore, Fig. 6 shows an example of curves of equal velocity at GERdp Bridge section resulting from River-Surveyor M9.

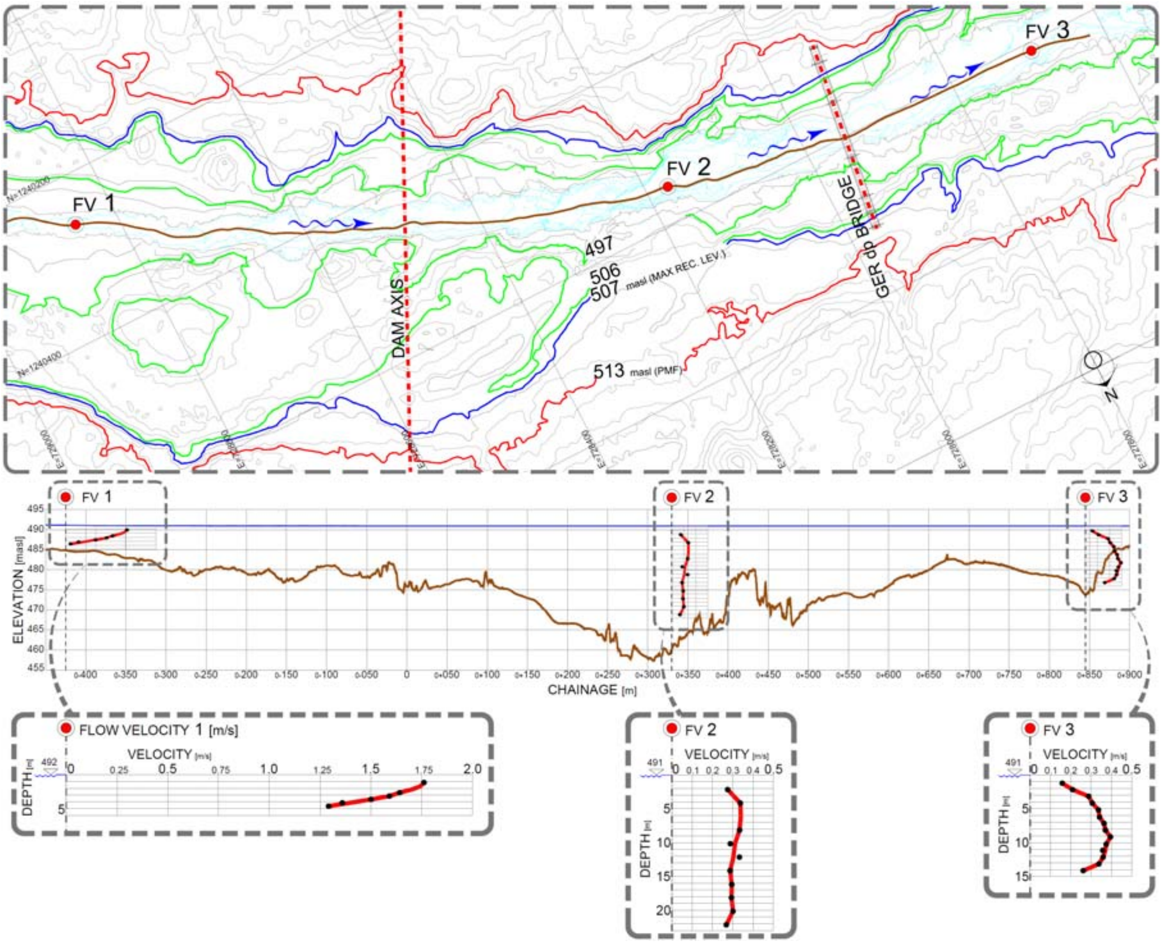

Fig. 5: Plan and section of the investigated Blue-Nile stretch between chainage 0-500 and chainage 0+900 and flow velocity profiles at different locations along the thalweg

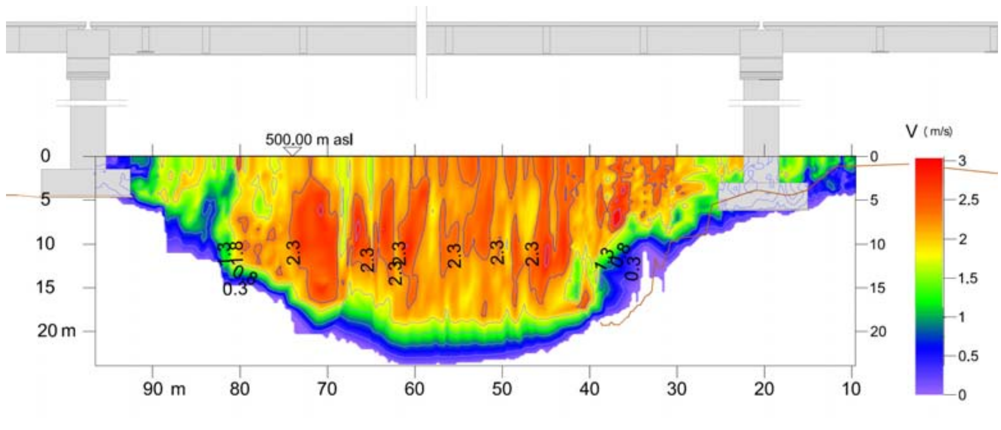

Fig. 6: Typical curves of equal velocity at GERdp Bridge section resulting from River-Surveyor M9

2. Manning's roughness coefficient evaluation

A preliminary characterization of Manning's roughness coefficient was carried out on the basis of a visual survey and following Cowan's criterion [2]. Assuming for the Cowan's basic and correction coefficients n_i the values suggested by Chow [1] and by Arcement and Schneider [3] result in a Manning's roughness coefficient n ranging between 0.05 and 0.10 (Tab. 1).

	n_0 Main Material	n_1 Degree of irregularity	n_2 Cross section variation	n_3 Obstructions	n_4 Vegetation	m Degree of meandering	n $(s/m^{1/3})$
	Irregular highly-fractured rock-masses	Moderate	Occasional	Minor	Low	Minor	
max	0.065	0.010	0.005	0.015	0.005	1.000	0.100
min	0.025	0.010	0.005	0.010	0.000	1.000	0.050

Tab. 1: Range of Manning's roughness coefficient along the surveyed stretch resulting from Cowan's criterion.

The above estimate applies to ordinary wet-season flows and does not consider the coefficient variability with water elevation or stage (and therefore with discharge). As known [1], the roughness coefficient in most streams decreases with increase in water elevation. When the water is shallow, the irregularities of the stream bottom are exposed and their effect is pronounced. Generally, this effect tends to decrease as the water elevation increases. However, the roughness coefficient may be large as well at a high stage, if the riverbanks are rough.

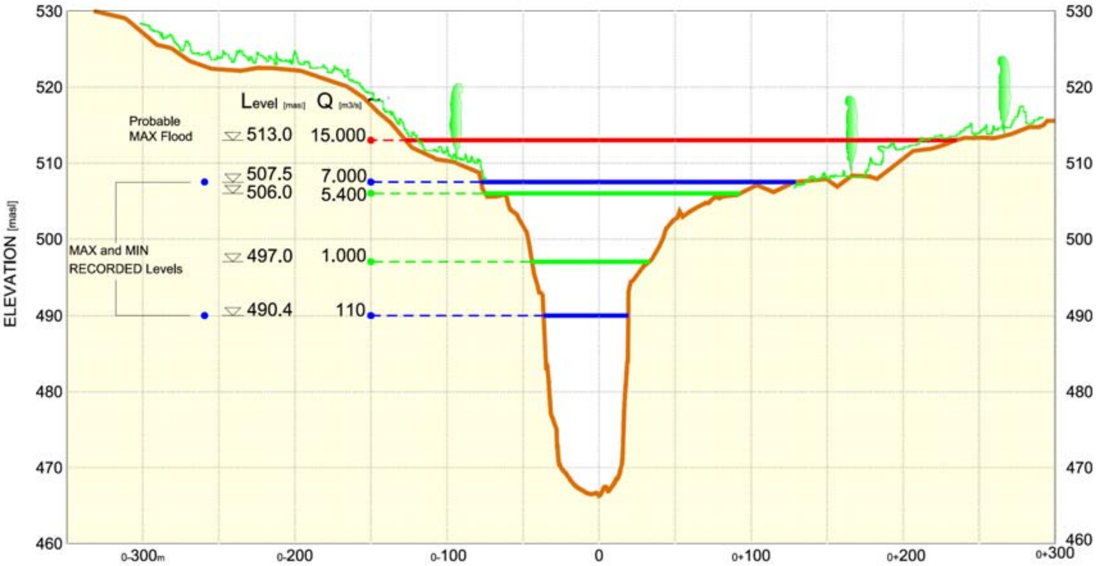

Fig. 7: Water elevations and discharges at reference section

The collected discharge and water-level dataset has made it possible to estimate the Manning's coefficient variability with river water elevation (i.e. stage) at a reference section (Fig. 7), solving for *n* - as suggested by Barnes [6] and Limerinos [7] - the Manning's equation expressed in the form of the well-known Slope-Area Method [4, 5].
As stated by Dalrymple and Benson [5], in this method the discharge is computed on the basis of a uniform-flow equation involving natural channel characteristics, water-surface profile and roughness coefficient. The assumption is that, lacking a better solution, the Manning's equation - developed for uniform flow conditions - is also valid for gradually varied flow such as that typical of a natural channel.
Plotting (Fig. 8) the Manning's roughness coefficients resulting - at different values of measured discharge - from the calculation performed using the slope-area form of the Manning equation has made it possible to assume the graphed relationship between *n* and Q.
With reference to Fig. 7 (i.e. to the reference section) and Fig. 8, the Manning's roughness coefficient appears to progressively decrease with increasing water elevation, i.e. with increasing hydraulic radius. In particular, four main stretches (Fig. 8) characterise the Manning's coefficient variation with water elevation and, therefore, with discharge.

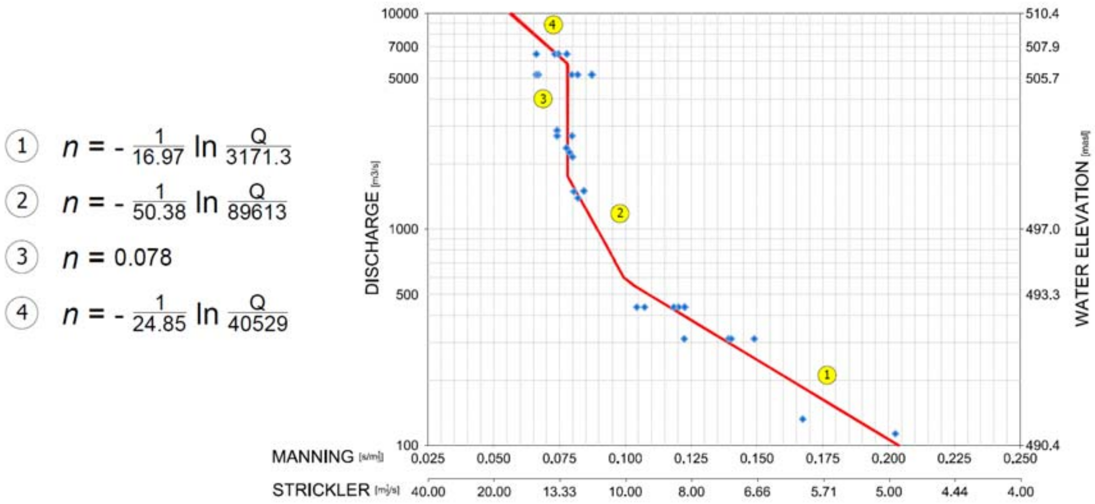

Fig. 8: Variability of Manning's roughness coefficient with discharge and water elevation at reference section

As shown in Fig. 8, *n* ranges between 0.200 s*m$^{-1/3}$ at lower water elevation and discharge (490 m asl, 100 m^3/s) to 0.090 s*m$^{-1/3}$ at a water elevation equal to 497 m asl (Q=1000 m^3/s). At higher water elevation the increment in hydraulic radius is compensated by the influence of rough riverbanks and *n* tends to reach a constant value. In particular, *n* can be assumed equal to 0.078 (equation 3) for a water elevation ranging between 499.6 to 506.9 m asl ($1800 \leq Q \leq 6000$ m^3/s). It is to be stressed that the evaluated Manning's coefficient at discharges within the range 1000 m^3/s $\leq Q \leq$ 6000 m^3/s fall within the range of variability resulting from the application of Cowan criterion.
No data could be collected at discharge greater than 7000 m^3/s. Therefore, equation 4 has been derived assuming a Manning's coefficient equal to 0.04 s*m$^{-1/3}$ at maximum probable flood. In-fact, at the highest water elevations lower values of the coefficient are expected to apply as: the increase in hydraulic radius overtakes the effect of the rough riverbanks; the degree of irregularity of the channel is expected to decrease and its effect can be considered minor; the cross-section variation is expected to become gradual; and the relative effect of the obstruction can be considered negligible.

3. Numerical modelling

In order to define the rating curve at several cross sections of the investigated Blue-Nile stretch, a simple numerical model that allows one-dimensional (1D) steady-flow river-hydraulics calculations has been implemented. In particular, the U.S. Army Corps of Engineers' (USACE) River Analysis System (RAS) developed at the Hydrologic Engineering Centre (HEC) was used [8, 9].

3.1 Implemented model

The implemented hydraulic model covers a river stretch of about 4.5 Km, starting roughly 1.0 Km upstream of the GERdp dam axis and ending approximately 3.5 Km downstream. Seventy-six cross sections define the boundary-geometry of the model. The topographic and bathymetric data collected during the previously recalled surveys have been used for defining the ground surface profiles of the natural channel (cross-sections).
As far as the flow boundary condition is concerned, the subcritical flow condition has made it necessary to provide a downstream boundary condition. A rating-curve has been therefore associated to the most downstream cross-section implemented in the model. This rating-curve (Fig. 9) has resulted from the interpolation/extrapolation of the data collected at chainage 3+300 during the direct discharge-stage measurement campaign. As it can be noticed, two branches characterise the rating-curve in the range 100-3000 m^3/s. The first one applies to the case of Roseires Reservoir at lower level (485 m asl) and the second one to the case of Roseires Reservoir at full storage level (493 m asl). In-fact, following the completion of Roseires dam-heightening project, impounding of Roseires Reservoir took place during October 2012 and, according to DIU (Dam Implementation Unit) of the Ministry of Water Resources and Electricity of Sudan, was completed on November 5, 2012.
As far as the energy-loss data are concerned, the graphical relationship between Manning's roughness coefficient and discharge (stage) depicted in Fig. 8 was implemented in the model, while standard values for gradual transitions (0.1 contraction, 0.3 expansion) was adopted.

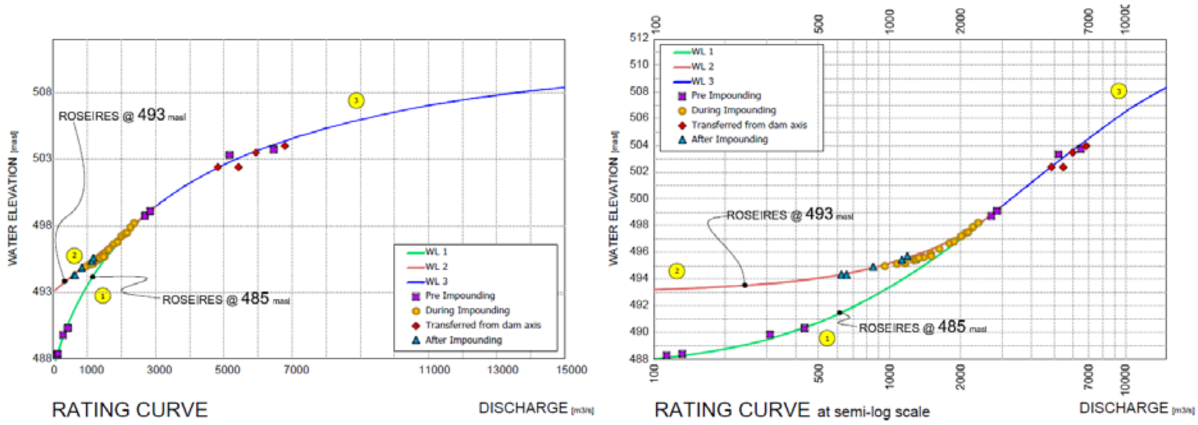

Fig.9: Downstream boundary condition in 1D numerical model (rating curve at chainage 3+300). Discharges as natural (left) and semi-logarithmic (right) scale

3.2 Model results

Two main factors influence the gradually varied flow profiles within the investigated river stretch: the presence of a natural sill at chainage 1+700 (Fig. 10); and the already observed variation of water elevation at Roseires reservoir. In the case of Roseires reservoir at 485 m asl (Fig. 11), the sill acts as critical-flow control at very low discharge and, as shown in Fig. 10, a hydraulic jump forms downstream the sill. As the discharge increases, the hydraulic jump moves upstream until it finally vanishes, the only remaining trace of it being a depression over the sill (drowned sill). On the other hand, in the case of Roseires reservoir at 493 m asl (Fig. 12), the flow does not become critical at the lowest discharge and the sill appears always drowned.

Fig.10: Natural sill located at chainage 1+700 during the dry season

Comparing the rating-curves resulting from the 1D model with observed data has made it possible to show the actual effectiveness of the model in describing the 1D hydraulic-features of the investigated river-stretch. Fig. 13 shows such a comparison at GERdp Bridge section, providing the rating-curve relationships. Within the discharge range 100 $m^3/s \le Q \le 7000$ m^3/s, the observed-data close-fitting shows the goodness of the assumed roughness-coefficient variation with water elevation (discharge), i.e. the goodness of the relationship shown in Fig. 8.

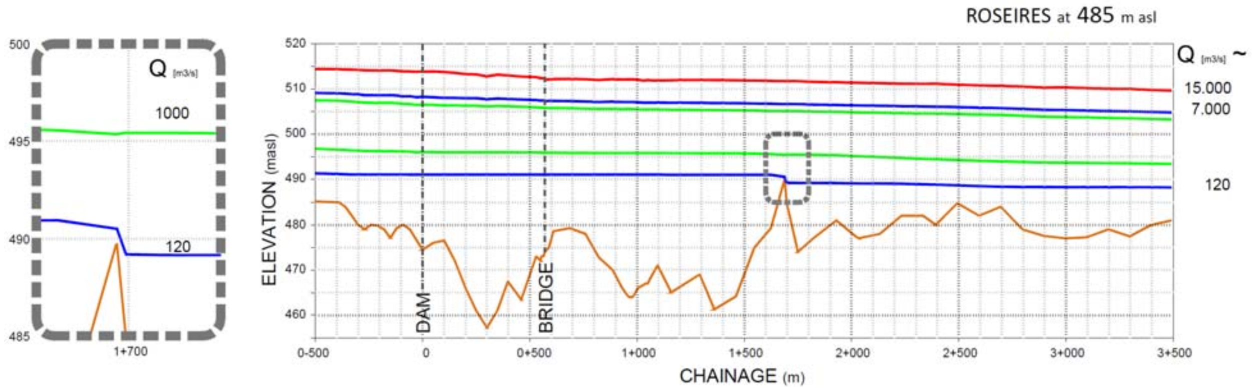

Fig. 11 - Gradually varied flow profiles resulting from 1D model. Roseires water elevation at 485 m asl.

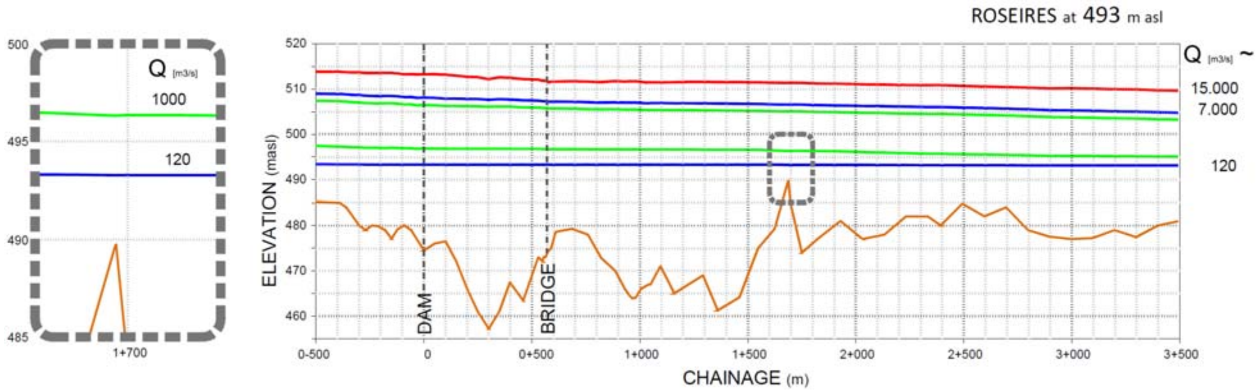

Fig. 12 - Gradually varied flow profiles resulting from 1D model. Roseires water elevation at 493 m asl

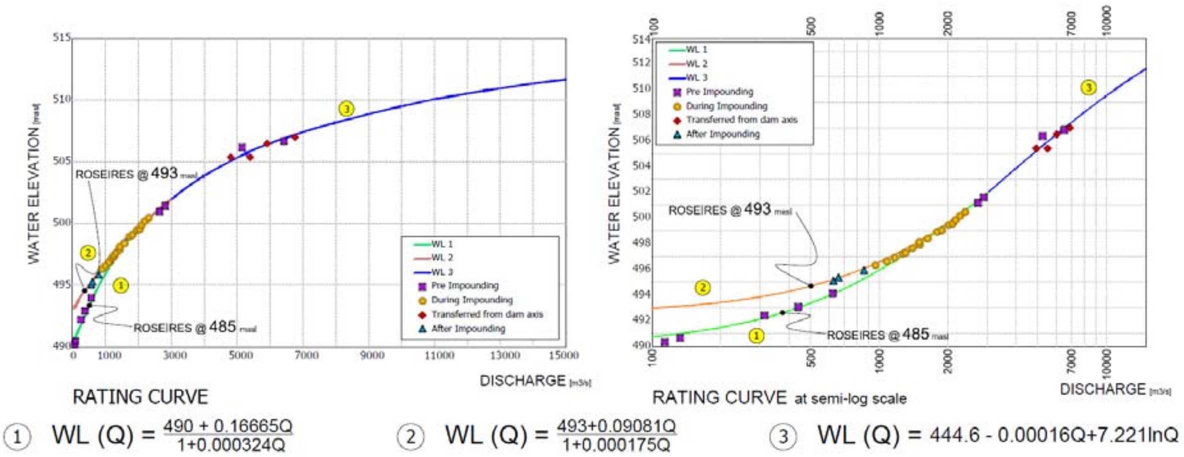

Fig. 13: Rating curve at GERdp Bridge resulting from 1D numerical model.
Discharges as natural (left) and logarithmic (right) scale

4. Conclusions

The overall investigation (surveys and measurement campaign) carried out along the stretch of Blue-Nile encompassing the GERdp site has made it possible to characterise the conveyance of this stretch of the river, providing an effective evaluation of the variability of Manning's roughness coefficient *n* with water elevation at a reference section and with discharge. As shown in Fig. 8, *n* ranges between 0.200 $s*m^{-1/3}$ at lower water elevation and discharge (490 m asl, 100 m^3/s) to 0.090 $s*m^{-1/3}$ at a water elevation equal to 497 m asl (Q=1000 m^3/s). At higher water elevation the increment in hydraulic radius is compensated by the influence of rough riverbanks and *n* tends to reach a constant value. In particular *n* has been assumed equal to 0.078 for water elevation ranging between 499.6 to 506.9 m asl ($1800 \leq Q \leq 6000$ m^3/s). At the highest water elevations lower values of the coefficient are expected to apply as the increase in hydraulic radius overtakes the effect of the rough riverbanks. The Manning's coefficient has therefore been set equal to 0.04 $s*m^{-1/3}$ at maximum probable flood.

The above recalled characterisation - together with the dataset collected during the discharge and water-level measurement campaign - has made it possible to implement a reliable numerical model, effectively describing the 1D hydraulic-features of the investigated stretch of the river. The implemented model has made it possible to define the rating curve not only at the monitored sections but at all the modelled sections, particularly at GERdp site, thus providing an essential tool for evaluating the tail-water effects to be considered in designing specific components of the project, and in optimizing the design with respect to power production.

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Vincenzo Millesi, while completing his degree in civil engineering at the University of Rome "La Sapienza", has been working for Studio Pietrangeli and has acquired substantial experience in the field and in-depth knowledge relating to the feasibility, design and construction of large-scale civil works such as dams and hydropower plants in Africa with particular regard to geomechanics, stability calculations and rock mass characterization.