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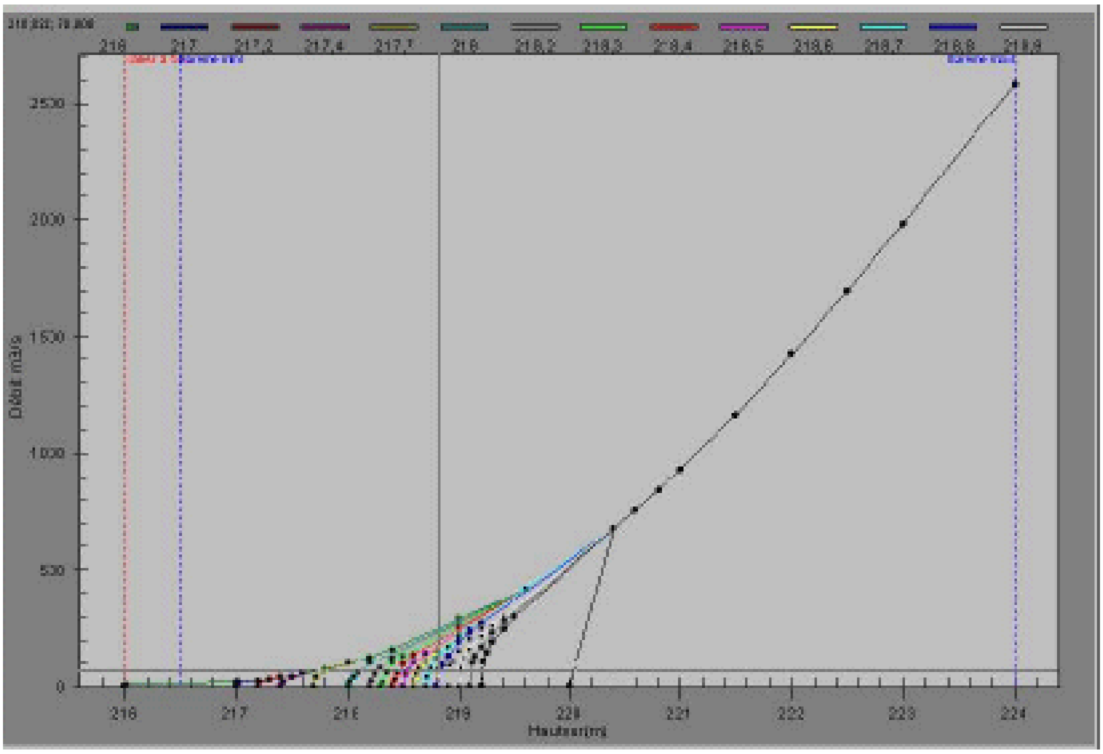

TRAINING SESSION ON CALIBRATION OF RATING CURVES

Accra, 23rd – 27th April 2007

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CALIBRATION OF RATING CURVES
METHODOLOGY, CAUTIONS, ADVICES

I- INTRODUCTION

The rating curve for a given hydrometric station is the definition of the relationship between the different water levels read on a staff gauge and the associated discharges. The water level series is defined by its validity period and its range, limited by the minimum and the maximum observed water levels.

It is obvious that this relationship exists in any case. But, in fact, it can be very difficult to determine, even roughly, due to scarce data, or to the high geometric and/or hydraulic variability of the reach.

To define this relationship, the hydrologist must have information concerning the reach of the river, the characteristics of the hydrometric station, the water level series and discharge measurements which are often available in variable quantity and quality. The rating curve should be defined from this data set by a methodical work which can be divided in eight steps, as follows:

- Examination of the station file
- Inventory of the water level series and of the discharge measurements
- Review of all the discharge measurements
- Analysis of the flow measurement distribution on the graph
- drawing of the rating curve
- Extension of the rating curve
- Establishment of rating table
- Final report on the establishment of rating curve.

This list can appear theoretical, but it is of a high interest to proceed this way. The calibration of a hydrometric station is always the tricky phase in the discharge calculation and a lot of errors rise if one or several of the steps are neglected.

II- STATION FILE EXAMINATION

The file of a hydrometric station should include information on:

- The location of the station and particularly the staff gauges cross section, the water level recorder cross section, the hydraulic control if it exists in the hydrometric reach;
- The geometrical characteristics of the reach and of the different cross sections, type of the river bed and of the banks, location and area of the overflowing zones, existence of natural or artificial obstacles such as curves, junctions, bridges, concrete slab,... ;
- The type of equipment: staff gauges, water level recorder, Foot Bridge, cable-way,

- History of the station: opening date, damages and repairs, rare events (floods, drying out of river);
- The history of monitoring: observer changes, reports of the field teams.

The study of the station file has to permit a good knowledge of the station with precise information on the stability of the river bed, the existence or not of a hydraulic control, changes in the station equipments or management, the different discharge measurement methodologies …

If the station file is incomplete or doesn't exist (uncommon case) a site visit is necessary. This visit has to be done to take information of high importance and with topographic equipment for cross section and longitudinal levelling, as well as staff gauges elevation.

III- DATA INVENTORY

This phase concerns the water level series and all the existing discharge measurements.

3.1. The water level series

The water level data comes from the observer readings and from the charts of the water level recorders. The staff gauges are normally graduated in centimetre, but they are not always in a strictly vertical position. In this case, an increase of 100 cm (fot example) doesn't relate to an increase of 100 cm in the depth of the water, and some corrections must be done.

The water level series, today are generally computerised and defined by:

- The duration: date and time of the beginning and the end of observations
- The range: maximum and minimum observed water levels
- The continuity: no gaps in the observations
- The reliability: observations dense enough with a good time distribution allowing right water level variations reconstruction
- The homogeneity: all the observations have to relate to a single cross section and a single set of staff gauges without any variation in the altitude.

A critical examination of the water level series and a good knowledge of the station file often allow dividing the single series into homogeneous sub-series, each one related to a specific rating curve.

3.2. The discharge measurements

A discharge measurement is defined by a discharge value and an *associated water level* (WL).

The *associated water level* is the one read at the staff gauge, if the height remained steady during the duration of the discharge measurement. Where the level changes during measurment, we must use:

- The arithmetic mean of the observed stages at the beginning and at the end of the measurement, if the stage variation is low;
- The weighted mean by the segment discharges on each vertical measurement if the variation is high:

$$\mathbf{WLa = \sum WLi*qi / \sum qi}$$

WLa : associated water level
Wli : water level related to each vertical measurement
qi : segment discharge related to each vertical measurement

All the stage/discharge pairs have to be taken into account, including the discharge measurements by floats, the discharge estimation using hydraulic formula such as Manning's formula, and the observation of no flow on the river.

IV- DISCHARGE MEASUREMENT ANALYSIS

Each discharge measurement should be checked before being plotted on the graph.

The duration of the measurement, the number of verticals, the methodology used, the location of the measurement cross section, the values of the cross section, the mean velocity, and the width of the river are generally good criteria to estimate the quality of a discharge measurement.

The accuracy of a discharge measurement relates to one of the two following terms:

- The associated water level, generally known with a good precision (less than 1%);
- the discharge, generally known with a precision of about 5% in the best cases, about 10% in case of very low water or high floods, and 25 to 50% in case of incomplete discharge measurements (floats or one and two point methods) or estimation by hydraulic formula.

After this work, two lists should be established:

- Discharge measurements time series, showing the measurement distribution for each homogeneous sub-series;
- the second one is an ascending order of magnitude of the water levels, and it shows the distribution of the measurements up to high water level range ; it allows also a quick comparison of discharges values for the same water level at different dates, and then to appreciate the stability of the stage/discharge relationship.

These lists must contain a maximum of information such as: date, water stage, discharge, wetted area, mean velocity, width, mean depth, method of measurement, trade mark and ID number of the current meter and propeller used, duration of measurement, etc. It is possible to add quality criteria on the measurement.

If this critical phase is neglected, this means that all the discharge measurements had the same precision and so the same weight on the graph, which is incorrect.

V- ANALYSIS OF THE POINT DISTRIBUTION

The rating curve for a hydrometric station is related to one of the theoretical diagrams shown in the figure 1.

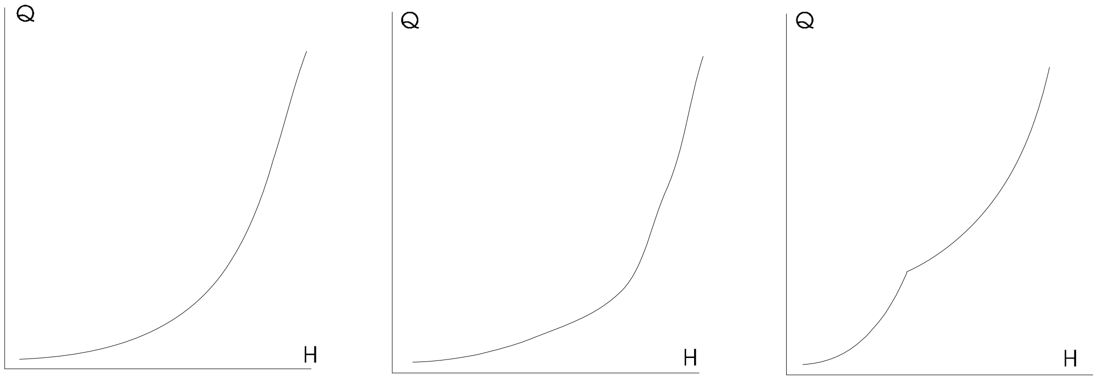
Three main types of rating curves:

- Single value stage-discharge relationship, for stations with a steady geometrical reach and a steady hydraulic control;
- loop rating curve (Hysteresis effect) for stations located in an unsteady geometrical reach of the river;
- loop rating curve for stations located in an unsteady hydraulic flow regime reach of the river.

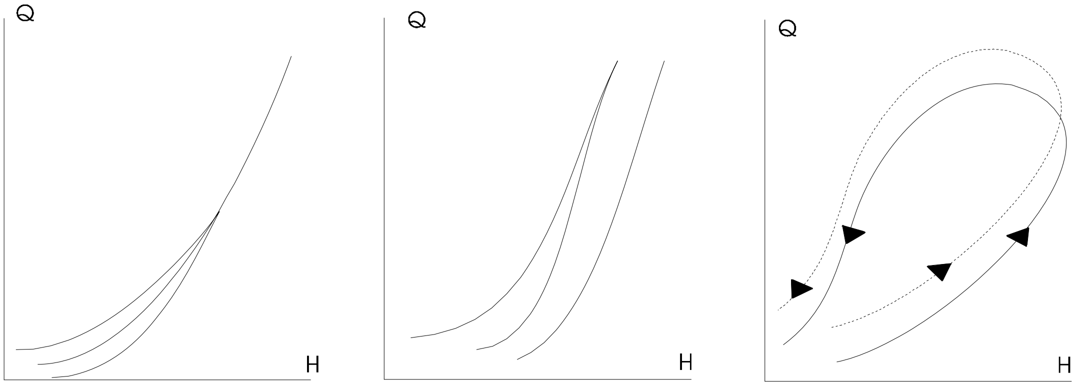
The point's distribution analysis on the graph enables one to identify the type of the rating curve.

TYPES OF RATING CURVES

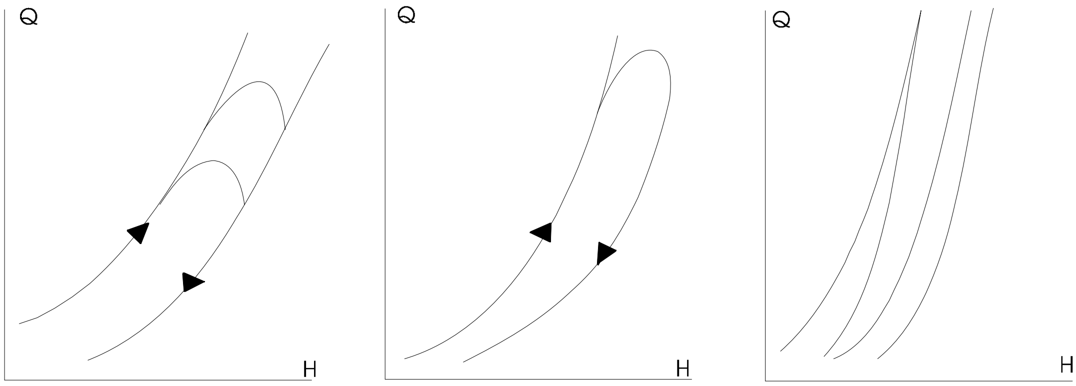
A- Single value stage-discharge relationship



B- Loop rating curve (unsteady geometrical reach)



C- Loop rating curve (unsteady hydraulic flow regime



5.1 Rating curve graph

The rating curve graph can be drawn up by hand or by automatic process, respecting the following rules:

- Arithmetic coordinates
- Plotting **ALL** the discharge measurements
- Use of different graphic symbols to easily identify the measurements belonging to a same time series (year for example) or any characteristic able to guide the analysis (flood or recession, different gauging cross sections, same current meter...).

It is important that the sheet format used for the graph allows a global vision, without any distortion of the point's distribution. It is recommended to plot all the gauging, in this way the operator will see any trend or specificity of point's distribution.

5.2. Point's distribution check

The analysis phase really starts after plotting all points. Any point scattering should be explained.

First the systematic trends are checked, that means the one which relate to several discharge measurements. The isolated points are checked in a second time. These points don't have to be cancelled « a priori » for bad quality reasons; they can be the single sign of a loop rating relationship (this case is quite frequent for the small catchments where about 90 % of the discharge measurements are carried out during the recession phase of the flood.

A systematic trend, during a specific period, can be the result of the use of a damaged current meter, or of the measurement methodology, or of some heterogeneity in the water levels series.

Figure 2 shows a systematic trend for 4 gauging of the year 1977 due to a wrong formula for the propeller used.

Figure 3 shows a strong scattering without any systematic trend. It could be due to imprecise measurements or loop rating relationship. A loop rating relationship is the effect of a high instability of the river bed geometry or of an unsteady flow regime, or both of them.

Geometric instability

The geometric instability of the channel can be graduated when the discharges increases or decreases with the wetted area for a given stage of the water, for example when the channel is filled by aquatic vegetation.

The geometric instability of the channel can be sudden in case of flash flood for example, or in case of human effect as a bridge construction. In these cases, the exact date of the modification should be rightly determined from the water level series or from the station file. It is noted that these events occur very rarely on the 31st December or the last day of the hydrologic year at 24h00! The geometric instability factor affects mainly the value of the cease to flow point. Some methods such as the one proposed by R. MANLEY allows to correct the drawing up of the rating curve in using all the gauging series.

Hydraulic instability

If the water surface slope is not the same during the flood and the recession time for a given stage, the gauging points are in a loop shape distribution on the graph.

Specific methods have to be used in this case; the deviations between the discharges during the rising or the recession limb of the hydrogram for a given stage can reach 30%.

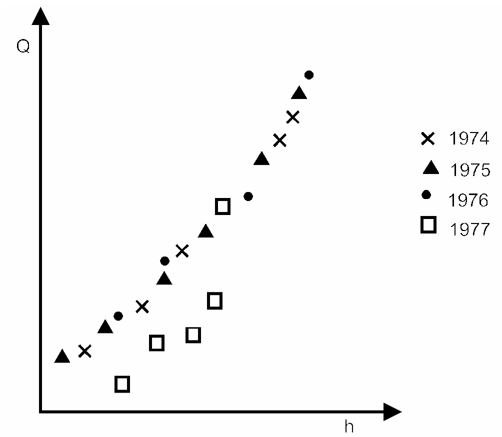


Fig.2 - Anomalie systématique

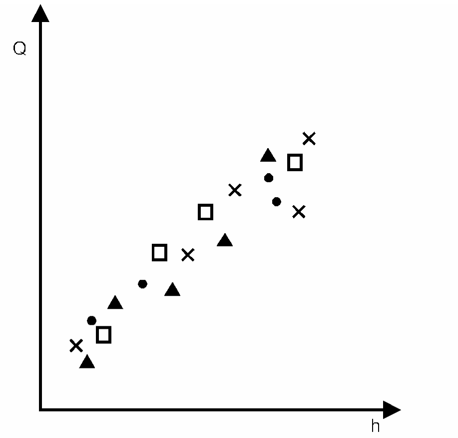


Fig.3 - Anomalie non-systématique

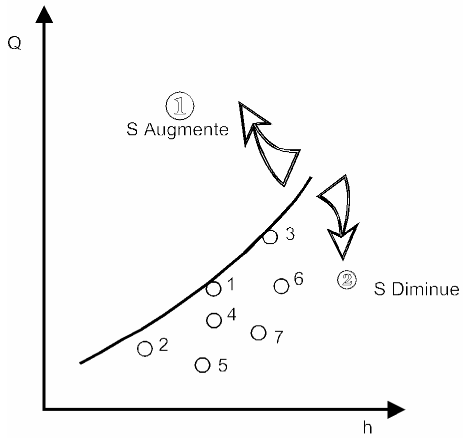


Fig.4 - Variation progressive de la section mouillée

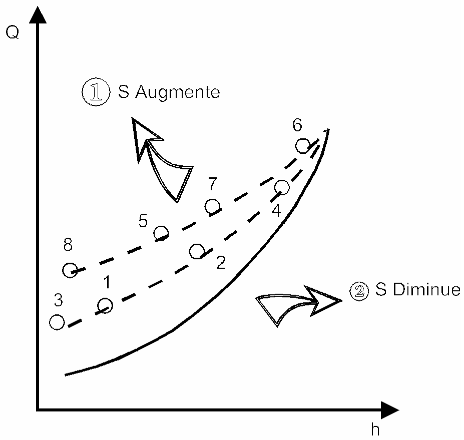


Fig.5 - Variation rapide de la section mouillée

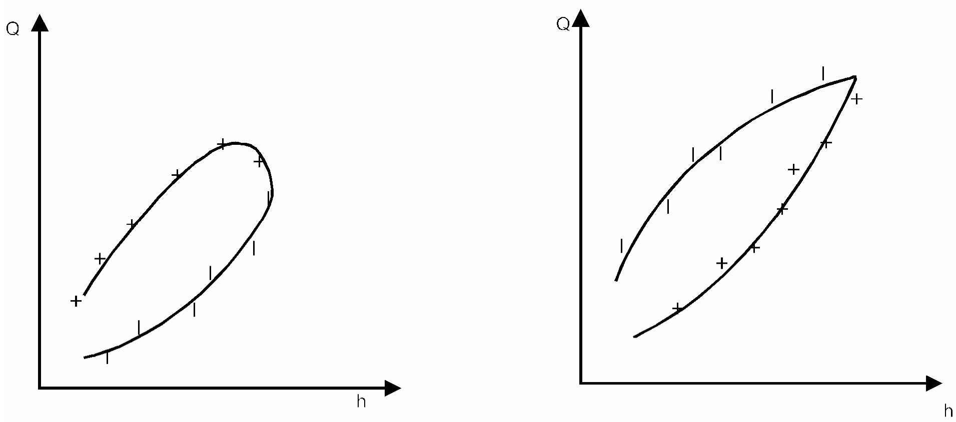


Fig.6 - Organisations cycliques

VI- RATING CURVE DRAWING UP

The drawing up must be done on arithmetic or logarithmic coordinate’s graph, but has to be:

- **Exact**,which means that it is in accordance with the analysis conclusion
- **Accurate**, which means that all the discharge values would be read with a minimum of error.

Figure 7 - Égale répartition des points

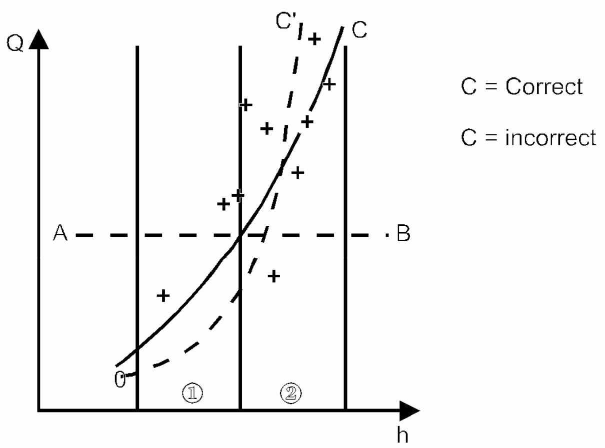
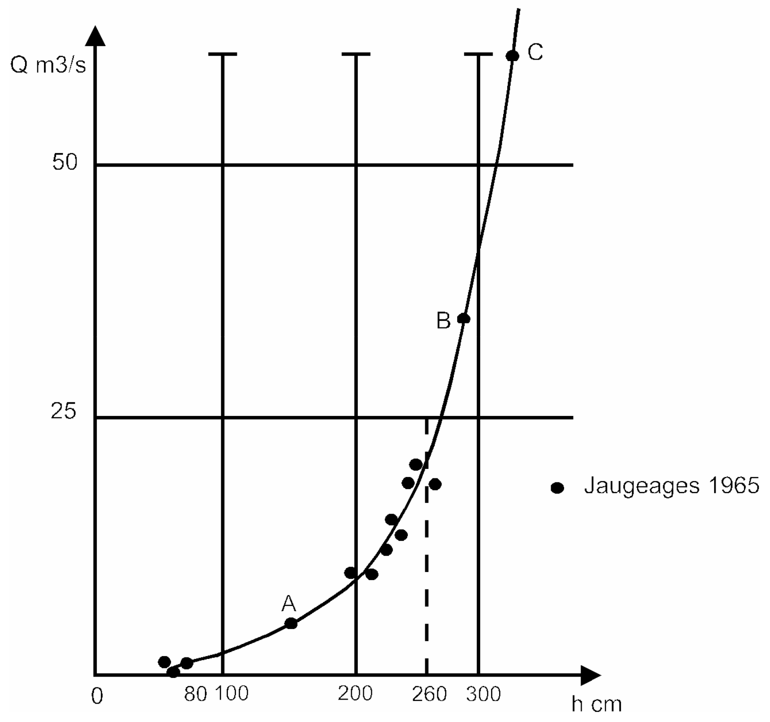


Figure 8 - Précision du tracé
(Oued NIORDE rn Mauritanie



Two rules have to be applied:

- The equal point distribution on both sides of the curve. This rule is applied by successive segments, as much limited than the point density allowed it, in such a way that all the unevenness of the drawing are taken into account (Fig.7).
- The least deviation to the curve; the deviations are taken on the discharge axe (the precision on the water levels being higher than the one on the discharges).

The drawing is done by segments, starting by the segments which have the most numerous points. A drawing based just on few isolated points will not be very accurate.

VII- EXTENSION OF THE RATING CURVE

The stage/discharge relationship has to be defined for the totality of the water level variation range. This range of variation, defined by the minimum and the maximum water stage read on the staff gauge is called “defined interval of the calibration”.

Generally, the discharge measurements are not enough numerous or the distribution is not good, and an extension of the rating curve has to be done. The methods are not the same for low water level extension and for high water level extension.

7.1. Some remarks:

7.1.1 Reference cross section

In a natural river, the stage/discharge relationship isn’t related to the totality of a reach, but only to the staff gauge cross section where the water levels are read. So, all the geometric and dynamic parameters relate to this cross section.

7.1.2 Drawing & extension

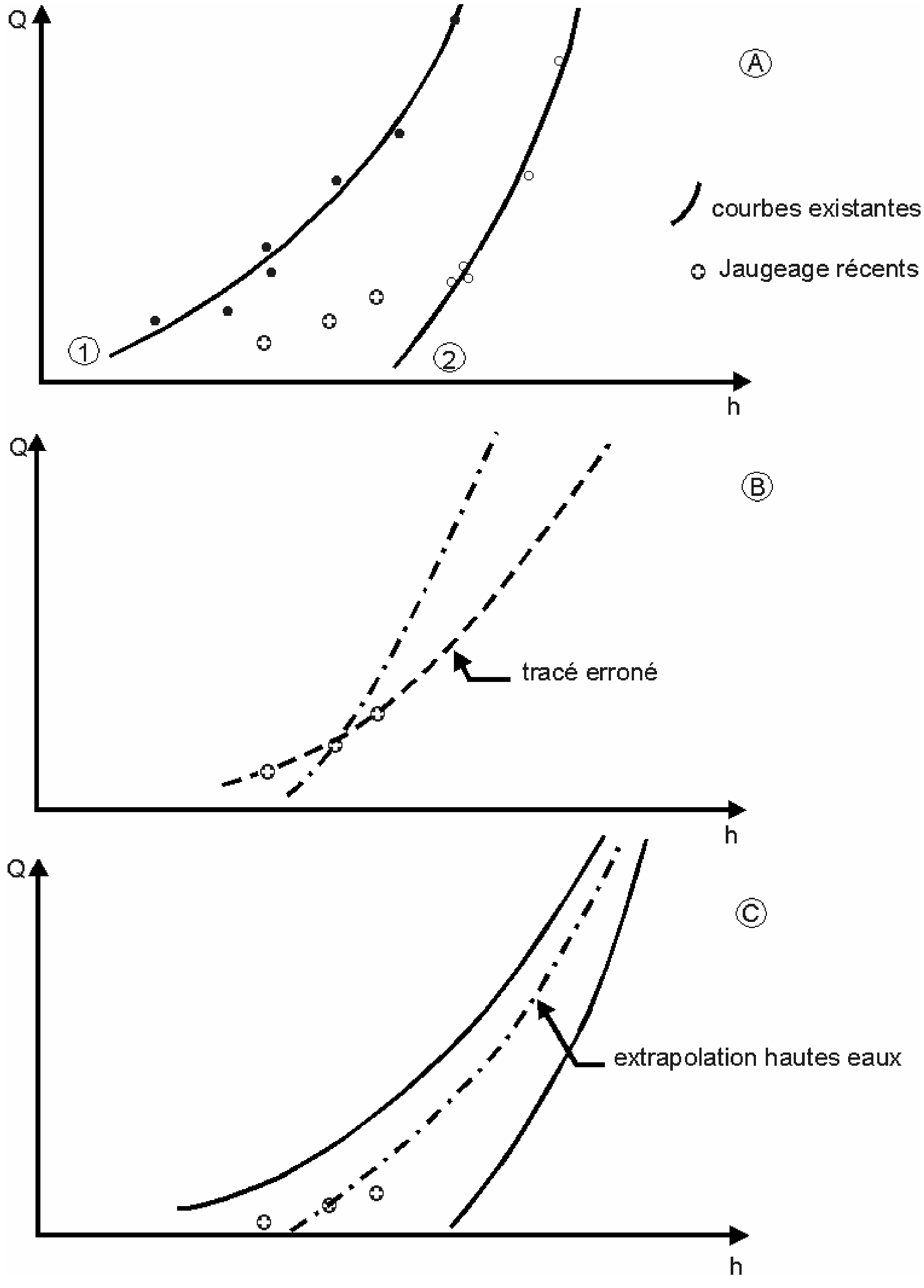
For stations with high geometric instability, the small number of gauging allows only the definition of some segments of the rating curve. In this case it’s very convenient to use the previous rating curves shape to avoid some major errors in the drawing up of the new one.

7.2 Mean & high water levels

The extension of a rating curve, is first a questioning of the continuity of flow conditions continuity: how the wetted area varied, or the mean velocity, or the surface water slope when the water level is rising up above the maximum gauged level?

The extension methods of rating curves can be applied only for the stations with invariable cross section, at least during the validity period of the rating curve.

Figure 9
Tarage de l'Oued Massa (Maroc)
(D'après B. BILLON)



The details of the different methods are not necessarily required to be explained here, but just the principle and constraints of use of each.

7.2.1. Logarithmic method

This method is the most widely applied, but it can be applied only in the very regular cross sections.

Principle:

If the rating curve is of an exponential type, at least in its upper part, it can be expressed by the mathematical formula:

$$\mathbf{Q = a\,(h - h_0)^{n}}$$

Where: Q = discharge
h = water level for the discharge Q
h_0 = water level for the discharge Q = 0
a and n = constants

The easier way to carry out this method is to plot all the gauging on a logarithmic coordinates graph, and the points should be aligned.

In most of the cases there is a break between the low flow gauging and the mean flow gauging. This means that the value of h_0 should be quit high, which shows that it corresponds to a filling up of the minor bed.

Constraints:
The logarithmic method is useful only under some restrictive conditions as:

- Single value stage/discharge relationship of exponential type, characterized by a good points alignment,
- Numerous gauging up to a sufficient water level, to insure a good line direction for the extension
- Regular shape cross section in the part of the water level extension
- Steady hydraulic control from medium to high water levels.

7.2.2. Stevens method

Principle

This method applied the Chezy's formula or the Manning's formula, so it can be applied only for the uniform flow.

STEVENS wrote the Chezy's formula as: $\mathbf{Q/A*R^{1/2} = C*S^{1/2}}$

Where: Q = discharge
A = wetted area

R = hydraulic radius
C = Chezy coefficient
S = slope

In the limits of use of the Chezy's formula, the two terms of the above equation don't varied a lot.

$Q/A*R^{1/2}$ = constant means that the function **$Q = f(A*R^{1/2})$** is a line starting from the origin in a rectangular coordinates graph. This line, drawn from the available gauging can be extended to the value of the geometric term related to the maximum water level.
The Chezy's formula can be replaced by the Manning's formula:

$$Q/A*R^{2/3} = K*S^{1/2} = \text{constant}$$

Where: $A*R^{2/3}$ is used as the geometric term.
Q = discharge
A = wetted area
R = hydraulic radius
K = Manning coefficient
S = slope

Constraints

Besides the uniform flow condition, the STEVENS method is applied only if :

- The cross section is stable: **$A*R^{1/2}$** cannot vary during the flood or the recession phase
- Numerous gauging are available in a correct line.

7.2.3. Slope - area method

This method is applicable to the irregular shape cross sections.

Principle

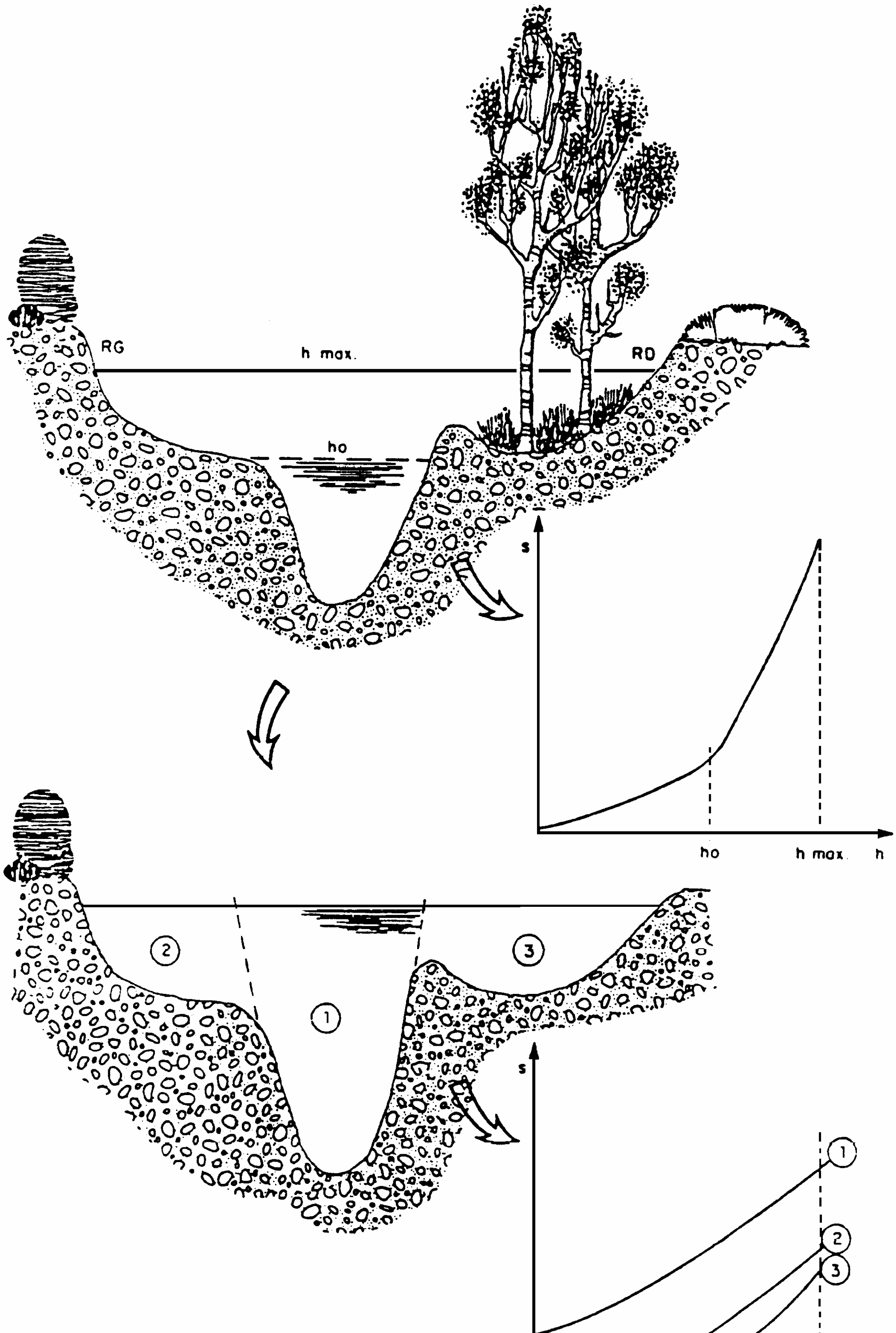
The extension of the rating curve is done in taking into account separately the two terms of the discharge:

- **The wetted area A,** which is known with a good precision if a cross section levelling is available
- **The mean velocity** for which the increase related to the water level is lower than the one of the discharge.

The extension of the rating curve is limited in this method to the extension of the stage/velocity curve.

For the irregular shape cross sections, the cross section has to be broken down in homogeneous sub-cross sections. For each of them a stage/area curve and a stage/velocity curve have to be drawn.

The extension of the stage/velocity curve can be easier by the use of the Manning's formula for the calculation of the maximum velocity.



Constraints

- This method is inapplicable in case of high variation of the cross section (digging / depositing during flood and recession cycles).

- Imperative need of a cross section levelling

- Necessity to know the surface water slope and its evolution when the discharge increases.

7.2.4 Hydraulic flow formula

Hydraulics used numerous formulas with which it is possible to make discharge calculation to complete the list of gauging for ungauged water levels. These calculated gauging are an indirect method of rating curve extension.

The used formulas belong to two categories:

- The first one referred to uniform flow conditions in steady regime: Chezy, Manning, Strickler. They gave accurate results when the water surface slope can be measured in the field;
- The second one allowed discharge calculation from the backwater curve or from the head loss generated by a natural or artificial singularity (bridge, sill …). These formulas are more complex than the previous one, the most used are of Aubuisson type, applicable to narrowing sections. The expression of the formula is:

$$Q = C\,S\,(2gy + aU^2 \Delta h)^{1/2}$$

In which :

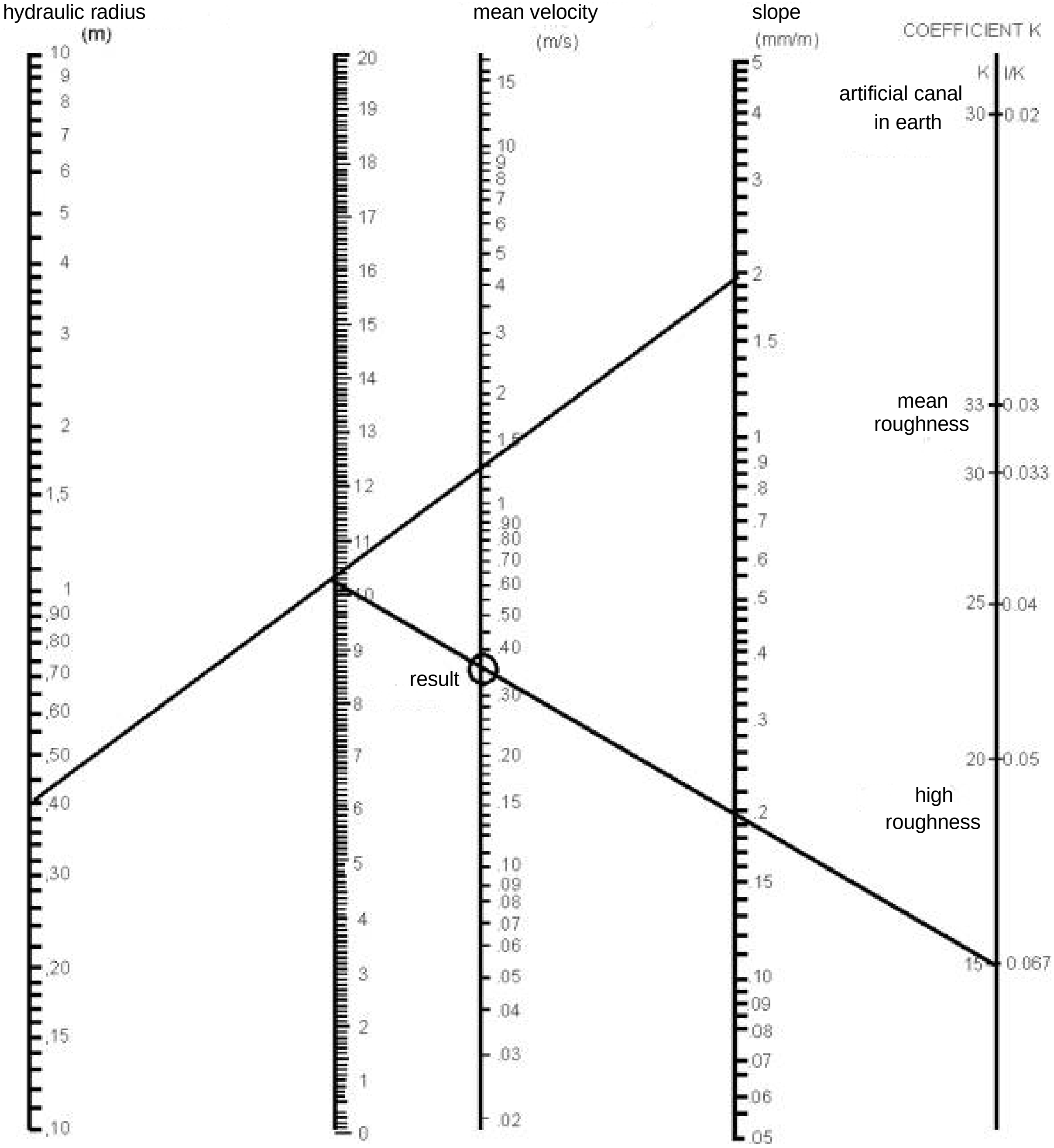
C is a one dimensional coefficient provide by a table and which varies from 0.5 to 1;
S is the wetted area at the narrowing section;
y is the lowering of the water surface profile;
a is a coefficient related to the velocities distribution through the cross section;
Δh is the head loss due to friction between the narrowing section and the upstream section.

Summary:

The extension of a rating curve is needed only to the maximum observed water level; the three useful methods shown above are only applicable to steady or rather steady cross sections.

In practice, the extension of a rating curve has to be done in using, if the hydraulic conditions allowed it, the three methods and by comparison of the results.

ABACUS FOR MEAN VELOCITY CALCULATION
using Manning-Strickler formula : $U = KR^{2/3} J^{1/2}$



Exemple : R = 0.4 m J = 2 mm/m K = 15 ⇒ U = 0.36 m/s

7.3 - Low water levels extension

The extension of the rating curve for low flows is an always a quite difficult operation in natural river beds, e.g. without any measuring devices such as Parshall flume or weir, for at least two reasons:

- the very bad sensibility of the natural cross sections for low discharges
- the high instability of the rating curve for low water levels, because of the high sensibivity to any changes in the geometry of the section.

For these two reasons , a very good hydrometric station for mean and high water levels could be unsuitable for low water levels. Carrying more discharge measurements is the only way to allow a good drawing of the rating curve.

In addition to these two disadvantages, is the lack of measurements:

- in quantity because the measurement of low water levels is often neglected by the hydrologists,
- in quality because the measurement conditions are quit difficult, wide cross sections with changes in the geometry, low velocities, etc.

7.3.1- Case of non perennial flow

If during the validity period of the rating curve the discharge is zero 0, the stage H_0 associated with this zero discharge should be the origin point of the rating curve.

It has to be noted the value of H_0 is very often different from 0.

Knowing the end point of the curve, the extension below the last gauging point is generally easy, in accordance with the shape (curvature) to avoid any discontinuity.

7.3.2- Case of perennial flow

When the flow doesn’t stop during the validity period of the rating curve, there is no practical rule to guide the extension of the curve.

- If the min observed water level is quit closed to the min gauges water level, the extension will be made in accordance with the general shape of the curve in this part of the drawing.
- If the min observed water level is quite different from the minimum gauges water level, the minimum discharge will be estimated taking into account the reduction of the cross section and the velocities.
- If the station is under a downstream control section, the extension could be done by a logarithmic method, the H_0 value being equal to the lower point elevation of the control section.

Summary :

- The extension has to be done to the min observed water level, no more.
- In case of ephemeral rivers, the H_0 value corresponding to zero discharge is of a high importance for the extension of the rating curve.