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NEAR CRITICAL FLOW IN ALLUVIAL CHANNELS

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ABSTRACT

The present text deals with the hydraulics of critical and near critical flows in open channels, resulting from the research by the author on the "regime", [1], of rivers and its significance in fluvial geomorphology. From these concepts, many observations of great importance for the understanding of processes and problems in river hydraulics have been made, such as those on the behavior of river channels in alluvial fans, the hydraulics of mud flow, the singular behavior of mountain torrents and the great impact that regime, as expressed by the magnitude of the "Froude" number has on the behavior of rivers. In this article the dependency of the flow regime with the concentration of flow in the cross section is examined, and a theory of "Near Critical Flow" is presented; it is proved that the characteristics of this type of flows are the same for any given cross section.

This work is derived from the study of river crossings of oil pipelines in mountain torrents in Colombia during the 1980s, the observation of river flow phenomena caused by the sudden melting of the Nevado del Ruiz Volcano's glacier ice snowcap in 1985 and numerous other incidents in South and Central America as well as work done by the author in 1990 in Bolivia designing a river control system for the Piraí River, in the Santa Cruz de la Sierra Area. It has also been developed from more than 15 graduate theses in the engineering faculties of the National and Los Andes Universities in Bogotá since 1990. In the course of these activities, a new understanding of critical and near critical flow in open channels has emerged.

THE CONCEPT OF REGIME IN CHANNEL HYDRAULICS

Flow regime in channel hydraulics refers to the total energy content of the channel and its division between potential and kinetic energy. The importance of this concept comes from the considerable variation in the behavior of free surface flows with different kinetic and potential energy content which can be mathematically proved to be a function of the Froude Number.

The Froude Number describes the relationship between two basic parameters of free surface channel flow: the average flow velocity, V, and the celerity of shallow surface waves, $\sqrt{gd}$, where, g, is the acceleration of gravity, and d, is the average flow depth :

$$F = \frac{V}{\sqrt{gd}} \qquad (1)$$

Even though the Froude Number is an non dimensional parameter and can have any positive value greater than zero, it's unusual to find flows in nature with Froude numbers much greater than 1.0; values slightly higher than 2.0 have been reported in the literature, but they have a considerable level of uncertainty. Under very special flow conditions, in hydraulic structures built of smooth materials, the Froude number can easily reach values of 10.0, and in the less frequent conditions of artificially concentrated flows, for example in sewers or in

[1] The regime of a river is defined by its energy content, expressed as a function of its velocity and the depth of its flow.

the steep spillway channels of large dams, it can reach even greater values. The flow regime in open channels, natural or artificial, is denoted in the literature according to the value of the Froude number, as follows : $0 \leq F \leq 1.0$, SUBCRITICAL; $F = 1.0$, CRITICAL; $F \geq 1.0$, SUPERCRITICAL

DIFERENTIATION OF FLOW REGIMES

Hydraulic engineers usually don't differentiate between flow dynamics or flow regimes for different Froude numbers as long as they are simply greater or lesser than 1.0, which is the condition for ***critical flow***. This is particularly true in the case of river engineers, who are used to nature's favorite range for lowland rivers, $0.1 \leq F \leq 0.3$. Few would accept *a priori* the difference between a flow with a Froude number from 1.2 to 2.5 or from 2.5 to 5.0. The Author wishes to emphasize in this article, however, that, essentially, flows with Froude numbers between 0.5 and 1.5 are indistinguishable in nature. This is the case particularly if they occur in channels capable of varying their roughness or their slopes, as is the case in piedmont streams on alluvial fans.

Critical Flow in Channels

Critical flow in an open channel of a specific cross section is defined as that which presents minimal specific energy conditions for a given channel. Specific energy, *E,* is defined as the total energy of the flow as related to the bottom of the channel:

$$E = y + \frac{\alpha V^2}{2g} \qquad \textbf{(2)}$$

Considering a constant flow in this channel, it is possible to prove that E is a unique function of y, given that $V = Q/A$, where A, the area of the cross section of the flow, is a unique function of y. In the case of a very wide rectangular channel, where $V = Q/by = q/y$; while $A = by$, the following is obtained :

$$E = y + \frac{\alpha q^2}{2g} \cdot \frac{1}{y^2} \qquad \textbf{(3)}$$

Plotting the function $E = f(y)$ Produces the curve in Figure 1 :

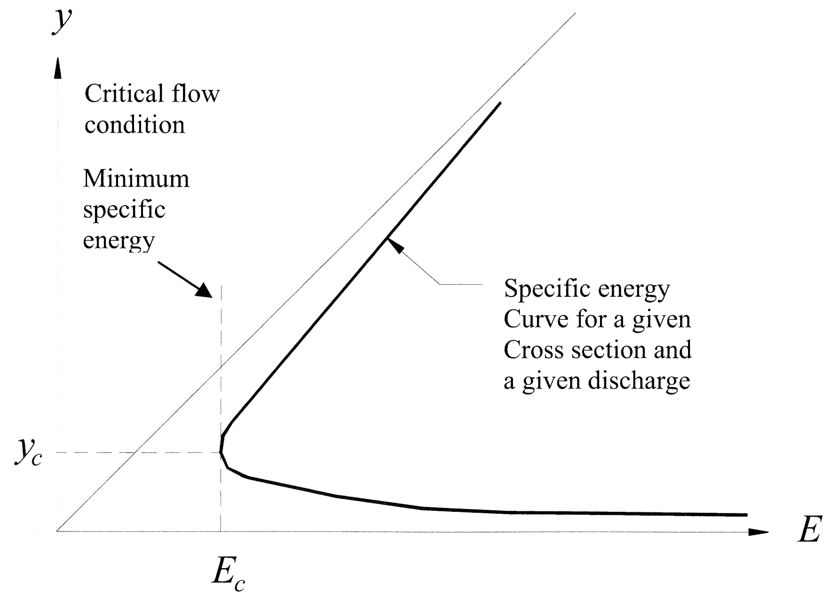


Figure 1. Generalized Specific Energy Curve in an Open Channel

This curve, is asymptotic to the ***E*** axis and to the 45° line that has been drawn to construct the graph. Deriving equation (2), in relation to ***y***, the condition of critical flow is obtained :

$$\frac{dE}{dy} = 0 \text{ , for a Coriolis coefficient of } \alpha = 1.0\text{, produces: } y_c^3 = \frac{q^2}{g} \text{ , y } E_c = 1.5\, y_c$$

Where sub index ***c*** indicates the condition of critical flow. The assumption $\alpha = 1.0$ is made for purposes of simplification without losing generality, given that α must be a constant for a channel of given cross section. The condition of critical flow is based in the quadratic nature of the function, and can also be expressed by:

$$1 = \frac{q^3}{y_c^3\, g} = \frac{V_c^2}{g\, y_c} \qquad (4)$$

Or also:

$$1 = \frac{V_c}{\sqrt{g\ y_c}} = F_c \qquad (5)$$

THE FROUDE NUMBER AND FLOW CONCENTRATION

To understand the conditions under which the Froude number of any given flow can be obtained; it is simply enough to write Manning's equation as a function of this parameter, (Ordóñez, 1992, 2005). For a rectangular channel :

$$V = \frac{q}{y} = \frac{1}{n} R^{2/3} S^{1/2} \qquad (6)$$

This equation can be expressed in terms of ***F*** and ***q*** as follows :

$$q_F = \frac{g^5 n^9}{S^{4.5}} F^{10} \qquad (7)$$

Sub index ***F*** in the flow per width unit serves to denote that this is the flow capable of producing a certain value of the Froude number. Equation (7) can be represented graphically as a function of ***n*** and ***S*** or be calculated as in Table 1:

Table 1. Values of the Froude Number Corresponding to Different Values for q, n and So

q	*n = 0.012*				*n = 0.020*				*n = 0.020*
(mcs/m)	*So = 0.0001*	*0.0003*	*0.0005*	*0.001*	*So = 0.0001*	*0.0003*	*0.0005*	*0.001*	*So = 0.010*
1	0.27	0.44	0.56	0.76	0.17	0.28	0.35	0.48	1.36
3	0.30	0.50	0.62	0.85	0.19	0.31	0.39	0.54	1.52
5	0.32	0.52	0.67	0.90	0.20	0.33	0.41	0.57	1.60
10	0.34	0.56	0.70	0.96	0.22	0.35	0.44	0.61	1.71
20	0.36	0.60	0.75	1.03	0.23	0.38	0.48	0.65	1.83
30	0.38	0.62	0.78	1.07	0.24	0.39	0.50	0.68	1.91
50	0.40	0.66	0.83	1.15	0.25	0.42	0.52	0.71	2.01
100	0.43	0.70	0.89	1.21	0.27	0.44	0.56	0.76	2.16

From equation (7), and Table 1 the following can be deduced :

- Critical flow conditions are not independent from roughness, as suggested by equation (4), because roughness and slope determine the flow concentration necessary to produce critical flow in a channel or, in fact, any Froude number.
- For high slopes, (higher than 1%), it is impossible to obtain sub critical flows even in conditions of high surface roughness.

- For moderate to low slopes, (lesser to 1°/$_{ooo}$), it is impossible to obtain supercritical flow, even in conditions of very low roughness.
- It is very difficult to obtain critical flow in intermediate slopes (between 1°/$_{oo}$, and 1°/$_{ooo}$), even for relatively low conditions of roughness.
- It is unlikely to obtain truly sub critical flows for intermediate slopes and normal or low friction coefficients since, in these conditions, ***F*** is always between ***0.6*** and ***1.5***, (*NC*).
- It is practically impossible to obtain flows with ***F > 2.0*** in natural channels, given the huge flow concentration required for even low roughness conditions.

Variation of the Froude Number in Open Channels

Equation (7) can also be used to calculate the variation in the Froude number in a channel :

Equation (7) can also be expressed as:

$$q = \frac{g^5 \quad F^{10}}{\alpha^9} \tag{8}$$

Where ***α*** is now the parameter defined by Maza-Álvarez as :

$$\alpha = \frac{S^{0.5}}{n} \tag{9}$$

From equation (8), the value of **F** can be deduced as well as its rate of change with ***q*** :

$$F = \frac{\alpha^{0.9}}{g^{0.5}} \quad q^{0.1} \tag{10}$$

$$\frac{dF}{dq} = 0.1 \quad \frac{\alpha^{0.9}}{g^{0.5}} \quad q^{\quad 0.9} \tag{11}$$

where:

$$F = F_o + \Delta q \quad \frac{dF}{dq} \tag{12}$$

Equations (10) through (12) demonstrate that the variation of the Froude number in a channel must increase monotonically with the flow per width unit ***q***. This is of utmost importance in the treatment of, for example, morphological phenomena such as the scouring of river beds, since it would be impossible that the Froude number decrease as the scouring process continues, if the value of ***q*** is increasing,(Ordóñez, 2005).

It is also clear that, as ***q*** increases, the variation on **F** is increasingly smaller, which means that a given reach of a river does not suffer great regime variation despite the value of ***q*** increasing greatly. This situation has been previously observed by the author in the discharge measurements at gauging stations, (Ordóñez, Aldana, 2003). Table 2 displays the results of using equation (12) for typical values for ***a***, and indicates that ***F*** does not increase more than 20% for variations in ***q*** of up to 500%, both for sub critical and supercritical flows. The table also shows that ***F*** does increase as ***q*** increases, although, as it has already been mentioned, only slightly; therefore, rivers tend to maintain their regime unchanged, within a characteristic range, in a given reach, under conditions of increasing flow.

It is worth noting, that the direct use of Manning's equation in the case of alluvial rivers, using the same exponents that are recommended for prismatic channel hydraulics, is not always correct; in fact, some authors have proposed to change them, (Einstein, Chien, 1956). The author also has shown that for example, in the case of the Saldaña River in Colombia, a large mountain stream with a very large sediment load, the exponent of the relation between ***F*** and ***q*** is closer to 0.5 than 0.1, although the trend of the curve is identical; and that a similar observation can be made considering the variation in the parameters for the whole section and the variation in the parameters for subsections of the same cross section. The results indicate that the curve ***dF/dq*** presents the same characteristics of equation (11), with the ***q*** exponent also different from ***-0.9*** but always negative.

Table 2.- Typical Variations of the Froude Number for Given values of a

q	S=0.0001 D=0.001m n = 0.013 α = 0.78					S=0.001 D=0.005m n = 0.017 α = 1.89				
	$F_{Manning}$	**(dF/dq)**	$F_{(16)}$	**Δq (%)**	**ΔF (%)**	$F_{Manning}$	**(dF/dq)**	$F_{(16)}$	**Δq (%)**	**ΔF (%)**
0.5	0.24	0.0477	0.24	-50	-8	0.53	0.1055	0.53	-50	-10
1	0.26	0.0255	0.26	-	-	0.57	0.0565	0.57	-	-
3	0.29	0.0095	0.29	300	12	0.63	0.0210	0.64	300	12
5	0.30	0.0060	0.30	500	15	0.66	0.0133	0.67	500	18
10	0.32	0.0032	0.32	1000	23	0.71	0.0071	0.72	1000	26
15	0.33	0.0022	0.34	1500	31	0.74	0.0049	0.75	1500	32
20	0.34	0.0017	0.35	2000	35	0.76	0.0038	0.77	2000	35
25	0.35	0.0014	0.36	2500	38	0.78	0.0031	0.79	2500	38
35	0.36	0.0010	0.37	3500	42	0.81	0.0023	0.81	3500	42
45	0.37	0.0008	0.38	4500	46	0.83	0.0018	0.83	4500	46
50	0.38	0.0008	0.38 *	5000	46	0.84	0.0017	0.84 **	5000	47

*** Although total variation is 60%, q variation is of 10,000%; also, the regime is very similar for F=0.24 o F=0.37**
**** Although total variation is 60%, q variation is of 10,000%; also, the regime is very similar for F=0. 53 o F=0.85**

A THEORY OF NEAR CRITICAL FLOW IN CHANNELS

Definition of Near Critical Flow

As it has been observed previously, flow regime in the vicinity of **"Critical Flow"** conditions is very difficult to differentiate given the "flat" character of the energy curve in Figure 1 near the "critical" point. This is why, in this area, it is preferable to differentiate a sector within which it is more appropriate to speak of **Near Critical Flow**. Given that, as previously stated, the highest velocity flows in nature, in torrential streams, are precisely as undefined in their regime as previously stated, and given that, as it will be proven in the present chapter, natural channel flows never achieve true super critical status, it is incumbent in this discussion to define with greater accuracy what is the range of Froude numbers in near critical flow. In other words, how "flat" is the energy curve at the critical point.

Torrential Flow and Near Critical Flow

Torrential Flow conditions are characteristic of steep rivers, (***So ≥ 0.001***), that flow through mountain and piedmont areas at very high velocities. The term "torrential", is very imprecise, and nobody has clearly defined it, but clearly applies to flows with high Froude number, close to the ***1.0*** of ***Critical Flow***. In practice, torrential status also refers to a hydrology with highly variable levels of flow intensity, with steep flow duration curves, intermittent flows and channels subject to sudden floods. Engineers must often interpret peculiar river behavior with little hydraulic or hydrological data, which frequently leads to mistakes, particularly in the case of extreme floods. To improve understanding of torrential flow, the following questions must be asked: How high, can ***high*** velocity be in an open channel? What phenomena occur when approaching this velocity? What causes such velocities to occur in an open channel; is it because of the slope, the flow intensity or the channel roughness?

In a study of the Piraí River, in Bolivia, (SEARPI, 1990), in the context of moderately high alluvial valley slope, the author observed first hand, the existence of normal flows that were very close to critical in, what was later evidenced as being, the moderately sloped portion, (***So ≤ 0.0005***), of the middle reach of a very extensive alluvial fan. These flows were indicative of an extreme flow dynamics, where the hydraulic characteristics were very difficult to estimate through conventional uniform and gradually varying flow modeling. The search for solutions to these problems led the author to make a series of observations, based on simple unidirectional flow equations for open channels that allow results more consistent with the real flow dynamics, than conventional modeling, and constitute what will be referred to in this volume the ***Near Critical Flow Theory***, these observations are as follows :

1. For a ***very wide*** rectangular section, its easy to ascertain that the relative specific energy E/E_c is a unique function of y/y_c :

$$\frac{E}{E_c} = \frac{y}{1.5y_c} + \frac{q^2}{3gy^2y_c} = \frac{2}{3}\frac{y}{y_c} + \frac{1}{3}\frac{y_C^2}{y^2} = f_1\ (\frac{y}{y_c}) \qquad \textbf{(13)}$$

2. It can also be ascertained, that the Froude number is a unique function of y/y_c as well:

$$F = \frac{V}{\sqrt{gy}} = \frac{q}{y\sqrt{gy}} \quad ; \quad F^2 = \frac{q^2}{gy^3} = \frac{y_C^3}{y^3} \ ; \ \text{ó} : \ F = f_2\ (\frac{y}{y_c})$$

For rectangular channels:

$$F = \ (\frac{y}{y_c})^{3/2} \qquad \textbf{(14)}$$

3. As explained, the two former conditions are properties of the flow itself and so do not depend on the transverse section. From equations (13) and (14), it follows that :

$$\frac{E}{E_c} = f_3(F)$$

For example, in a rectangular channel : $\frac{E}{E_c} = \frac{2}{3}F^{\,2/3} + \frac{1}{3}F^{4/3}$ **(15)**

This equation leads to the interesting conclusion that specific relative energy in an open channel is a unique function of the Froude number, which allows for the graph in Figure 7 to be drawn, combining equations (13), (14) and (15) :

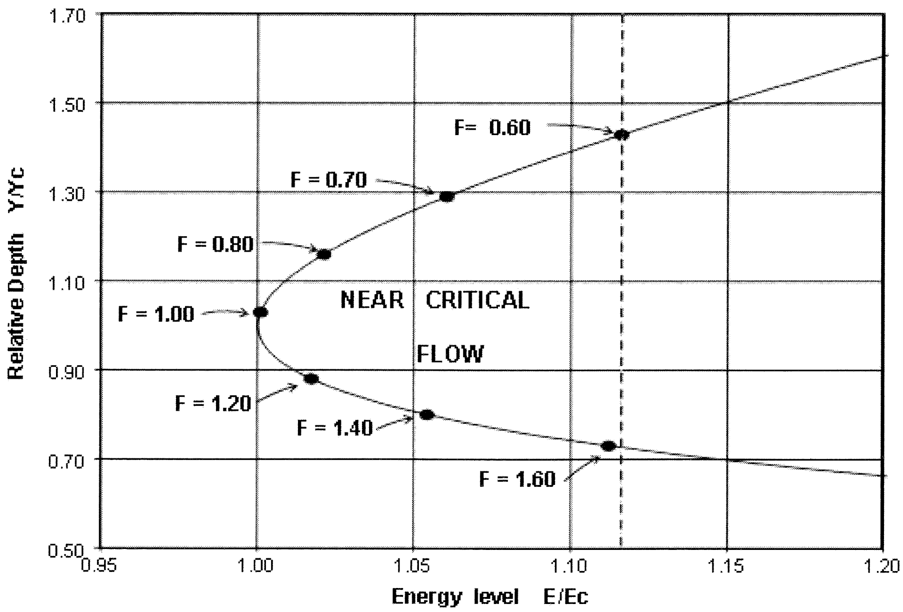


Figure 7. Generalized Specific Relative Energy Curve in a Very Wide Rectangular Channel. Ref. [3]

4. This diagram shows that, even though it takes a great amount of energy in excess of critical energy to produce a low velocity flow with a Froude number lesser than 0.6 or a high velocity one with Froude number greater than 1.6, the amount required for the flow to acquire numbers between 0.6 and 1.6 is practically the same.

   The author recommends that the graph Figure 7 be considered the standard diagram for Near Critical Flow.

5. For purposes of completing the theory, it must be said that an equation similar to (15) can be written for specific relative force, (Naranjo, Palacio, 2000).

$$\frac{F_e}{F_{ec}} = \frac{2}{3}F^{2/3} + \frac{1}{3}F^{-4/3} \qquad \textbf{(16)}$$

Instability of Near Critical Flow

Figure 7 shows that, for a rectangular channel, flows with $\boldsymbol{0.55 \leq F \leq 1.6}$ have energy levels that differ from critical level in less than ***12%,*** which allows for the inference that there is no way to differentiate these flows (or even those of slightly greater range) in natural channels, because their proximity to critical flow makes them similarly unstable.

Considering the difficulties of measuring the hydraulic parameters of a river with greater precision than 10 to 15%, specially near critical flow conditions, its possible to conclude that there is no way to recognize the regime of a river in the $\boldsymbol{0.55 < F < 1.6}$ range; where $\boldsymbol{E/E_c \leq 1.12}$; this is the reason why rivers of very steep slopes present highly unstable flows and regimes which constantly change between subcritical and supercritical; it is also why they cannot be classified as or the other, and should simply be considered ***near critical***, their dynamics being essentially different from either type and from ***critical flow*** itself. In this range, flow is of an undulating nature and can present great fluctuations in velocity.

Near Critical Flow in Prismatic Channels

As the author has demonstrated in several previous publications, this same condition presents itself for prismatic channels of any shape, which implies that it is a basic condition of flow and does not simply dependant on the shape of the cross section of the channel, (Ordóñez, 2002,1994, 1992). Although the existence of an intermediate flow level, between sub critical and supercritical, may seem to be an exclusive condition of rectangular channels, the same range of Froude numbers, $\boldsymbol{0.55 \leq F \leq 1.6}$, produce the same instability conditions for $\boldsymbol{E/Ec \leq 1.12}$ in any other prismatic section, than the one that occurs for a normal, or a very wide rectangular section, (Ordóñez, 2002).

The preceding raises two more observations of the near critical flow theory:

6. Table 3 indicates the value range for F in each $\boldsymbol{E/Ec \leq 1.12}$ case. As it is shown, all sections present similar behavior, indication that this condition is a property of flow in the vicinity of critical conditions and not of the section itself. The table also indicates the range of values for y/y_c for near critical flow is within $\pm\, 35\%\, y_c$.

7. The author also puts forward that in near critical range, the value $\Delta y = \pm 1/3\, y_c$ is the order of magnitude of the ondulatory free surface profile that occurs in these naturally unstable flows. Some experimental evidence regarding this has been presented by Sánchez J. R. (1992).

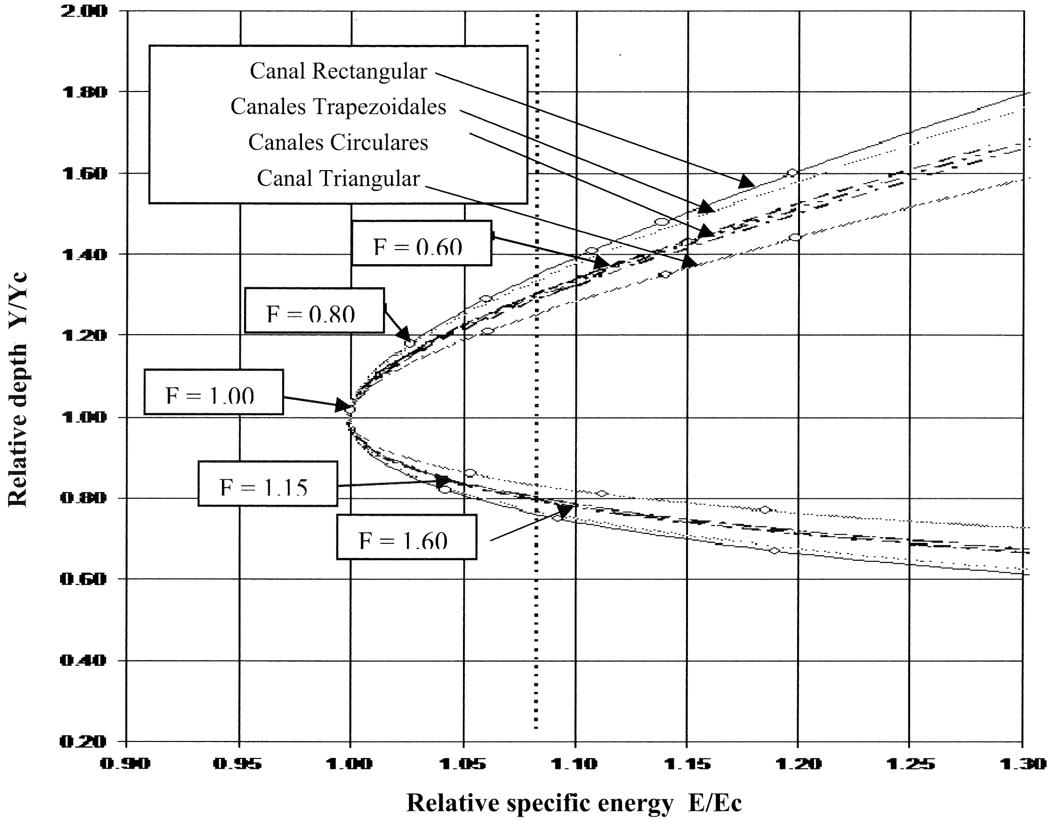


Figure 11. Relative Specific Energy for prismatic channels of varied cross section

The values on Table 3 indicate that, regardless of the shape of the section, flows with Froude number values in the ***0.55≤ F ≤ 1.65*** range also display values of ***E/Ec ≤ 1.12***, that is, values of specific energy that differ in at least 12% with energy levels corresponding to critical flow. Given that, in practice, it is impossible to measure ***y*** or ***V*** with precision greater than 15%, the characteristics of flows in this range make them essentially unrecognizable from each other.

Table 3 Values for E/Ec for values for 0.55≤ F ≤ 1.65 in prismatic section channels

F	TRIANGULAR	RECTANGULAR	TRAPEZOIDAL	CIRCULAR	PARABOLIC
0.55	1.09	1.14	1.09	1.09	**1.12**
0.60	1.07	**1.11**	1.07	1.07	1.10
0.70	1.04	1.05	1.04	1.04	1.05
0.90	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00
1.20	1.01	1.02	1.01	1.01	1.01
1.40	1.04	1.05	1.04	1.04	1.04
1.60	1.09	1.11	1.09	1.09	1.09
1.65	1.10	**1.13**	1.10	1.10	1.10

Calculation of Near Critical Flow Parameters

According to the theory that has been presented, the calculation of characteristic parameters of near critical flow must follow the procedure listed below :

1. Verification that the flow is, in fact, ***near critical***. To this end, proof of morphological and hydraulic type is necessary. Regarding morphology, the following must be ascertained:
    - Whether or not the river is ***"braided"***.
    - Whether or not it flows over an ***"alluvial fan"***.
    - Whether or not its slope is greater than 1 in one thousand

Regarding hydraulics, the following must be ascertained :

- Whether or not it is a ***"torrential"*** stream.
- Whether or not all or part of the section flows with $F \geq 0.55$

2. Calculate the characteristics of the main flow, or the most likely maximum value of q, which can be estimated through equation (7) for F=1.0. If this calculation yields too high a value, (greater than 30 cm/sec), calculate for a lesser value, F=0.8 for example, or use the maximum value of 30 cm/sec, uncommon in natural channels.
3. Determine the critical depth for the calculated value of q.
4. Calculate the maximum and minimum values of the depth, as $1.4Yc$ and $0.7Yc$.
5. Calculate the maximum and minimum values of velocity, as $q/0.7Yc$ and $q/1.4Yc$.
6. In case that the calculation of flow confinement dikes is required, a dike height in excess of $1.4Yc$ must be employed. If the design of structures that will have to withstand maximum flow velocity, use $q/0.7Yc$ as the value.

Although these calculations might seem arbitrary, it should be taken into account that no uniform flow model, be it gradually varied or non permanent, can accurately calculate the hydraulics of a channel for near critical flows. In these cases the model assumes that the conditions are identical to critical flow, which can induce mistakes in the determination of parameters for the design of flood prevention hydraulic structures. The suggested method will always provide results that are more consistent with the actual flow conditions and lead to more conservative determinations of design parameters.

Another very important condition in natural channel design for this Froude number range is the critical revision of hydrological conditions, since floods with high recurrence intervals are usually accompanied by mud flows where the total volume of the hydrographs may be double or triple the volume of water, examples in the following sections are demonstrative of this fundamental characteristic of the calculation required for these types of practical situations.

5 CONCLUSIONS

Through theoretical analysis and practical examples, the influence of river regime, (expressed by the magnitude of the Froude number), over the hydraulic behavior of rivers, has been explained. A theory of near-critical flow has been presented, which permits to calculate the characteristic parameters for this type of flows. This also gives clues about the substantial differences that exist between the sub critical regimes of low land rivers and the near critical regimes of piedmont torrential streams.

Based on simple uniform flow concepts, the author has also obtained an equation which shows the variation of hydraulic regime in an alluvial channel as the flow discharge increases. The base of this equation is the Manning equation, written in terms of the Froude number; this derivation proves theoretically some of the previous observations made by the author, based on the study of data on river discharge measurements in hydrometric stations in Colombia :

1. The value of the Froude number of the flow indicates the level of energy it has. Relative specific energy is a function of the Froude number of the flow.
2. The Froude number in a channel must rise monotonically with the flow per width unit in uniform flow conditions.
3. The variation of the Froude number in a given reach of an alluvial channel is very small in comparison with the discharge variation.

The dynamics of torrential floods in medium and high slope piedmont streams, (So > 0.001), is the dynamics of near critical flows, with Froude numbers between 0.6 y 1.5. Higher Froude numbers apparently do not occur in nature, while the erroneous selection of lower numbers in this type of rivers, may result in errors in the estimation of the effective width of the main flow. In near critical flow the unstable nature of critical flows applies, with a strong oscillation in the surface, that generates effective depths greater than those that can be calculated for sub critical flow, as well as radically higher velocities.

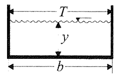
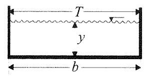
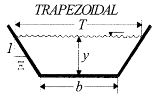
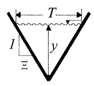
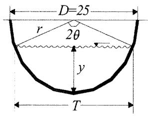
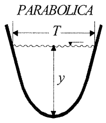
FORMA	y_c	E_c	F	E/E_c
RECTANGULAR 	$\sqrt[3]{\frac{\alpha Q^2}{b^2 g}} = \sqrt[3]{\frac{\alpha q^2}{g}}$	$\frac{3}{2} y_c$	$\left(\frac{y}{y_c}\right)^{-1.5}$	$\frac{2}{3} F^{-2/3} + \frac{1}{3} F^{4/3}$
RECT. MUY ANCHO 	$\sqrt[3]{\frac{\alpha q^2}{g}}$	$\frac{3}{2} y_c$	$\left(\frac{y}{y_c}\right)^{-1.5}$	$\frac{2}{3} F^{-2/3} + \frac{1}{3} F^{4/3}$
TRAPEZOIDAL 	$\sqrt[3]{\frac{\alpha Q^2}{b^2 g}} \cdot \sqrt[3]{\frac{1+ 2Z/b\ y_c}{(1+Z/b\ y_c)^3}}$	$y_c + \frac{D_c}{2} = C y_c$ $1.0 \leq C \leq 1.5$	$\sqrt{\frac{A_c^2 D_c}{A^2 D}} = f\left(\frac{y}{y_c}\right)$	$\frac{1}{C} \cdot \frac{y}{y_c} (1+C_2 F^2)$ $C, C_1, C_2 = f(b, Z)$
TRIANGULAR 	$\sqrt[5]{\frac{4\alpha Q^2}{Z^2 g}}$	$\frac{5}{4} y_c$	$\left(\frac{y}{y_c}\right)^{-2.5}$	$\frac{4}{5} F^{-2/5} + \frac{1}{5} F^{8/5}$
CIRCULAR 	Tablas C_3 E_c $0 \leq \frac{E_c}{D} \leq 2.1$ $0.464 \leq C_3 \leq 0.75$ $C_3 = f\left(\frac{E_c}{D}\right)$	$y_c + \frac{D_c}{2} = C y_c$ $1.33 \leq C \leq 2.16$	$\sqrt{\frac{A_c^2 D_c}{A^2 D}} = f\left(\frac{y}{y_c}\right)$	$\frac{1}{C} \cdot \frac{y}{y_c} (1+C_2 F^2)$ $C, C_1, C_2 = f\left(\frac{y}{D}\right)$
PARABOLICA 	$\frac{3}{2} \sqrt[3]{\frac{Q^2}{g T_c^2}}$	$\frac{4}{3} y_c$	$\left(\frac{T_c}{T} \cdot \frac{y_c}{y}\right)^{1.5}$	$\frac{5}{4} \cdot \frac{y}{y_c}$

Table 5. Flow characteristics of the prismatic sections

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