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Analysis of Manning coefficient for small-depth flows on vegetated beds

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Abstract:

The Manning formula's main limitations are analysed when applied in extreme conditions, and more specifically with small-depth flows on natural-vegetation beds. A thorough analysis is made of research carried out on macro-rough beds, placing particular emphasis on vegetated beds. Research carried out to date on the roughness of vegetated beds and macro-roughness is commented on, including that carried out at the Laboratory of Hydraulics and Hydrology of the Forestry Engineering Faculty (Polytechnic University of Madrid). The work was done in two phases, the first in a laboratory channel with artificial vegetation and the second in natural beds. The results of the experimental research allow the development of a new approximate method of determining Manning coefficient according to the Froude number. This method may be applied in extreme conditions, both in small depths and steep slopes. It was proved that the Manning coefficient depends not only on roughness height, but also on depth and slope values; thus, it is advisable to choose the appropriate method for its calculation. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS roughness; Manning coefficient; flows; runoff velocity

INTRODUCTION

The Manning formula is one of the most widely used formulas for calculating flow velocity in open channels. It calculates flow velocity as a function of hydraulic radius, slope and a roughness coefficient that quantifies the brake effect of the pouring liquid bed. This is not the only formula to quantify flow velocity, but it is the most commonly used and continues to be preferred for researchers in bed roughness.

A widely used application of the Manning formula is in quantification of channel-draining flow velocity. It provides accurate results partly due to the equation's origin, which was developed in laboratory channels after exhaustive analysis on roughness coefficients, and partly to the occurrence of flows in optimal draining conditions (i.e. small slopes, constant and regular sections, smooth draining surfaces). However, the formula is far less accurate when getting away from these optimal conditions. This lack of accuracy is mainly due to the following reasons:

1. Both the Chezy and Manning formulas match the weight component in the tangential slope direction P_x and the bed resistance tension on flowing water F .

When matching these two forces, the hypothesis is that the whole flow resistance effect exists between the contact surface of the wet perimeter and the upper soil layer. This is only a correct hypothesis when the bed allows for real smoothness, and the depth remains great enough. This only occurs in artificial channels flows, normally with regular and constant sections.

If these strict conditions do not apply, e.g. in small-depth beds (macro-rough) and in flows with highly variable sections, which are common characteristics in small-depth flows on native-vegetation sloping beds

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(very heterogeneous), then the roughness induces resistance not only in the layer in contact with the wet perimeter, but also due to the existence of relatively big vertical elements (herbaceous species' leaves, shrubs and/or trees' stems) within the flow that are responsible for a resistance force with different effects, including an additional resistance to be summed up to that induced by the direct contact of bed and flow. This resistance will grow bigger, logically, with the vegetation elements' size or with diminishing depth, i.e. when the relative roughness becomes smaller.

2. The Manning roughness coefficient is not constant, it depending on depth and slope: the greater the depth, the smaller the coefficient; this is due to the minimization of the relative roughness, with the effect being similar to a slope increase.

Research in this area can be classified in two types, according to the objectives and methods:

1. The first type includes research whose main target is the development of new formulas and calculation methods of flow velocity, especially when the Manning formula premise is inexact (e.g. Jarret, 1990).
2. The second type concerns research on Manning coefficients that allows for the determination of an exact numeric coefficient in every application and in every bed type when the formula is nowadays not exact (tables). And there is also the development of methods or formulas capable of determining the coefficient in extreme conditions (e.g. Ree and Palmer, 1949; Temple, 1980; Kao and Barfield, 1978; Jin *et al.*, 2001). In both cases the Manning formula is considered, rather than some of its modified forms. Within this group, a second division may be established according to the research method:

- Research in the laboratory or in natural channels. With this first method, the Manning roughness coefficient can be deduced from depth analysis and/or the flow velocity in tests.
- Using the hydrogram method, by means of artificial rain to generate runoff on a plot. A hydrogram is created and then the coefficient is worked out. This method is normally used for small-depth flows.

RESEARCH ON VEGETAL ROUGHNESS BEDS

Ree and Palmer (1949) were the first researchers to analyse the roughness coefficient in vegetated beds. They concluded that this coefficient is not constant, but varies according to the draining layer's weight influence. Thus, they established the coefficient's dependence on the product of velocity v and hydraulic radius R : the bigger this product, the smaller the coefficient n . In other words, the roughness resistance becomes smaller when vR increases.

The USDA Soil Conservation Service (1954) then created tables to determine the Manning coefficient when applied to different bed channels.

Another research method is based on experimental tests using artificial elements (cylinders, sticks, etc.) to simulate natural vegetation and quantifying their flow resistance. Einstein and Banks (1950) developed an equation for sticks' density. Also, Robinson and Albertson (1952) tested artificial standard roughness; similarly, Sayer (1961) determined the flow delay for various roughnesses. Kowobari *et al.* (1972) not only analysed the roughness coefficients, but also developed a flow resistance model. Taylor and Brooks (1962) differentiated two kinds of roughness, one due to bare soil and another to vegetation, and Petryck and Bosmojian (1975) established a model through the differentiation of the dragging force on the bed and the resistance of vegetation on the flow.

Temple (1980, 1982, 1983) carried out important research on flows in vegetated beds by trying to develop a model for flow resistance in herbaceous-vegetation channels and a method for calculation in channels covered with weeds.

Temple determined the vegetation conditions affecting resistance, and thus the Manning coefficient, according to two parameters, one dependent on vegetation (C_1) and another due to flow conditions (R_v).

The importance of Temple's research lies in the development of a fairly accurate method to determine the herbaceous vegetation resistance according to its size and density, thus obtaining a quantitative value for the roughness coefficient.

The research was based on a modification of the dragging force equation, expressed as

$$\tau_c = \gamma d[(1.0 - C_F)]j$$

where C_F is an empirical parameter describing the vegetation cover's ability to dissipate whirlpool turbulence, d is the average flow depth, γ is water specific weight, and j is bed slope.

Now, substituting:

$$j = (n_s/n)^2$$

where n_s is the Manning soil number and n is the total Manning number, we obtain

$$\tau_c = \gamma d[(1.0 - C_F)(n_s/n)^2]$$

The vegetation cover coefficient C_F fluctuates with the values in USDA Soil Conservation Service (1954) tables, according to the herbaceous vegetation type.

To determine coefficient C_1 , Temple also used the USDA Soil Conservation Service (1954), where this coefficient is a function of the type and density of grass. Once C_1 is determined, the parameter n_r is established, which is quite similar to the Manning roughness coefficient.

Kao and Barfield (1982) carried out research that was similarly targeted, i.e. development of a method for the design of grassy channels. They used artificial vegetation to simulate herbaceous vegetation in laboratory channels and obtained a mathematical formula that considered the resistance coefficient R_d of the leaves.

The analytical phenomenon approach is different from that formerly commented on for Manning formula deduction. Now, it is based on the following equations:

$$\text{Weight component} = \sum \text{Resistance forces}$$

$$\text{Resistance forces} = \text{Leaf resistance} + \text{Dragging bed forces}$$

Kao and Barfield (1982) displayed their results following the graphic way developed by Ree and Palmer (1949), i.e. by plotting the νR values on the x axis using a logarithmic scale and plotting the Manning roughness coefficient values on the y axis.

These graphs show an initial zone where the νR values are small and the curve increases slightly. This νR increase implies an increase in the Manning coefficient. A maximum is reached, whereupon the curve starts to descend. From this maximum onward, an increase in νR means that the Manning value decreases, since increasing depth means that the vegetation becomes immersed. In addition, though its total resistance remains constant when depth increases, the drag force also increases and the relative resistance diminishes; therefore, the roughness coefficient also diminishes.

Jin *et al.* (2001) carried out research to estimate the Manning coefficient, when applied to small depths and not-immersed vegetation in a laboratory channel, based on the development of a two-part Manning coefficient, one concerning the soil friction n_0 and the other the vegetation resistance on the flow n_v . The conclusions, among others, were: in small-depths flows with not-immersed vegetation, a flow depth increase implies a slight velocity increase (far below if using the Manning formula); the velocity depends on the slope and vegetation density, since an increase in depth, and thus in the drag force, means an increase in vegetation resistance on the flow. The soil roughness coefficient n_0 is relatively unimportant compared with the vegetation roughness coefficient.

Jarret (1990), from the US Geological Survey and Rocky Mountain Hydraulics Laboratory, carried out further tests on macro-roughness beds. He focused not on vegetation roughness, but on torrent-bed roughness. However, this is referred to since it is an analysis on natural macro-rough beds and high slopes. When relating

the Manning coefficient values and relative roughness, it will be observed that an increase in the n latter means n diminishing. From these data, Jarret (1990) tested a new Manning coefficient formula (as a function of slope and hydraulic radius) and a flow velocity formula (consisting of a modification of the original Manning formula exponents and, more specifically, on a diminishing slope exponent).

As was previously commented upon, the second research type concerns the hydrogram method. This method was developed on agricultural plots, with the main target being the analysis of runoffs and particularly the n roughness coefficient, jointly with other hydraulic parameters.

Emmet (1970) worked on superficial flow behaviour in natural beds with a wide slope interval. Other workers would obtain a really wide variation range for the Manning coefficient, and generally high values. For example, Burman and Black (1970) and Ree *et al.* (1977) observed values between 0.21 and 0.60 in land plot tests. A similar study was carried out by Foster *et al.* (1982) using dyes in the water flow.

Neibling and Foster (1977) obtained smaller Manning coefficient values compared with those obtained in other studies, mainly due to velocity monitoring with colorants and to the use of a method that increased velocity. Engman (1986) researched coefficients for superficial runoff on plots under artificial rain and with a range of soils.

Determination of the Manning roughness coefficient in slopes with small depths and natural-vegetation beds

The Laboratory of Hydraulics and Hydrology of the Forestry Engineering Faculty (Polytechnic University of Madrid) carried out certain research on slope flows, when characterized by native vegetated beds and small depths, similar to runoff flows, so as to analyse and measure the hydraulic parameters describing these flows.

This research contributes with innovative work on small-depth flows on high slopes and with native vegetation, but considering all three together (and not only with herbaceous vegetation, as in many previous studies).

MATERIALS AND METHODS

The experimental tests consisted of two different phases, one carried out in the laboratory (**where a velocity measurement methodology based on colourings and needles for depth measurement were tested**) and the other on real slopes, situated in Puebla de Valles municipal district (Guadalajara, Castilla la Mancha, Spain), **whose geographical coordinates are latitude 40°56' and longitude 3°16'**. In this second phase, field equipment was used that consisting basically of a channel to set the flows through, which included the following elements (see Figure 1): an upper weir-tank, channel walls, a lower weir-tank, and a sticks board (for depth measurement). Apart from these elements, a motor-pump was needed and a water tank large enough to store the water volume needed for the tests. Other complementary instruments were also required.

Before the tests are done, the afore mentioned equipment must be installed in every chosen bed. Field channels dimensions were approximately 1 m in width and over 12 m in length.

The importance of this research lies in getting values for hydraulic flows parameters on the same slopes where runoffs responsible of erosion and water floods flow. In order to carry out the tests on different slopes, the equipment is collapsible and easily transported to different testing beds.

The test consists briefly in reproducing a runoff flow on the slope, inside the channel walls. The water comes from the upper weir-tank, previously filled by way of pumping equipment from an exterior weir, prepared specifically for the testing.

When the weir-tank is full, water pours through the spillway; flow entering the channel can thus be measured with this spillway (triangular type, 30° opening, thin crested). As water spills onto the bed, most of the water volume entering is infiltrated into the soil, and captured by vegetation and/or wets the soil, and only a small part of the volume entering drains off the bed. However, as time goes by, normally after no more than 10 min, the soil and vegetation environment becomes saturated and flow increases, although in many experiments it

Figure 1. Field channel equipment diagram

will not reach the total flow entering, since some is lost through infiltration through the walls and some gets to the lower soil horizons.

When water goes into the lower tank and pours through the spillway, the water loss rate is checked with these measurements (flows balance). The test was considered to be valid when the flow difference was smaller than 15%. From then on, flows were measured, considering the calculated flow as the average value between the flows coming into and going out and with the help of the needles-carrier board.

The needles-carrier board consists of a metallic frame with a number of thin steel sticks set into it, containing a wire thinner than the stick in their lower part, and a millimetre-rule. These sticks allow for depth measurement and, thus, determination of average flow in every section. By using these two parameters (and using slope values), the velocity, the Manning roughness coefficient, and the Reynolds and Froude numbers can be calculated.

Apart from the aforementioned condition, that of flow difference being smaller than 15%, flow erosion wear was demanded to be a minimum, so that in cases where gullies existed, the bed and the last test were rejected. By doing so, a certain regularity in the flows was obtained.

The number of sections where measurements were done varied for every test, from a minimum of two to a maximum of four.

The average depth for a section was calculated with the measured depth values, and with these values the average depth for all sections was calculated again, obtaining the final average depth value in a test.

RESULTS AND DISCUSSION

The test sites are listed in Table I, with a description of the vegetation type and slope value. Eleven tests were carried out, and since every test would include several measurements, the total number of measurements was 38. The calculations leading to hydraulic parameters determination were done in two different ways: first, by obtaining an average value in every test; second, by making a calculation in every section and getting a value for every one of these sections. The average resulting values in every test are shown in Table II, and the average hydraulic parameter values in every test are shown in Table III.

It is also necessary to highlight some of the differences existing between the different beds. Bed number three is one of the types with *Cistus ladanifer* shrubs; this typically Mediterranean shrub, usually known as rockrose, is very common in degraded areas. It characteristically inhibits the presence of other species, e.g.

Table I. Test beds and summary of vegetation types and slopes

Test beds	Channel vegetation characteristics (main species)	Slope (%)
1. Grassland	Grassland consisting of species such as <i>Dactylis</i> sp., <i>Lolium</i> sp., <i>Festuca</i> sp., <i>Trifolium</i> sp., Familia Compositae, etc. Cover reaches 80%	11.7
2. Scrubland on previous works	Grassland with same species as in bed 1, but with lighter cover	29.5
3. Scrubland with rockrose and rosemary	Scrubland consisting basically of <i>Rosmarinus officinalis</i> , <i>Cistus ladanifer</i> , <i>Thymus</i> sp. Same species as in bed 2, but bushes (height 50–80 cm) being dominant	37.0
4. Scrubland and pine forest	Grassland consisting basically of Graminae	15.3
5. Pine forest	Dominant species in the scrubland: <i>Cistus ladanifer</i> , <i>Rosmarinus officinalis</i> , <i>Thymus</i> sp. Wooded area: scattered pine trees (<i>Pinus pinaster</i>) Young pine forest (~40 years), dominated by <i>Pinus pinaster</i> and <i>Pinus nigra</i>	13.8
6. Pine forest	Scrubland and grassland similar to 4 Young pine forest (~40 years), dominated by <i>Pinus pinaster</i> and <i>Pinus nigra</i> Scrubland and grassland similar to 4 and 5	15.2

Table II. Average results on natural beds tests

Bed	Test	Flow (m ³ s ⁻¹)	Depth (m)	Velocity (m s ⁻¹)	Manning coefficient	Froude number	Reynolds number
1 (grassland)	1	0.0042	0.029	0.129	0.244	0.242	3.741
	2	0.0151	0.046	0.293	0.143	0.436	13.478
	3	0.0270	0.061	0.395	0.125	0.510	24.095
2 (cut scrub.)	1	0.0083	0.031	0.243	0.211	0.441	7.533
	2	0.0045	0.030	0.136	0.368	0.251	4.080
3 (rockrose)	1	0.0028	0.025	0.100	0.505	0.202	2.500
	2	0.0133	0.032	0.371	0.158	0.663	11.872
4 (scrub./pine)	1	0.0031	0.019	0.141	0.190	0.326	2.679
	2	0.0061	0.020	0.263	0.106	0.594	5.260
5 (pine forest 1)	1	0.0086	0.023	0.389	0.075	0.819	8.947
6 (pine forest 2)	1	0.0035	0.018	0.177	0.147	0.421	3.186

Table III. Average hydraulic parameters in every test

Depth (m)	Velocity (m s ⁻¹)	Manning coefficient	Froude number	Reynolds number
0.028	0.169	0.241	0.351	4259

herbaceous vegetation. That is why roughness is mostly due to *Cistus ladanifer* stems. This peculiarity, the absence of herbaceous vegetation, leads to the appearance of small channels as the flow increases, consequently producing a reduction in the Manning roughness coefficient. However, these small channels are not big enough to modify the bed.

As for pine stands, the presence of pine leaves on the soil is also a reason for the reduction in herbaceous vegetation, which means that the roughness coefficient will tend to diminish.

As was mentioned previously, tests with a flow balance smaller than 15% were considered valid. This requisite could seem excessive, but it must be taken into consideration that these types of flow research on slopes with natural vegetation have a large heterogeneity, both in the own vegetation and in the bed microtopography, resulting in dissimilar values. In fact, this occurred with depth values, and, consequently, with the hydraulic parameters obtained through these data. However, agreement between experiments and real conditions is achieved on some occasions, in situations analogous to those in which run-off phenomena in slopes are produced. Thus, results in tests on pasture beds were homogeneous, whereas the heterogeneity increased for the other beds.

If work is to be done in laboratory channels, then flow control conditions and hydraulic variables measurements could be a lot better in comparison with test conditions in real beds. Especially difficult in those cases would be to represent real vegetation and soil conditions present in natural mountainous slopes with enough similarity to achieve a good representation of natural phenomena in the test.

Table III shows clearly that the main testing flow characteristics are the small velocity values, thus indicating a high roughness ($n = 0.24$).

When comparing these results on natural beds with those of Kao and Barfield (1978, 1982)●, it is clear that the Manning coefficient values for bed 1 on grass have a similar order of magnitude as those obtained by Kao and Barfield (1978, 1982)● for soft-rigidity vegetation with a leaf density of 13.170 m⁻².

Another interesting comparison is that between our data and the values from Jarret's (1990) formula for the matching depths and slopes at the flows tested. Similar order of magnitude values are obtained when the results are displayed in a graphical form like that in Figure 2.

Apart from these comparisons, the research looked for a certain correspondence between the resulting Manning coefficient values and other hydraulic parameters. After several attempts with different parameters, just one possible matching was found, between the Manning coefficient and Froude number.

The Manning equation can be expressed as

$$v = \frac{1}{n} R^{3/2} j^{1/2}$$

where v is the flow velocity, R is the hydraulic radius, and j the bed slope. With the test channels being quite wide (up to 1 m) and the depth much smaller (just a few centimetres), the hydraulic radius can be changed for the depth, resulting in the following Manning equation:

$$v = \frac{1}{n} d^{3/2} j^{1/2}$$

On the other hand, the Froude number F has the following expression:

$$F = -\frac{v}{\sqrt{gd}}$$

Figure 2. Comparison between Manning coefficient values in natural beds (lecho natural) tests and matching values obtained through the Jarret (1990) formula

where d is the flow depth and g is the acceleration due to gravity. Obtaining velocity as a function of the Froude number and substituting in the Manning equation, we get the following:

$$n = \frac{(gd)^{-1/2} d^{2/3} j^{1/2}}{F}$$

and simplifying:

$$n = \frac{g^{-1/2} d^{1/6} j^{1/2}}{F}$$

Thus, it can be observed that the Manning roughness coefficient depends on the sixth root of the depth, the square root of the slope, and is inversely proportional to the Froude number.

So, regression curves between the Manning roughness coefficient and the Froude number, with no consideration of the other variables, will be similar to the former expression, i.e. the Froude number must be inversely proportional to the Manning roughness coefficient.

After observation of the data distribution in the graph of these parameters, it could be seen that beds with lower slopes reached lower values compared with those of higher slope. Thus, the data were separated into two graphs, one with test values with slopes lower than 20% and the other with slopes higher than 20%. After the separation, it can be seen that the Froude number adjustment was better. This is why two regression curves for the Manning coefficient and Froude number are displayed, the first for slopes under 20% in Figure 3 and the second for slopes over 20% in Figure 4. Figure 3 shows the curve for n values and slopes under 20% and Figure 4 shows the curve for n values and slopes over 20%.

The curve with the bigger correlation coefficient is of the power type:

$$Y = 0.0682X^{-0.9579}$$

where Y is the Manning coefficient, X is the Froude number and the regression coefficient $r^2 = 0.9747$.

In the second curve (Figure 4), the power function is defined by the expression

$$Y = 0.0994X^{-1.0085}$$

where the variables X and Y have the same meaning and $r^2 = 0.9868$.

Figure 3. Regression graph of Manning coefficient values for bed slopes <20% versus Froude number

Figure 4. Regression graph for Manning coefficient values for bed slopes >20% versus Froude number

The Manning coefficient being related to Froude number means new ways to determine n for small-depths flows on natural vegetation beds and in high slopes. Therefore, a new approximate method for the Manning coefficient determination is shown in the following section.

Approximate method for Manning roughness coefficient calculation after research on natural-vegetation beds

Considering (1) that values obtained for the Manning coefficient are of the same order of magnitude as those obtained by Kao and Barfield (1978) and Jarret (1990), (2) that there is not much research on the Manning coefficient in natural-vegetation beds with small depths and high slopes, and (3) the good adjustment of the regression curves when related to the Froude number, it seems convenient to use all these results in the Manning coefficient approximation in flows with these characteristics.

In order to apply the present research's results in an actual bed, the bed's characteristics should conform to the values examined in this study. These bed and flow conditions are discussed below.

Slope. The minimum slope was for the grass bed (11.2%) and the maximum slope tested was in a rockrose bed, reaching 37.5%. Thus, the slope analysed should be situated between these two extremes; however, a value in excess of this maximum would be admitted.

Depth. Since the research focused on small depths, the method is directly applicable to those, with no lower limit. With regard to an upper limit, some tests were made with depths over 10 cm, but these values were only local. Therefore, this method is to be applied for depths under 10 cm, but could be exceptionally used for depths under 15 cm, when the flow Froude number is low enough.

Vegetation. Existing vegetation in the study bed must be analogous to any other described in the tests, i.e. with similar density and structure, though not necessarily the same species. **In this sense, it is important to consider that the vegetation structure and density depends on the environmental conditions, and particularly on the available moisture for plants. More specifically, the annual precipitation in the study area reaches 785 mm and the annual average temperature is 12.2 °C. Soils have a loamy texture and are not very permeable.**

Froude number. The Froude number interval varies between 0.15 and 0.9. Froude numbers under 0.15 should also be accepted, although numbers over 1.0 are very rare on small-depth flows.

The calculation process for the Manning coefficient approximation with the method developed by the Laboratory of Hydraulics and Hydrology (Forestry Engineering Faculty) is as follows.

The Manning coefficient approximation is carried out for a certain slope and flow, so that the following calculations must be made once we have a certain flow q_0 :

1. According to slope value P , the first ($j < 20\%$) or second ($j > 20\%$) curve will be used.
2. A first Manning coefficient value n_0 is selected, between those possible in the graph (0.1–0.6), according to the visual characteristics of the place whose Manning coefficient is being evaluated.
3. Velocity is calculated through flow data q_0 , slope j and the Manning coefficient previously selected. So as to, Manning formula is applied, specifically for the unitary flow:

$$V_0 = [(1/n_0)q_0^{2/3} j^{1/2}]^{3/5}$$

4. Once V_0 is determined, the flow area per unit width is calculated with the continuity equation. Since the section is rectangular, with unit width, the area per unit width is similar to the depth, and, as was previously mentioned, the depth can be considered equal to the hydraulic radius:

$$y_0 = q_0/V_0$$

5. Once V_0 is determined, depth is calculated through the continuity equation:

$$y_0 = q_0/V_0$$

6. After V_0 and y_0 , the Froude number is calculated.
7. This Froude number value allows us to determine, by means of the matching regression curve equation, the new Manning coefficient n_1 , which remains closer to the flow characteristics. A value for the relative error must also be chosen (e.g. 15%). Should this n_1 value be too close to n_0 (i.e. relative error smaller than the pre-set one), then the process would have come to its end, thus validating the depth and velocity obtained. On the contrary, i.e. when the difference between n_0 and n_1 exceeds the former quantity, n_0 would be substituted by n_1 and the process should be iterated until this difference is less than the previously fixed relative error.

With the purpose of clarifying the process, the following case study shows in a practical way the above recommendations.

Case study

Supposing we have a unitary flow of 15 l s^{-1} pouring on a slope of 17% on a vegetated bed which keeps up pre-set conditions.

1. Slope is lower than 20%, so we are to use the first curve.
2. A random value is chosen for the Manning roughness coefficient, according to slope characteristics, e.g. 0.2.
3. Velocity is calculated through the Manning equation for the flow conditions given.

$$V = [(1/n)q_0^{2/3}j^{1/2}]^{3/5} = 0.287 \text{ m s}^{-1}$$

4. Once the velocity is known, the depth is calculated:

$$y = q_0/V_0 = 0.052 \text{ m} = 5.2 \text{ cm}$$

5. Using the depth and velocity values, the Froude number is determined:

$$F = 0.402$$

6. Introducing the Froude number in the regression equation for slopes lower than 20%, the most accurate Manning coefficient value is obtained:

$$n = 0.0682F^{-0.9579} = 0.163$$

7. The relative error is therefore

$$E = [(n_0 - n_1)/n_0] \times 100 = 18.5\%$$

The error is bigger than 15% (fixed as the maximum allowable), so the whole process should be re-done, getting 0.137 as the new Manning coefficient value.

8. The relative error is thus analysed once again; but its value is 16.01%, so the process must be reiterated, reaching a relative error of 14.8%, and validating, therefore, the matching Manning coefficient, which turns out to be $n_3 = 0.117$.

9. Also, the depth and velocity values corresponding to the drainage characterized by 15 l s^{-1} unitary flow and 17% slope, are the following. They are compatible with the Manning coefficient value.

$$v_3 = 0.306 \text{ m s}^{-1} \quad d_3 = 0.048 \text{ m} = 4.8 \text{ cm}$$

CONCLUSIONS

1. Manning coefficient values vary according to bed slope, as proved by Kao and Barfield (1978, 1982) and Jarret (1990), and also in our own research at the Laboratory of Hydraulics and Hydrology of the Forestry Engineering Faculty. Variations in the values diminish when the slope increases.
2. Manning coefficient values obtained in our tests are similar in order of magnitude to those resulting from application of the Jarret (1990) formula and the values obtained by Kao and Barfield (1978).
3. Application of the Manning formula to small-depth flows must be carried out with specific roughness coefficient values, determined in specific research. Coefficient values tested on large-depth flows should not be applied, even those with analogous roughness.
4. Flow depth diminishes with Manning formula accuracy. Should the bed be composed of gravel, then the relative roughness parameter could be used in order to quantify the inaccuracy of the Manning formula. When working with small relative roughness, generic and conventional Manning coefficient values should not be used; the Jarret (1990) method would be otherwise advisable in gravelly beds.

5. In those cases of non-gravelly beds and application conditions fulfilment, the following methods may be used.

In grassy beds, any of the methods of Kao and Barfield (1978), Temple (1983), and Jin *et al.* (2001) would be appropriate. The first is advisable when depths are small and/or the vR parameter is small. When depths are higher the second method is more advisable, since Temple considers variations in grassy vegetation in detail.

In native-vegetation beds, with small-depths flows and especially in high slopes, the method developed by the Laboratory of Hydraulics and Hydrology of ETSI Montes may be used under conditions previously described. This method is even advisable in grassy and highly sloped beds (considering slopes to be high from 10%), since Temple (1983) and Kao and Barfield (1978) carried out exhaustive tests, phenomenon analysis and data recompilation, but not for high slopes.

ACKNOWLEDGEMENTS

The experimental phase of the present research began in 1993, simultaneously with field work in research project FOR 90-1005-C02-01, 'Analysis of protecting efficacy of forest cover, implantation and silvicultural treatments' directed by Professor Rafael Serrada Hierro. Its implementation was possible thanks to support from the Agricultural and Environmental Regional Ministry of Castilla-La Mancha, in Guadalajara province (Spain), and more specifically from the Fire-fighting Service. Also, Puebla de Valles City Council in Guadalajara (Spain) must be acknowledged for land cession for field tests.

Special thanks are due to Professor Juan Ángel Mintegui Aguirre, who contributed and guided greatly all through the research process. Thanks also to Professor José Luis García Rodríguez, Professor José Carlos Robredo Sánchez and forestry engineer Manuel Guijarro for their contributions in the field work implementation described in this text.

Finally, it is to be said that project FOR 90-1005-C02-01 was financed by CICYT (Education and Sciences Ministry), and the other research commented through the present document was financed in the final phases by the LUCDEME Project (Environment Ministry).

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 - AQ7 Stories?
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 - AQ10 adjustment? Don't thank you mean it is correlation? (and then it would be "correlation with n was better")
 - AQ11 Don't think you mean adjustment
 - AQ12 concrete = sand + cement + gravel.
 - AQ13 Kao year(s)?
 - AQ14 still?
 - AQ15 vol no?
 - AQ16 Missing vol. no?
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